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DRAFT General Mission Analysis Tool (GMAT) Architectural Specification

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Preface

Welcome to the programming side of the General Mission Analysis Tool, GMAT! This document describes the design of the GMAT system, starting from an overview of the requirements for the system and the architecture built to meet these requirements, and proceeding through descriptions of the design for the components that fit into this architecture.

The purpose of this document is to give the reader an understanding of the design goals and implementation of GMAT. It is written to prepare you to work with GMAT at a source code level. In this document we present the rationale for GMAT's architectural design based on the requirements for the system, and then construct the architecture based on that rationale.

The architectural framework is presented taking a top-down approach. First we define a way to think about GMAT's structure in terms of high level functionality, grouped into logical packages. Then we examine key elements of these packages, and explain how they interact to complete a few typical tasks. With a few exceptions, we do not document the details of the classes and objects in the system. That task is left to the GMAT API, generated using the Doxygen[doxygen] open source tool.

Intended Audience

This document is written primarily for people interested in working with GMAT's source code, either to enhance the system by adding new components, to debug existing features in a way consistent with GMAT's design, to gain insight into pieces of the system that they may want to use elsewhere, or to learn how GMAT was assembled to help design a similar system. The primary audience for this document is the software development community – programmers, system analysts, and software architects.

Analysts that are interested in understanding how GMAT performs its tasks can gain an understanding of the system by reading the first few chapters of this document. If some element of GMAT is not behaving the way you expect, you might also want to look up the description of that object in later chapters. In addition, many of the details about how calculations are performed in GMAT are contained in the Mathematical Specifications[MathSpec]. If you are more interested in understanding how to use GMAT as an analyst, you might want to read the User's Guide[UsersGuide] rather than this document.

Assumed Background

The GMAT design was developed using object-oriented technologies. The design is presented using Unified Modeling Language (UML) diagrams, using a style similar to that presented in **UML Distilled**[fowler]. You can find a description of the use of UML diagrams as used in this document in Appendix A. While you don't need to be an expert in either of these fields to understand the content presented here, you will benefit from some preliminary reading at an introductory level.

The GMAT design leverages several industry standard design patterns. The patterns used are summarized in Appendix B. If you are unfamiliar with the design pattern literature, you'd benefit from reading – or at least skimming – some of the standard texts (see, for example, **Design Patterns**[GoF]).

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GMAT is written in C++. On the rare occasions that actual code is presented in this document, that code is in C++. As you go deeper into the GMAT's design, the underlying coding language will become more important. Therefore, if you plan to work with the GMAT source code, you'll need to have an understanding of the C++ programming language.

In addition, the standard GMAT GUI is written using the wxWidgets[wx] GUI toolkit. If you plan to work with GMAT's GUI code, you'll want to bo some preliminary exploration of wxWidgets. A good place to start is the wxWidgets book[smart], which, while slightly out of date at this writing, does present a rather complete description of wxWidgets.

Useful Preliminaries

This document describes the GMAT source code – sometimes at a very high level, but also at times at a rather low level of detail. You'll benefit from having a copy of the current source available for viewing at times when the descriptions found here are not as clear as you'd like. You can retrieve the source code either at the GMAT website (http://gmat.gsfc.nasa.gov/downloads/source.html) or from the download pages or the code repository at SourceForge (http://sourceforge.net/projects/gmat).

This document does not describe the detailed design of every class in GMAT, in part because the resulting document would be extremely large, but also because GMAT is an evolving system. New features are being added to the program as the system grows, so the best view of the details of GMAT can be seen by examining the current code base. If you want a structured view into these details, you should run the open source tool Doxygen[doxygen] on the source code tree. Doxygen will create an extensive hyperlinked reference for the GMAT code that you can browse using any HTML browser.

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Part I

System Architecture Overview

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Chapter 1

Introduction

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Early in 2002, Goddard Space Flight Center (GSFC) began to identify requirements for the flight dynamics software needed to fly upcoming missions that use formations of spacecraft to collect data. These requirements ranged from low level modeling features to large scale interoperability requirements. In 2003 we began work on a system designed to meet these requirements; this system is GMAT.

The General Mission Analysis Tool (GMAT) is a general purpose flight dynamics modeling tool built on open source principles. The GMAT code is written in C++, and uses modern C++ constructs extensively. GMAT can be run through either a fully functional Graphical User Interface (GUI) or as a command line program with minimal user feedback. The system is built and runs on Microsoft Windows, Linux, and Macintosh OS X platforms. The GMAT GUI is written using wxWidgets, a cross platform library of components that streamlines the development and extension of the user interface.

Flight dynamics modeling is performed in GMAT by building components that represent the players in the analysis problem that is being modeled. These components interact through the sequential execution of instructions, embodied in the GMAT Mission Sequence. A typical Mission Sequence will model the trajectories of a set of spacecraft evolving over time, calculating relevant parameters during this propagation, and maneuvering individual spacecraft to maintain a set of mission constraints as established by the mission analyst.

All of the elements used in GMAT for mission analysis can be viewed in the GMAT GUI or through a custom scripting language. Analysis problems modeled in GMAT are saved as script files, and these files can be read into GMAT. When a script is read into the GMAT GUI, the corresponding user interface elements are constructed in the GMAT GUI.

The GMAT system was developed from the ground up to run in a platform agnostic environment. The source code compiles on numerous different platforms, and is regularly exercised running on Windows, Linux, and Macintosh computers by the development and analysis teams working on the project. The system can be run using either a graphical user interface, written using the open source wxWidgets framework, or from a text console.

The GMAT source code was written using open source tools. GSFC has released the code using the NASA open source license.

1.1 The Tool

Figure 1.1 shows a sample run using GMAT on Windows XP. GMAT can be run using either a custom scripting language or components configured directly from the user interface. GMAT scripting is designed to run either from within GMAT, or from inside of the MATLAB product from MathWorks.

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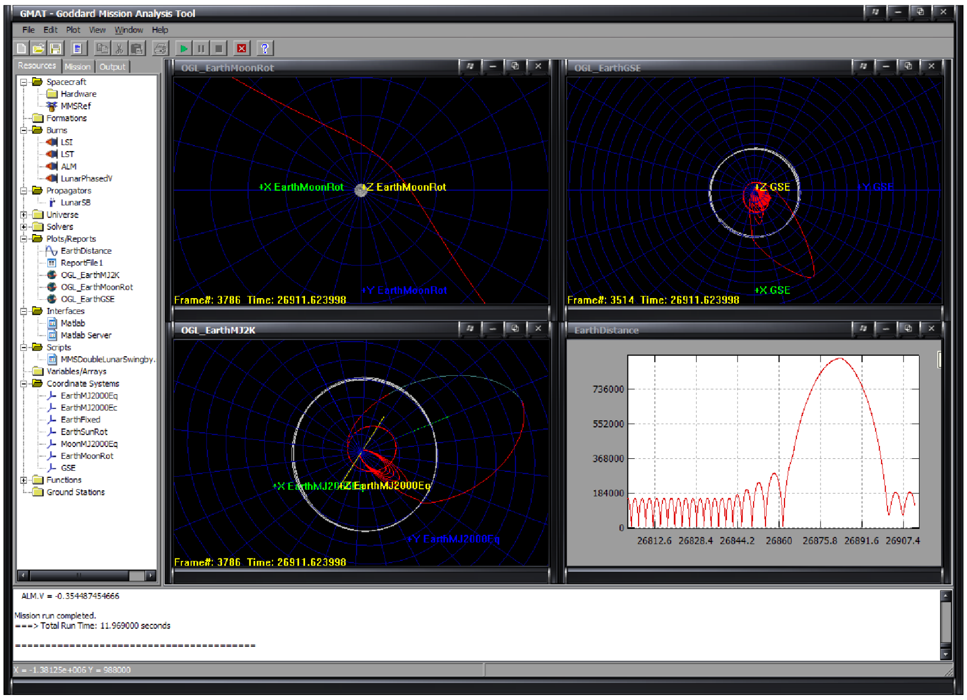

```
 ALM.V = -0.354487454666

Mission run completed.
===> Total Run Time: 11.969000 seconds

==========================================
```

X = -1.38125e+006 Y = 988000

Figure 1.1: A Sample GMAT Run

1.2 Design Criteria

There are several high level requirements for GMAT that drove the design of the system. These requirements can be summarized in five broad categories: MATLAB Accessibility, Extensibility, Formation Modeling, Parallel Processing, and Open Source Availability. The system is designed to run on Macintosh, Windows, and variants of Unix (including Linux) – through a recompilation of the source.

1.2.1 MATLAB Accessibility

MATLAB is a tool used at many facilities in the aerospace community to develop new algorithms and to prototype approaches unique to new missions under consideration. MATLAB as a system is quite flexible, but is rather slow for precision orbit modeling work. GMAT, by design, performs detailed orbit and attitude modeling, providing an engine that can be called from MATLAB for tasks that present performance issues when built in the MATLAB language.

1.2.2 User Extensibility

One prime driver for the development of GMAT was to provide a tool that allows users to try new components and models in the system without rebuilding it from scratch. This capability is partially satisfied by the MATLAB interface described above. Components of GMAT can also be added to the system by writing new code that can be compiled into shared libraries and incorporated into the system at run time. All of the operating systems GMAT supports provide native methods for this capability, and the system is designed to make the addition of new components simple using these capabilities.

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1.2.3 Formation Modeling

The current tool set used to model formations treats a formation of spacecraft as individual spacecraft, modeled independently and then compared by matching states at specific epochs, either on a small scale (taking single steps for each and then comparing the states) or on a large scale (propagating ephemerides for each spacecraft and then going back afterwards to compare states at specific epochs. GMAT provides the ability to treat a collection of spacecraft as a single entity, making the modeling more streamlined and providing the ability to handle formations and constellations as simple entities.

1.2.4 Parallel Processing Capabilities

Some satellite analysis tasks require the execution of many separate orbit propagations, including mission tuning (aka targeting or optimizing) and other mission refinements, in order to adequately model the mission scenarios under analysis. These tasks can take as many as several hundred separate runs, each consisting of several minutes or more of run time on current hardware, in order to determine the results of the analysis problem. GMAT is designed to enable the parallelization of these tasks across multiple processors, either within the same computer or, eventually, across a network of computers. While the current implementation does not leverage this capability, it is designed to make the transition to multiple processors and distributed computing as simple as possible.

1.2.5 Open Source Availability

GMAT is available for external users in both executable and source code form, subject to the NASA Open Source licensing agreement. This redistribution requirement drove design issues related to the selection of external libraries and packages used by GMAT.

1.3 Design Approach

The categories described above drove the architecture of GMAT. The following paragraphs describe the architectural elements used to address these requirements.

1.3.1 Modularity

GMAT is a complicated system. It is designed to be implemented using a "divide and conquer" approach that uses simple components that combine to satisfy the needs of the system. This system modularity makes the individual components simple, and also simplifies the addition of new components into the system. In addition, each type of resource has a well defined set of interfaces, implemented through C++ base classes. New components in each category are created by implementation of classes derived from these base classes, building core methods to implement the new functionality – for example, forces used in the force model for a spacecraft all support an interface, GetDerivatives(), that provides the acceleration data needed to model the force. Users can add new components by implementing the desired behavior in these interfaces and then registering these components in the GMAT factory subsystem.

1.3.2 Loose Coupling

The modularity of the components in GMAT are implemented to facilitate "plug and play" capability for the components that allows them to be combined easily using a set of common interfaces. Components built in the system have simple interfaces to be able to communicate with MATLAB and with one another. Dependencies between the components are minimized. Circular dependencies between components minimized.

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1.3.3 Late Binding

GMAT is designed to support running of multiple instances of a mission simultaneously in order to satisfy parallel processing requirements. This capability is built into the system by separating the configuration of the components used in the mission from the objects used during execution. Configured objects are copied into the running area (the "Sandbox") and then connected together to execute the mission. The connections between the components cannot be made until the objects are placed in the Sandbox because the objects in the Sandbox are clones of the configured objects. This late binding makes parallelization simple to implement when the system is ready for it – parallelization can be accomplished by running multiple Sandboxes simultaneously.

1.3.4 Generic Access

GMAT components share a common base class that enforces a set of access methods that are used to serialize the components, facilitating both file level read and write access to the components and simplifying communications with MATLAB and other external tools. This capability is implemented using parameter access methods that are themselves serialized, providing descriptors for each parameter. Connections between components are specified at this level by establishing parameters that identify the connected pieces by name. Data generated by the system is passed out of the Sandbox through a message interface, using "publish and subscribe" design.

1.4 Document Structure and Notations

GMAT is written in ANSI C++. The system is object-oriented, makes extensive use of the standard template library (STL), and is coded based on a style guide[shoan] so that the code conforms to a consistent set of conventions. The source is configuration managed in a CVS repository hosted at GSFC.

This document provides a fairly in-depth introduction to the design of the software. Throughout this document, the architecture of the system is described using C++ nomenclature. The design of the system is illustrated using Unified Modeling Language (UML) diagrams to sketch the relationships and program flow elements. While this document is extensive, it does not completely document all of the intricacies of each GMAT class. These details can be found most accurately in the source code, which is available on request under the NASA Open Source licensing agreement. The code includes comments written in a style compatible with the Doxygen documentation system. When the source code is processed by Doxygen, the output is a complete reference to the GMAT Application Programmer's Interface (API).

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Chapter 2

The GMAT Design Approach

2.1 Approach to Meeting Requirements

2.2 GMAT's Design Philosophy

2.3 Extendability Considerations

2.4 Platform Considerations

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Chapter 3

System Architecture Overview

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The purpose of this chapter is to introduce the key architectural elements of GMAT, and to explain at a high level how they interact to solve mission design problems. If you are trying to understand how GMAT works, or if you are refreshing yourself in the basics of the GMAT architecture, this chapter is where you should start. After reading this chapter, you should have a high level understanding of how the components in GMAT interact to perform mission analysis.

The chapter is written so that as you read further, you will obtain a deeper the view into the system architecture. We begin by identifying the key system components and grouping them according to the functions they perform. These groupings are referred to as "Packages" and are used to provide a framework for the discussion about how GMAT works.

After presenting the functional GMAT's components, we present a high level view of how these components interact and describe which components interact with each other. This description provides an overview of how messages and data flow in the system. The next level of detail describes how the architecture handles a simple application there a user open the system, creates a spacecraft, configures a mission sequence, and runs the mission.

Later chapters build on these materials. The remainder of this document is organized to take the package descriptions presented at the start of this chapter, and present the design of the elements of these packages. Since the document is structured that way, we'll begin this chapter by examining the logical packaging of GMAT's components.

3.1 The GMAT System Framework

The GMAT architecture can be described as a set of components grouped into functional packages[1] that interact to model spacecraft missions. The system is built around four packages that cooperatively interact to model spacecraft in orbit. Figure 3.1 shows an overview of this package grouping. GMAT functionality can be broken into Program Interfaces, the core system Engine, the Model used to simulate spacecraft and their environment, and Utilities providing core programmatic functionality. The constituents of these packages are described throughout this document; this chapter provides a framework for the more detailed discussions that follow.

Each of these functional categories can be broken into smaller units. The next level of decomposition is also shown in Figure 3.1. This next level of packaging – referred to as "subpackaging" in this document – provides a finer grained view of the functions provided in each package. The next level of decomposition

[1]Note that these divisions are functional, and not enforced by any physical packaging constraints like a namespace or shared library boundaries.

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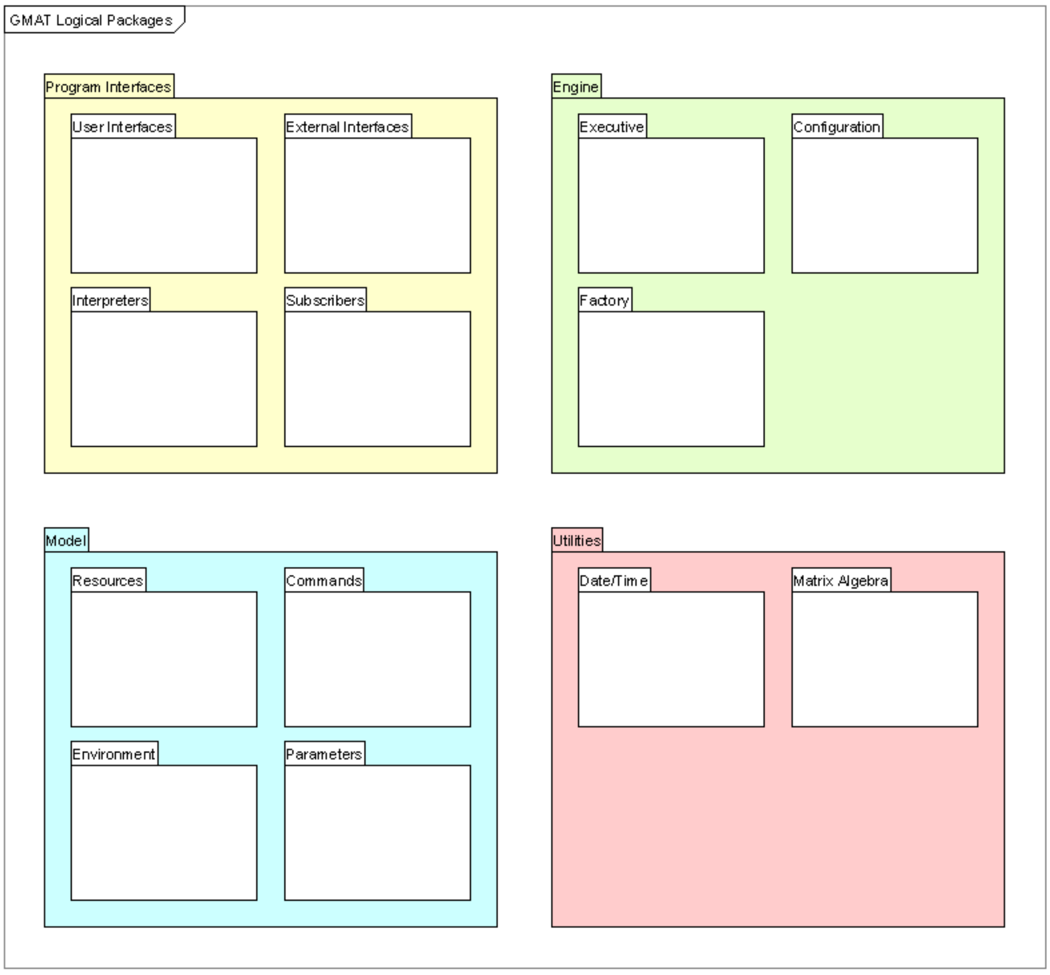

Figure 3.1: Top Level GMAT Packages: Logical Grouping

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below the subpackages provides a view into the class structure of GMAT, as will be seen in the next few paragraphs.

3.1.1 Package and Subpackage Descriptions

Figure 3.2 presents the packages and subpackages in a slightly different format from that shown in the last figure. The top level packages are represented by specific colors matching those in Figure 3.1[2]. The package names are listed at the top of each column, with the subpackages shown indented one level from these packages. One additional level is shown in this diagram, showing representative members of the subpackages. The deepest level items in this figure are classes contained in the subpackages; for example, the Executive subpackage in the Engine package contains the Moderator, Sandbox, and Publisher classes. These elements will be used in the discussion of how the packages interact in the next few pages of this document.

As is shown in these figures, three of these packages can be further broken into subpackages. The following paragraphs present an overview of the packages and their subdivisions.

Program Interfaces All two-way communications between users and external programs and GMAT are contained in the Program Interface package. This package can be broken into four subpackages:

- *User Interfaces* Users view GMAT through a user interface – usually through the GMAT Graphical User Interface (GUI), but also potentially through a command line interface into GMAT called the GMAT console application, or Console. These interfaces are contained in the UserInterface subpackage.

  GMAT's GUI is coded using the wxWidgets cross-platform library[wx]. The GUI provides a rich environment that provides access to all of the features of GMAT through either panels customized for each component or through a text based script. Missions saved from the GUI are saved in the script format, and scripts loaded into the GUI populate the GUI elements so that they can be viewed on the customized interface panels.

  The console version of GMAT can be used to run script files and generate text data with little user interaction. The console application can run multiple scripts at once, or individual scripts one at a time. This version of the system is currently used for testing purposes, in situations where the overhead of the full graphical user interface is not needed.

- *Interpreters* The user interface components communicate with the core GMAT system through an interface layer known as the Interpreter subpackage. This layer acts as the connection point for both the scripting interface and the GUI into GMAT.

  The Interpreter subpackage contains two specific interpreters: a GuiInterpreter, designed to package messages between the GUI and the GMAT engine, and the ScriptInterpreter, designed to parse script files into messages for the engine, and to serialize components in the engine into script form for the purposes of saving these objects to file.

  The Interpreter subpackage is designed so that it can be extended to provide other means of controlling the GMAT engine. All that is required for this extension is the development of a new interpreter, and interfaces for this new component into the Moderator, a component of the Executive subpackage in GMAT's Engine package.

- *External Interfaces* GMAT provides an interface that can be used to communicate with external programs[3]. These interfaces are packaged in the ExternalInterfaces subpackage.

- *Subscribers* Users view the results of a mission run in GMAT through elements of the Subscriber subpackage. Subscribers are used to generate views of spacecraft trajectories, plots of mission parameters, and reports of mission data in file form.

[2]This color scheme will be used for the remainder of this chapter as well.

[3]At this writing, the only external interface incorporated into the core GMAT code base is an interface to the MathWorks' product MATLAB[matlab].

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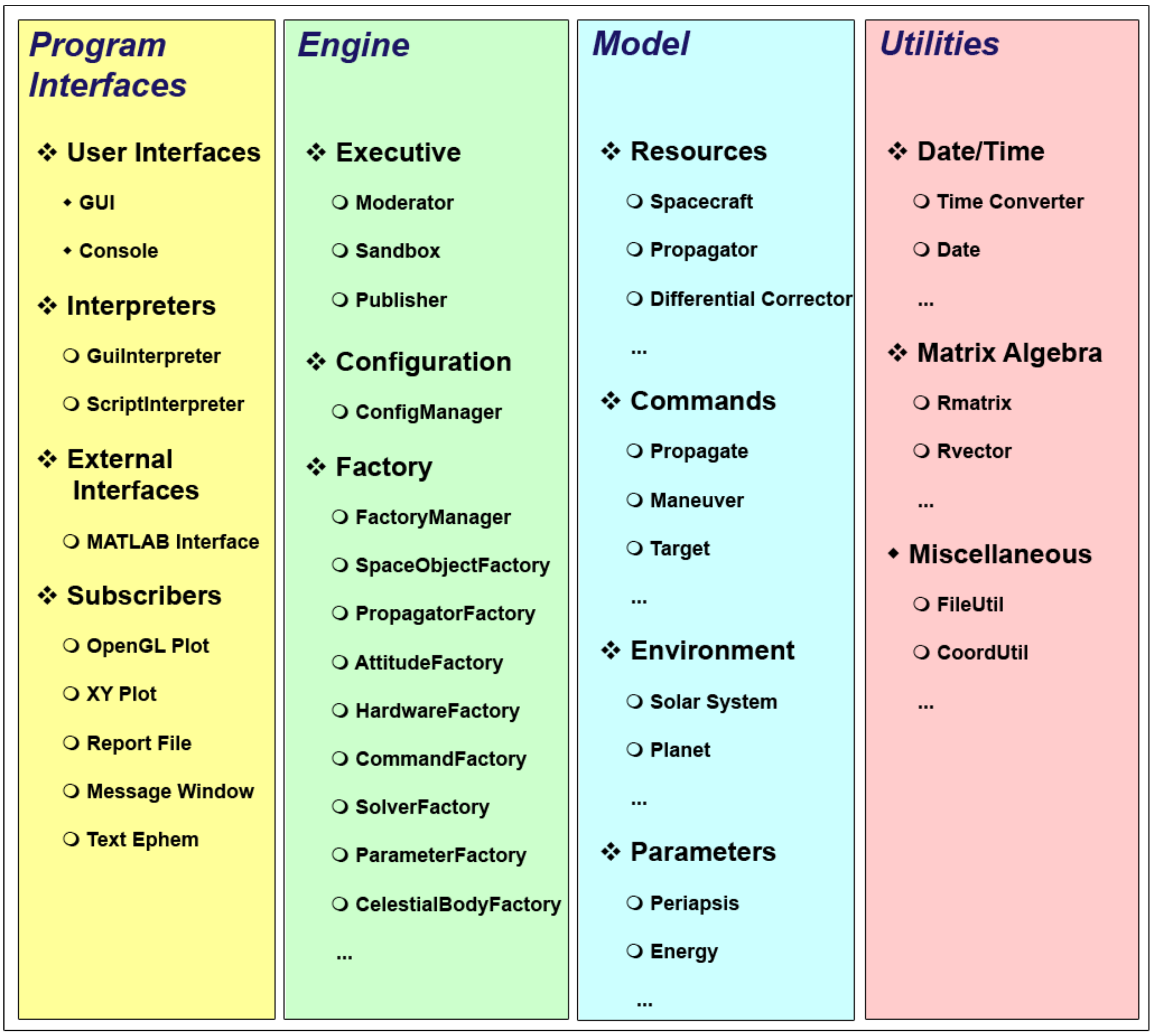

Figure 3.2: Packages, Subpackages, and Some Details
Subpackages are indicated by a cluster of diamonds
Objects and Classes are marked by a circle
Other constructs are marked by a single diamond

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The Engine The interfaces described above exist on top of a core simulation engine used to control the model of flight dynamics problems in GMAT. This engine consists of the control and management structures for the program. The elements of the model used to simulate the spacecraft mission are introduced in the next package description. The Engine package consists of three subpackages:

- *Executive* The Executive subpackage contains the central processing component for GMAT (called the Moderator), a connection point used to capture and distribute the results of a mission run (the Publisher), and the workspace used to run a mission (the Sandbox).

  The Moderator acts as the central communications hub for the GMAT engine. It receives messages from the program interfaces through the interpreters, and determines the actions that need to be taken based on these messages. The Moderator sends messages to the other components of the Engine to accomplish the requested tasks.

  GMAT is designed to run missions inside of a component called the Sandbox. When a user requests a mission run, the Moderator sets up the Sandbox with the elements configured for the run, and then turns control over to the Sandbox to execute the mission.

  The Publisher acts as the connection between data generated in the Sandbox and the views of these data presented to the User. It receives data or instructional messages from the components in the Sandbox, and passes those messages to the corresponding Subscribers.

- *Configuration* When GMAT builds a model, it starts by building components that will be connected together based on a sequence of instructions. Each component is an instance of a GMAT class; as they are built, these components are stored in a local repository of objects. The repository holding model components is known as the configuration. The Configuration subpackage consists of this repository and an interface used to access it, called the ConfigurationManager.

  The components stored in the configuration are all derived from a base class named GmatBase, described in Chapter 9. In GMAT, every object that a user creates and uses to simulate a spacecraft mission is derived from this base class. The configuration is maintained as a collection of pointers to GmatBase objects. The ConfigurationManager works with this collection to maintain the configuration repository.

- *Factory* The model elements stored in the configuration are created on request from the users. The subpackage responsible for processing requests for new model elements is the Factory subpackage. It consists of an interface into the subpackage – the FactoryManager – and a collection of factory classes used to create specific types of model elements.

  Each factory in GMAT creates objects based on the type requested. For example, Spacecraft or Formation objects are created through a call is the corresponding type of object into the SpaceObjectFactory. Similarly, if a user needs a Prince-Dormand 7(8) integrator, a call is made to the PropagatorFactory for that type of integrator. The factory creates the object through a call to the class's constructor, and returns the resulting object pointer.

  The Factory subpackage is constructed this way to facilitate extensibility. Users can add user generated classes by creating these classes and a Factory to instantiate them. That factory can then be registered with GMAT's FactoryManager, and users will be able to access their specialized classes in GMAT without modifying the configured GMAT code base. Eventually, users will be able to load their objects through shared libraries (aka dlls in the Windows world) at run time.

  The FactoryManager registration process takes a factory and asks it what type of objects it can create, and sends the corresponding requests to the correct factory. Details of the factories themselves can be found in Chapter 11. Extensibility is discussed in Chapter 32.

The Model The Engine package, described above, provides the programmatic framework necessary for building and running a simulation in GMAT. The objects that are used to model the elements of the simulation are contained in the Model package. All of the elements of the Model package are derived from a common base class, GmatBase, described in Chapter 9.

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When a user configures GMAT to simulate a spacecraft mission, the user is configuring objects in the Model package. In other words, the Model package contains all of the components that are available to a user when setting up a mission in GMAT. The model elements can be broken into four subpackages:

- *Environment* The environment subpackage provides all of the background environmental data used in GMAT to model the solar system, along with the components needed to perform conversions that require these elements.
- *Resources* All of the model elements that do not require some form of sequential ordering in GMAT are called Resources. These are the model elements that appear in the Resource tree in the GUI – excluding the Solar System elements – and they are the elements that are stored in the configuration subpackage, described above.
- *Commands* Commands are the elements of the model that describe how the model should evolve over time. Since commands are sequential, they are stored separately, and in sequential order, in the Command subpackage. The sequential set of commands in GMAT is called the Mission Control Sequence.

  The Mission Control Sequence is a list of commands. Commands that allow branching manage their branches through "child" lists. These branch commands can be nested as deep as is required to meet the needs of the model.
- *Parameters* Parameters are values or data containers (e.g. variables or arrays) that exist external to other objects in the GMAT model. These objects are used to perform calculations of data useful for analysis purposes.

Utilities The Utility package contains classes that are useful for implementing higher level GMAT functions. These core classes provide basic array computations, core solar system independent calculations, and other useful low level computations that facilitate programming in the GMAT system.

3.1.2 Package Component Interactions

The preceding section provides a static view into the components of GMAT. In this section, a high level view of the interactions between the elements of these packages will be described. Figure 3.1 shows the static package view of GMAT. Each top level package is color coded so that the system components shown in the interaction diagram, Figure 3.3, can be identified with their containing package. The legend on this figure identifies the package color scheme.

Users interact with GMAT through either a Graphical User Interface (GUI) written using the cross-platform GUI library wxWidgets, or through a console-based application designed to run scripts without displaying graphical output. These interfaces communicate with the GMAT engine through interpreter singletons[4]. The GUI application interacts with the engine through both the Script and GUI Interpreters, while the console application interacts through the script interpreter exclusively. These interpreters are designed to mediate two-way communications between the GMAT engine and users. The GUI and console applications drive the GMAT engine through these interpreters.

The Interpreters in turn communicate with GMAT's Moderator singleton. The Moderator is the central control object in the GMAT engine. It manages all program level communications and information flow while the program is running. It receives messages from the interpreters, processes those messages, and instructs other components of the engine to take actions in response to the messages. The messages sent by the interpreters fall into several distinct groups:

[4]The GMAT engine is run through a set of singleton class instances. The singleton design pattern used for these instances is introduced in Appendix B. The important thing to know about singletons for this discussion is that there is only one instance of any singleton class; hence a running GMAT executable has one and only one ScriptInterpreter, and Moderator, and at most one GUIInterpreter. Other singletons will be introduced during this discussion as well, when the factories and configuration are discussed.

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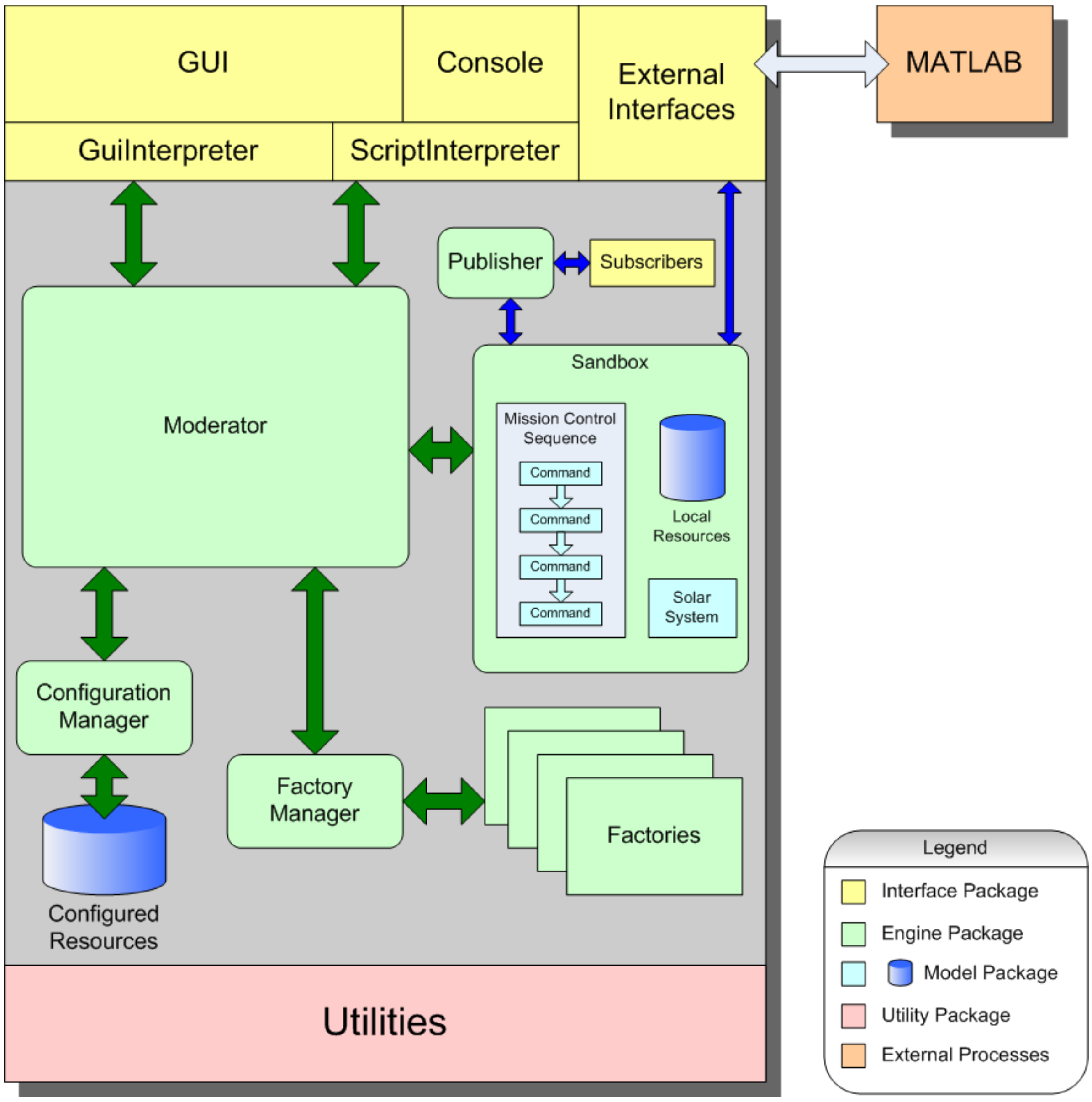

Figure 3.3: Subsystem Interactions in GMAT
Green arrows show information flow between the core Engine components, while blue arrows show information flow that occurs when a mission is executed.

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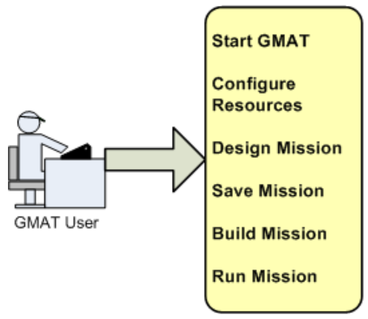

Figure 3.4: User Interactions

- **Object Creation** messages are used to request the creation of resources stored in the configuration database or the creation of commands stored in the Mission Control Sequence.
- **Object Retrieval** messages are used to access created objects, so they can be modified by users or stored to file.
- **Run** messages prepare the Sandbox for a run of the Mission Control Sequence, and then launch execution of the Mission Control Sequence.
- **Polling** messages are used to control an executing Mission Control Sequence, and are used to coordinate external communications (for example, the startup process for MATLAB) and user actions taken during the run.

The message and information flow in the Engine are shown in Figure 3.3 with double headed arrows. The green arrows show the central message and information flow in the engine, while the blue arrows show information flow that occurs while a mission control sequence is executing. These messages are described briefly here, and more completely through examples later in this chapter.

The Moderator responds to requests for new resources or commands by requesting a new object from the FactoryManager. The FactoryManager determines which Factory class can supply the requested object, and sends a "create" request to that factory. The Factory builds the requested object, and sends the pointer to the new object to the FactoryManager, which in turn sends the pointer to the Moderator. The Moderator sends the new object's pointer to one of two locations, depending on the type of object created. If the object is a Resource, the object pointer is passed to the ConfigurationManager. The ConfigurationManager adds the resource to the database of configured objects. If the requested object is a command, it is added to the Mission Control Sequence. The Moderator then returns the pointer to the interpreter that requested the new object.

Object retrieval is used to retrieve the pointer to an object that was previously created. The Moderator receives the message asking for the object. If the object is a configured resource, it calls the Configuration-Manager and asks for the resource by name. Otherwise, it traverses the Mission Control Sequence until it finds the requested command, and returns the pointer to that command.

Run messages are used to transfer the resources and Mission Control Sequence into the Sandbox and start a run of the mission. When the Moderator is instructed to run a Mission Control Sequence, it starts by loading the configured components into the Sandbox. The Moderator requests objects from the Configura-tionManager, by type, and passes those objects to the Sandbox. The Sandbox receives the object pointers, and clones each object into a local resource database. These local clones are the objects that interact with the commands in the Mission Control Sequence to run a mission. The Moderator then passes the Mission Control Sequence to the Sandbox so that the Sandbox has the list of commands that need to be executed to run the mission. Next Moderator tells the Sandbox to initialize its components. The Sandbox initializes

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each of the local components, and establishes any necessary connections between components in response to this message. Finally, the Moderator instructs the Sandbox to execute the Mission Control Sequence. The Sandbox starts with the first command in the sequence, and runs the commands, in order, until the last command has executed or the run is terminated by either a user generated interrupt or an error encountered during the run.

Polling messages are used to process messages between the Moderator and the Sandbox during a run. Typical messages processed during polling are user requests to pause or terminate the run, or to open a connection to an external process (including the startup of that process).

The descriptions provided here for these message types may be a bit confusing at first. The following section provides representative cases of the message passing and object interactions in GMAT when a user performs several common interactions.

3.2 GMAT Workflow Overview

When users run GMAT, they follow a work flow like that shown in Figure 3.4. Users start the program, configure resources, plan their mission, save the configuration, build the mission if working from a script file, and run the mission. The following sections describe the top level actions taken by GMAT when a user initiates each of these actions.

3.2.1 The GMAT Startup Process

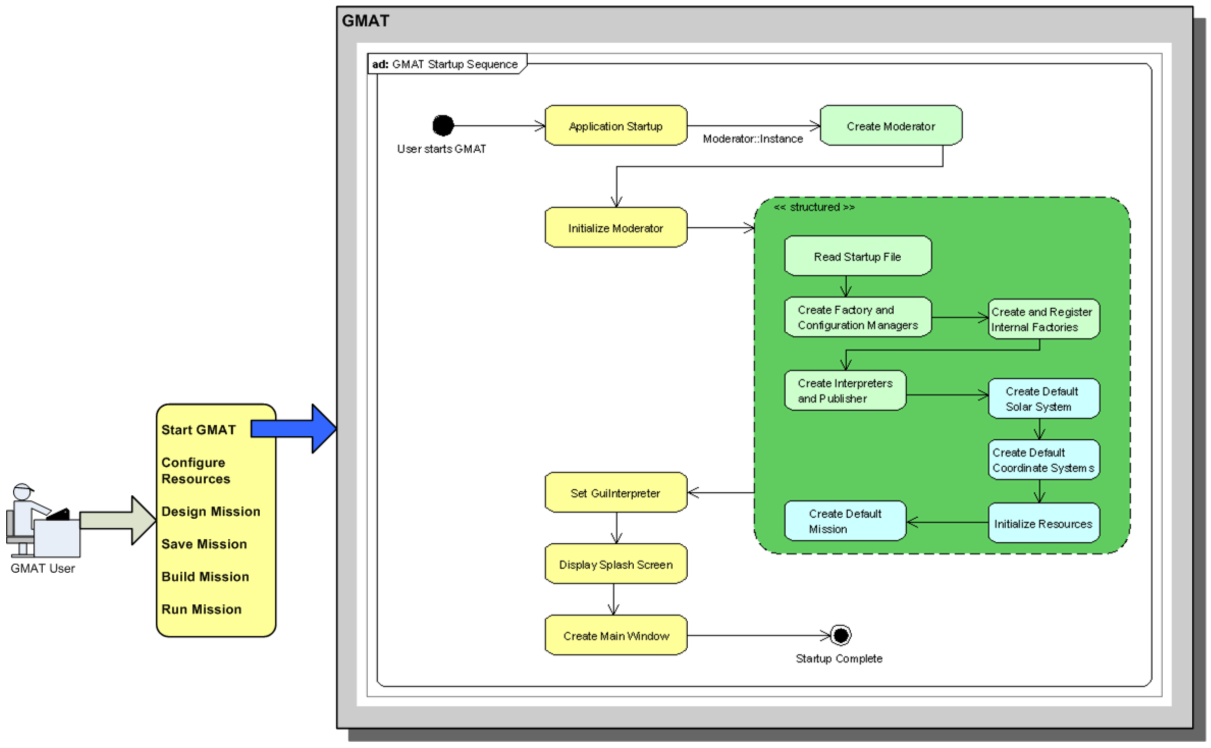

Figure 3.5: The Startup Process

The startup process for GMAT, shown in Figure 3.5, launches the executable program and prepares the engine for use. Most of the work performed during startup is performed by the Moderator. When the

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application launches, the first action taken is the creation of the Moderator singleton, made by calling the static Instance() method on the Moderator class. This freshly created Moderator is then initialized by the application through a call to the Initialize method.

The procedure followed in Initialize() is shown in the large green structured flow box in the figure. The Moderator reads the GMAT startup file, setting linkages to the default files needed to model and display running missions. The startup file resides in the same folder as the GMAT application, and contains path and file information for planetary ephemerides, potential models, graphical images used to provide texture maps for bodies displayed in the GUI, atmospheric model files, and default output paths for log files and other GMAT generated outputs.

Upon successful read of the startup file, the Moderator starts creating and connecting the main components of the engine. It begins by creating the components used for building model elements. The FactoryManager and ConfigurationManager are created first. Next the Moderator creates each of the internally configured factories, one at a time, and passes these instances into the FactoryManager. This process is called "registering" the Factories in other parts of this document. Upon completion of Factory registration, the Moderator creates instances of the ScriptInterpreter and GuiInterpreter singletons and the Publisher singleton. This completes the configuration of the core engine elements, but does not complete the Moderator initialization process, because GMAT starts with several default model elements.

The Moderator creates a default Solar System model, populated with a standard set of solar system members. Next it creates three default coordinate systems that always exist in GMAT configurations: the Earth-Centered Mean of J2000 Earth Equator system, the Earth-Centered Mean of J2000 Ecliptic system, and the Earth-Centered Earth body-fixed system. Next the Moderator sets the pointers needed to interconnect these default resources. Finally, the Moderator creates a default mission, and upon success, returns control to the GMAT application.

The Application retrieves the pointer for the GuiInterpreter, and sets this pointer for later use in the GUI. It then displays the GMAT splash screen, and then finally creates and displays the main GMAT Window. At this point, the GMAT GUI is configured and ready for use building models and running missions.

3.2.2 Configuring Resources

Figure 3.6 shows the top level set of actions taken by a user when configuring a typical resource – in this case, a Spacecraft object – from the GUI. The user starts by using a right click on the Spacecraft folder (or control-click on the Mac) in the resource tree on the left side of the main GMAT window. This action opens a context menu; the user selects "Add Spacecraft" from this menu, and a new spacecraft resource appears in the resource tree. This action is represented by the box labeled "Create the Spacecraft" in the figure. The user may also elect to change the name of the new Spacecraft. This action is taken with a right click (control-click on the Mac) on the new resource in the resource tree, and selecting "Rename" from the resulting context menu.

Once a resource has been created, the user can edit the properties of the resource. From the GUI, this action is performed with a double click on the resource. The double click opens a new panel tailored to the type of resource that is selected; for a Spacecraft, the panel shown in Figure 3.7 opens. The second block in Figure 3.6, labeled "Set Spacecraft Properties", represents the actions taken in GMAT when the user performs this selection, and when the user makes changes on the resulting panel.

Changes made in a GUI panel like the one shown here are not automatically made on the underlying objects in GMAT. Changes made on the panel are fed back to the internal objects when the user selects either the "Ok" or "Apply" button on the bottom of the panel. This updating of the resource is represented by the "Update Configuration" block in Figure 3.6.

Each of these blocks can be further decomposed into the internal actions performed in GMAT when the user makes the selections described here. The following paragraphs describe in some detail how GMAT reacts to each of these user actions.

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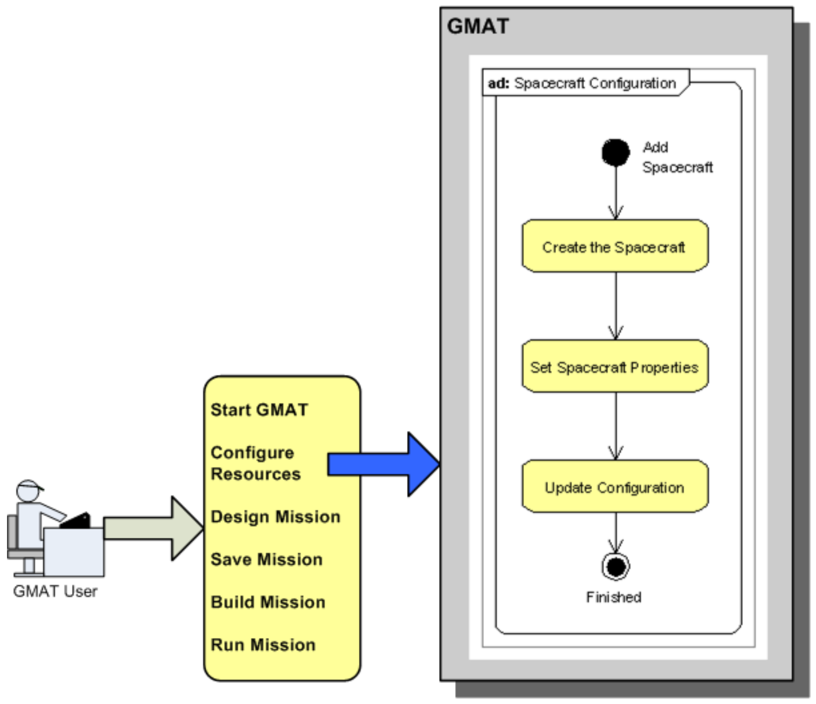

Figure 3.6: Configuration Example: Spacecraft

3.2.2.1 Creating the Spacecraft

Figure 3.8 shows an example of the process followed in GMAT when a new resource is created from the GUI. The user selected "Add Spacecraft" from the option menu on the Spacecraft node of the resource tree (accessed with a right click – control-click on the Mac – on the node). This selection triggered the chain of events shown in the sequence diagram in the figure[5]. The sequence starts with a CreateObject() call from the GUI to the interface into the GMAT engine. The interface between the GUI and the GMAT engine is a singleton instance[6] of the GuiInterpreter class, and is shown in green in the figure.

The GuiInterpreter singleton receives the call to create an object of type Spacecraft. It makes a call, in turn, into the singleton responsible for running the GMAT engine. This singleton is an instance of the Moderator class[7]. The call into the Moderator is made in step 1 of the diagram; the call is made through the CreateSpacecraft() method of the Moderator.

User configured objects in GMAT are always created through calls into a subsystem referred to collectively as the Factory subsystem. Factories are responsible for creating these objects. The factory subsystem is managed through a singleton class, the FactoryManager. The Moderator accesses the factories through this singleton. In step 2 of the figure, the Moderator makes a call to the CreateSpacecraft() method on the FactoryManager. The FactoryManager finds the Factory responsible for creating objects of the type requested – in this case, a Spacecraft object – and calls that factory in turn. Spacecraft are created in GMAT's SpaceObjectFactory, so the FactoryManager calls the CreateSpacecraft() method on the SpaceObjectFactory, as is shown in step 3.

The SpaceObjectFactory creates an instance of the Spacecraft class by calling the class's constructor, as

[5]For an introduction to the UML diagram notation used throughout this document, see Appendix A

[6]Singletons, and other design patterns used in GMAT, are introduced on Appendix B.

[7]For the purposes of this discussion, the singleton instances will be referred to by their class name for the remainder of this discussion.

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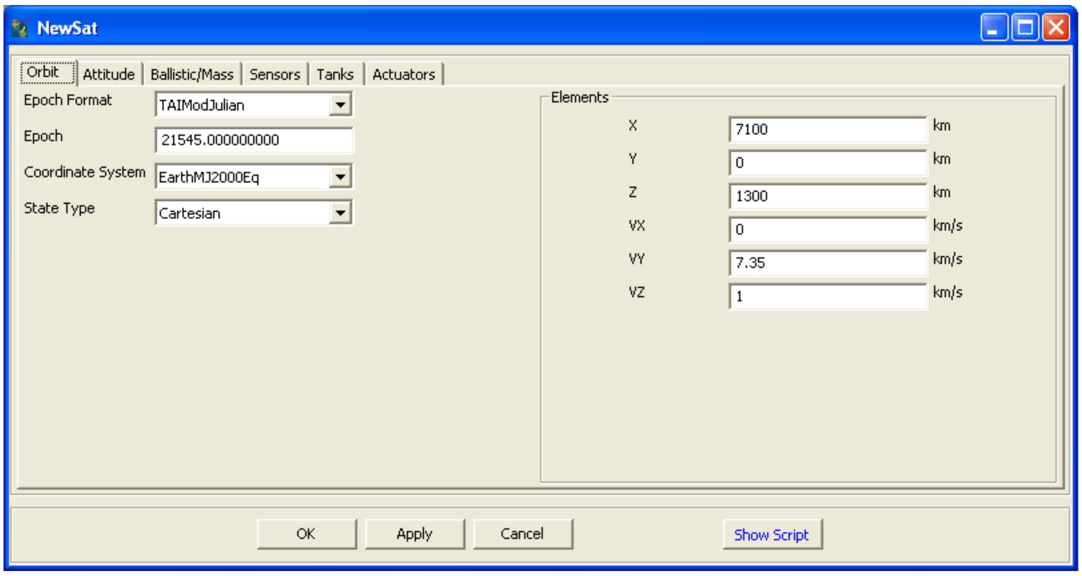

Epoch Format	TAIModJulian
Epoch	21545.000000000
Coordinate System	EarthMJ2000Eq
State Type	Cartesian

Elements

X	7100	km
Y	0	km
Z	1300	km
VX	0	km/s
VY	7.35	km/s
VZ	1	km/s

Figure 3.7: The Spacecraft Configuration Panel

shown in step 4. The constructed object is given a name, and then returned through the FactoryManager to the Moderator. The Moderator receives the new object, and adds it to the database of configured objects in GMAT.

All configured GMAT objects are managed by a singleton instance of the ConfigurationManager class. The ConfigurationManager is used to store and retrieve objects during configuration of the model. The Moderator adds created components to the configuration by calling Add() methods on the Configuration-Manager. For this example, the new Spacecraft is added to the configuration through the call shown in step 5.

Once the steps described above have been completed successfully, the Moderator returns control to the GuiInterpreter, which in turn informs the GUI that a new object, of type Spacecraft, has been configured. The GUI adds this object to the resource tree, and returns to an idle state, awaiting new instructions from the user.

3.2.2.2 Setting Spacecraft Properties

The Spacecraft that was created above has default settings for all of its properties. Users will typically reset these properties to match the needs of their mission. The process followed for making these changes from the GUI is shown in Figure 3.9.

As was discussed in the introduction to this section, Spacecraft properties are set on the GUI panel shown in Figure 3.7. Users can open this panel at any point in the model setup process. Because of the free flow in the configuration process, the Spacecraft pointer may not be accessible when the user elects to open the configuration panel with a double click on the Spacecraft's name on GMAT's resource tree. Therefore, the first action taken when the panel is opened is a call from the panel to the GuiInterpreter to retrieve the configured Spacecraft with the name as specified on the Resource tree. The GuiInterpreter passes this request to the Moderator. The Moderator, in turn, asks the ConfigurationManager for the object with the specified name. The ConfigurationManager returns that object to the Moderator, which passes it to the GuiInterpreter. The GuiInterpreter returns the object (by pointer) to the Spacecraft Panel.

The Spacecraft Panel creates a temporary clone of the configured spacecraft so that it has an object

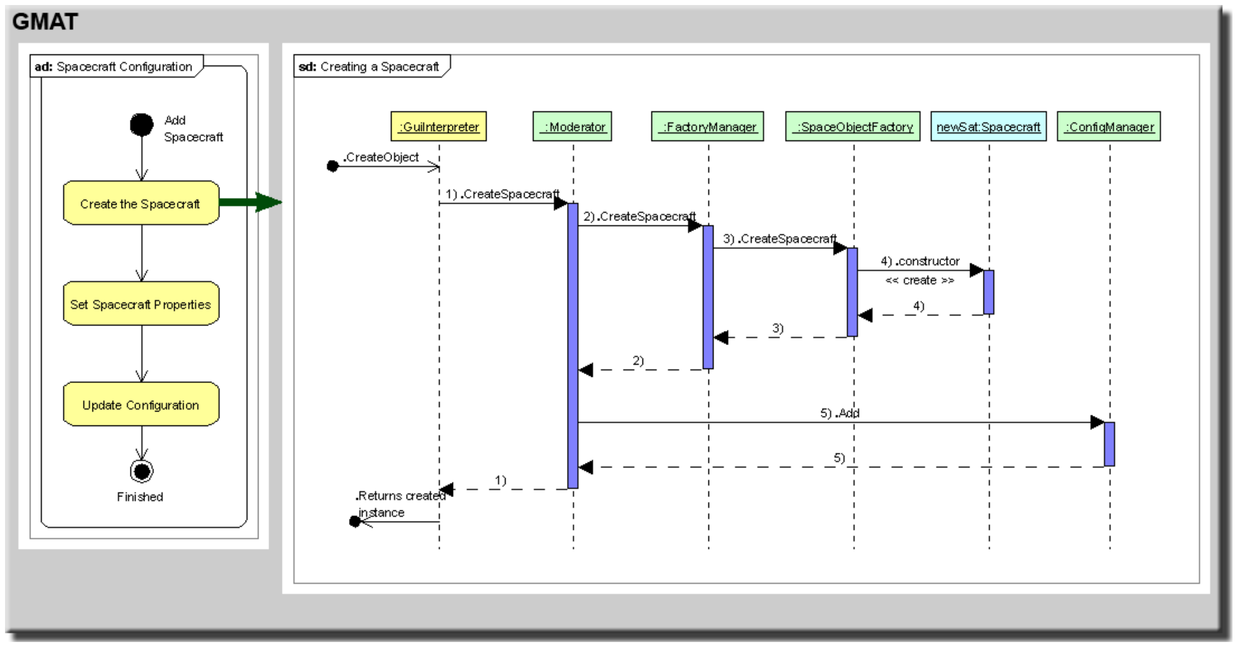

Figure 3.8: Configuration Example: Creating the Spacecraft

that can be used for intermediate property manipulations[8]. This clone is set on the Spacecraft Panel's subpanels, accessed through a tabbed interface shown in the snapshot of the panel. Each subpanel accesses the properties corresponding to the fields on the subpanel, and sets its data accordingly. The Spacecraft Panel is then displayed to the user. The user then makes any changes wanted for the model that is being configured.

3.2.2.3 Saving the Spacecraft

The final step in the spacecraft configuration process is saving the updated data into the configuration. That process is shown in Figure 3.10.

The Spacecraft Panel has several tabbed subpanels. The SpacecraftPanel begins the save process by calling each of these subpanels in turn, setting the corresponding Spacecraft data one subpanel at a time on the locally cloned Spacecraft. Once all of the subpanels have synchronized their data with the clone, the copy constructor of the configured Spacecraft is called with the cloned Spacecraft as the input argument. This action updates the configured Spacecraft, completing the save action.

There are two buttons on the Spacecraft Panel that can be used to perform the save action. The button labeled “Apply” saves the updated data to the configured object and leaves the Spacecraft Panel open for further user manipulation. The “OK” button saves the data and closes the panel. The latter action destroys the instance of the panel. Since the panel is going out of scope, the cloned Spacecraft must also be deleted, as is shown in the figure.

[8]The Spacecraft is unique in this respect; other objects configured in the GMAT GUI are manipulated directly, rather than through a clone. The Spacecraft is in many respects a composite object; this added complexity makes the intermediate clone a useful construct.

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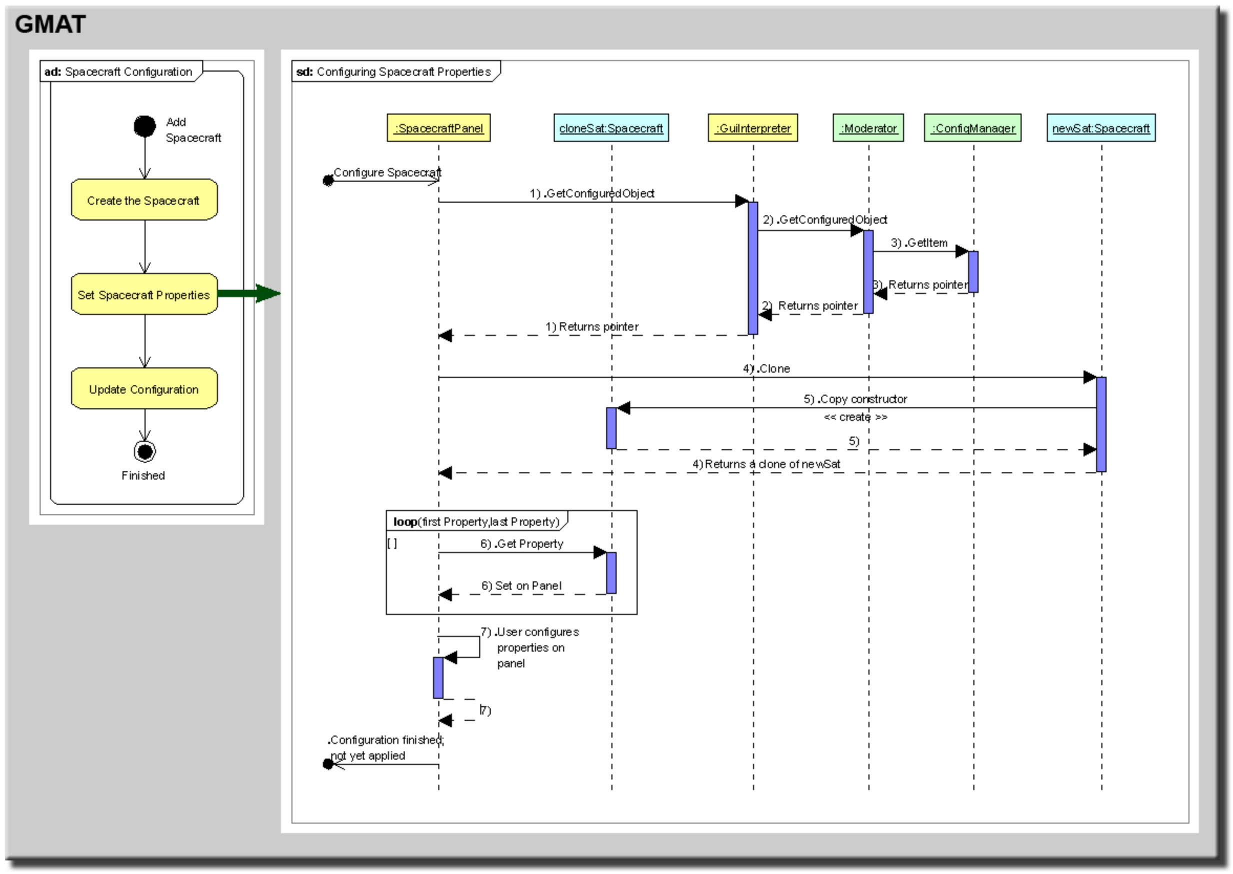

Figure 3.9: Configuration Example: Setting Spacecraft Properties

3.2.3 Configuring Commands

The previous paragraphs describe the interactions between core GMAT components and the internal message passing that occurs when a component of a GMAT Model is configured for use. The following paragraphs describe the analogous configuration for the commands in the Mission Control Sequence.

The Mission Control Sequence is shown in the GMAT GUI on the tab labeled "Mission," shown for a modified Hohmann transfer problem[9] in Figure 3.11. The sequence is shown as a hierarchical tree of commands. Each level of the hierarchy is a separate list of commands. The top level list is the main control sequence. Commands that branch from this list are shown indented one level from this sequence. Commands branching off of these commands are indented an additional level[10]. This process continues until all of the commands in the sequence are incorporated into the tree structure.

The Mission Control Sequence shown in the figure consists of seventeen commands, grouped as seven commands in the main (i.e. top level) sequence, five additional commands branched off of this sequence to perform one set of maneuver targeting, and an additional five commands to perform targeting for a second maneuver. The main sequence of commands shown here is the sequence Propagate – Propagate – Target – Propagate – Propagate – Target – Propagate. The Target commands are used to tune the maneuvers at

[9]The modification made here is along the transfer trajectory from the initial orbit to the final orbit. The spacecraft in this example is propagated through one and a half orbits on the transfer trajectory, rather than the typical half orbit needed for the problem.

[10]In some cases sequences of similar commands are also indented to simplify the display of the Mission Control Sequence.

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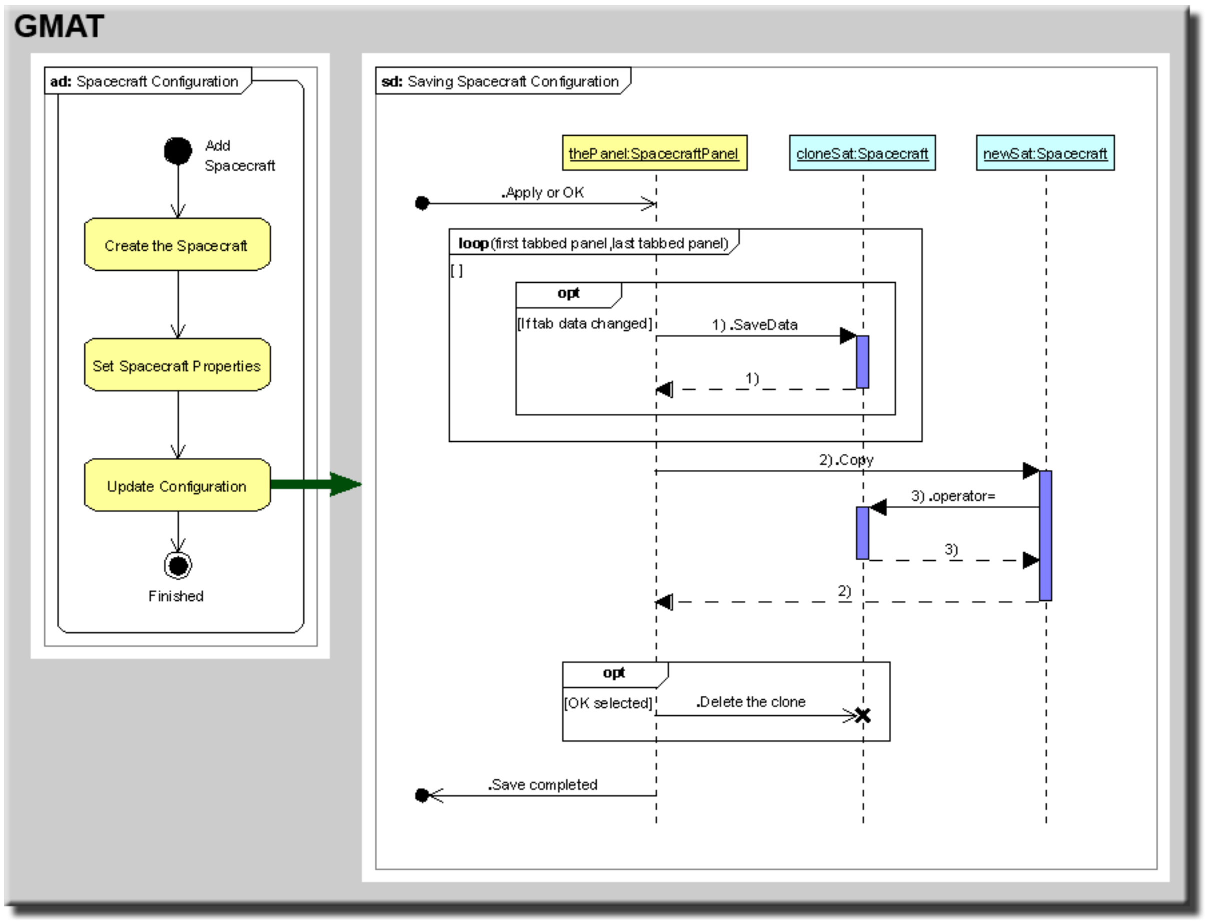

Figure 3.10: Configuration Example: Saving the Spacecraft

each end of the transfer orbit by applying the command sequence Vary – Maneuver – Propagate – Achieve – EndTarget. The inner workings of these commands is beyond the scope of this chapter; the important thing to observe at this point is the sequencing of the commands, and the presentation of this sequencing to the user by way of GMAT's GUI.

The tree shown in the GUI is populated by traversing the linked list of commands comprising the Mission Control Sequence. Each node of the Mission Tree is an instance of the class MissionTreeItemData. This class includes a pointer to the corresponding GmatCommand object in the Mission Control Sequence. When GMAT needs to build or refresh the Mission Tree, it accesses the first node in the Mission Control Sequence and creates a corresponding MissionTreeItemData instance. That instance is passed the pointer to the GmatCommand, and uses that command pointer to configure its properties in the tree. GMAT then asks for the next node in the sequence, and repeats this operation until the tree is fully populated.

Some GmatCommands are derived from a subclass named BranchCommand. These commands manage child linked lists, like the ones shown for the target commands in the figure. When the GUI encounters a BranchCommand derivative, it indents the nodes displayed on the Mission Tree to indicate this nested level for the child sequence of the branch command. All of the commands that allow this type of nesting are terminated with a corresponding "End" command – for this example, the Target command terminates the targeting child sequence when it encounters an EndTarget command.

Users interact with the Mission Control Sequence either through GMAT's scripting interface, or through

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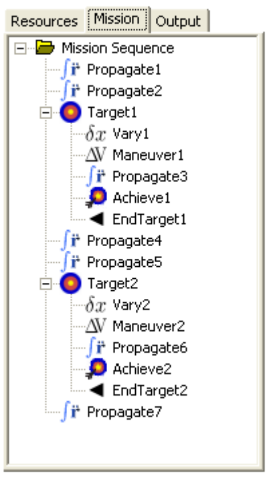

Figure 3.11: The Mission Tree in GMAT's GUI

manipulations made in the GUI. Manipulations made while scripting are pretty straightforward; they consist of editing a script file of commands and then instructing GMAT to parse this script. This process will be described later. Figure 3.12 shows the steps a user takes when adding a command to the Mission Control Sequence from the GUI.

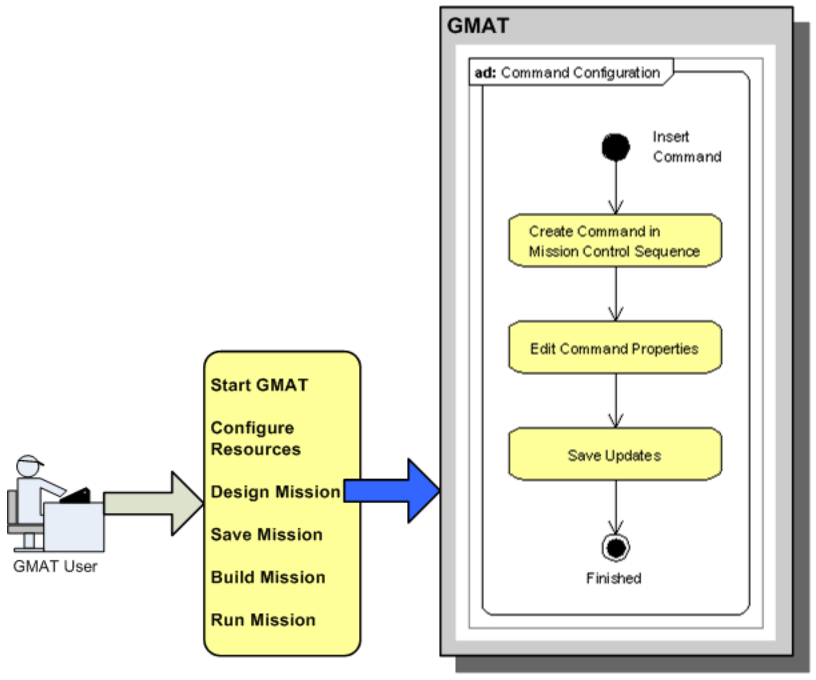

Figure 3.12: Configuration Example: A Mission Control Sequence Command

The Mission Control Sequence is a doubly linked list of objects that describes the sequence of actions that GMAT will run when executing a mission. Each node in the linked list is an object derived from the command

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base class, GmatCommand, as is described in Chapter 26. Since GmatCommand objects are doubly linked in the list, each command has a pointer to its predecessor and to the next command in the list. When a user decides to add a command to the Mission Control Sequence, a node in the Mission tree is selected and right clicked (or control-clicked on the Macintosh). This action opens a context menu with "Insert Before" and "Insert After" submenus as options. The "Before" and "After" selections here refer to the location of the new command. The user selects the desired command type from the submenu, and the requested command is added to the Mission Control Sequence in the specified location. This set of actions corresponds to the first block in the activity diagram, labeled "Create Command in Mission Control Sequence."

Most of the commands in GMAT require additional settings to operate as the user intends – for example, Propagate commands require the identity of the propagator and spacecraft that should be used during propagation. The second block in the figure, "Edit Command Properties," is launched when the user double clicks on a command. This action opens a command configuration panel designed to help the user configure the selected command. The user edits the command's properties, and then saves the updates back to the command object by pressing either the "Apply" or "OK" button on the panel. This action is performed in the "Save Updates" block in the figure, and is the final step a user takes when configuring a command.

Each of these high level actions can be broken into a sequence of steps performed between the core elements of GMAT, as is described in the following paragraphs, which describe the interactions followed to add a Maneuver command to the Mission Control Sequence.

3.2.3.1 Creating a Maneuver Command

Figure 3.13 shows the process followed when a Maneuver command is created and inserted following an existing command from the GMAT GUI. The process starts when the user selects a command on the mission tree, right clicks it, and chooses the "Insert After" option from the resulting context menu. The resulting submenu contains a list of available commands; the following actions occur when the user selects "Maneuver" from this list.

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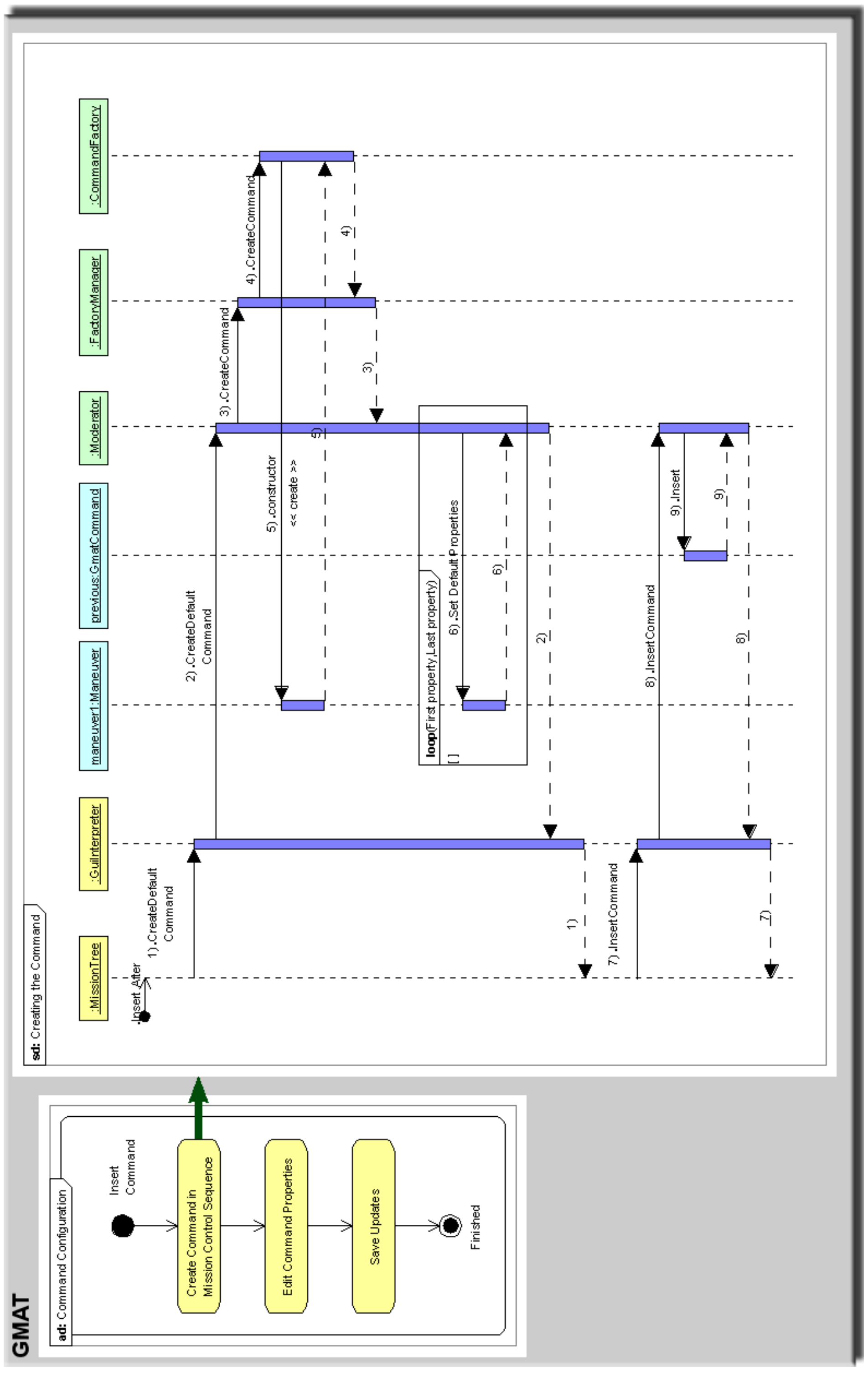

Figure 3.13: Command Creation Example: Creating a Maneuver Command

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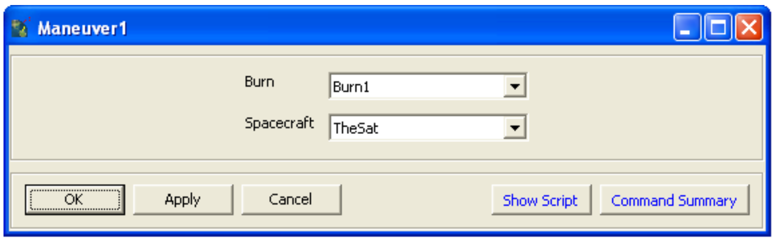
Maneuver command creation starts when the MissionTree[11] object sends a request to the GuiInterpreter for a new Maneuver command instance. The GuiInterpreter sends the request to the Moderator, which sends the request to the FactoryManager. The FactoryManager finds the factory that creates Maneuver commands, and asks that factory for an instance of the Maneuver command. The resulting instance is returned from the factory, through the FactoryManager, to the Moderator. The Moderator sets some default data on the command, and then returns the command pointer to the GuiInterpreter. The GuiInterpreter passes the command pointer to the MissionTree.

Each node in the MissionTree includes a data member pointing to the corresponding command in the Mission Control Sequence. This structure simplifies the interactions between the GUI and the engine when a user makes changes to the Mission Control Sequence. Since the MissionTree already has a pointer to the command preceding the new Maneuver command, it has all of the information needed to request that the new command be added to the Mission Control Sequence. The new Maneuver command is added to the Mission Control Sequence from the MissionTree. The MissionTree passes two pointers through the GuiInterpreter to the Moderator: the first pointer identifies the command selected as the command preceding the new one, and second pointer is the address of the new Maneuver command. The Moderator passes these two pointers to the head of the Mission Control Sequence using the "Insert" method. This method searches the linked list recursively until it finds the node identified as the previous command node, and adds the new command immediately after that node in the list, resetting the linked list pointers as needed. This completes the process of adding a command to the Mission Control Sequence.

3.2.3.2 Configuring and Saving the Maneuver Command

When a new command is added to the Mission Control Sequence, it is incorporated into the sequence with default settings selected by the Moderator. Most of the time, the user will want to edit these settings to match the requirements of the mission being modeled. Command configuration is performed using custom panels designed to display the properties users can set for each command. Figure 3.14 shows the panel that opens when a user double clicks a maneuver command – like the one created in the example described above – in the mission tree.



Burn: Burn1
Spacecraft: TheSat

Figure 3.14: The Maneuver Command Configuration Panel

The sequence diagram in Figure 3.15 shows the top level messages that are passed when the Maneuver command is configured using this panel. This view into the command configuration includes a bit more detail about the GUI messages than was shown in the Spacecraft configuration presented previously.

The configuration process starts when the user double clicks on the command in the mission tree. The double click action sends a message to the MissionTree requesting the configuration panel for the selected node in the tree. The MissionTree finds the item data, and sends that data to the main GMAT window,

[11]Here, and throughout this document, specific instances of singleton classes are referred to by the class name – "MissionTree" in this case. When the class or user experience of the instance is discussed, it will be referred to less formally – "mission tree", for example. So as an example of this style, we might discuss the user selecting an object on the mission tree in the GUI, which causes the MissionTree to perform some action.

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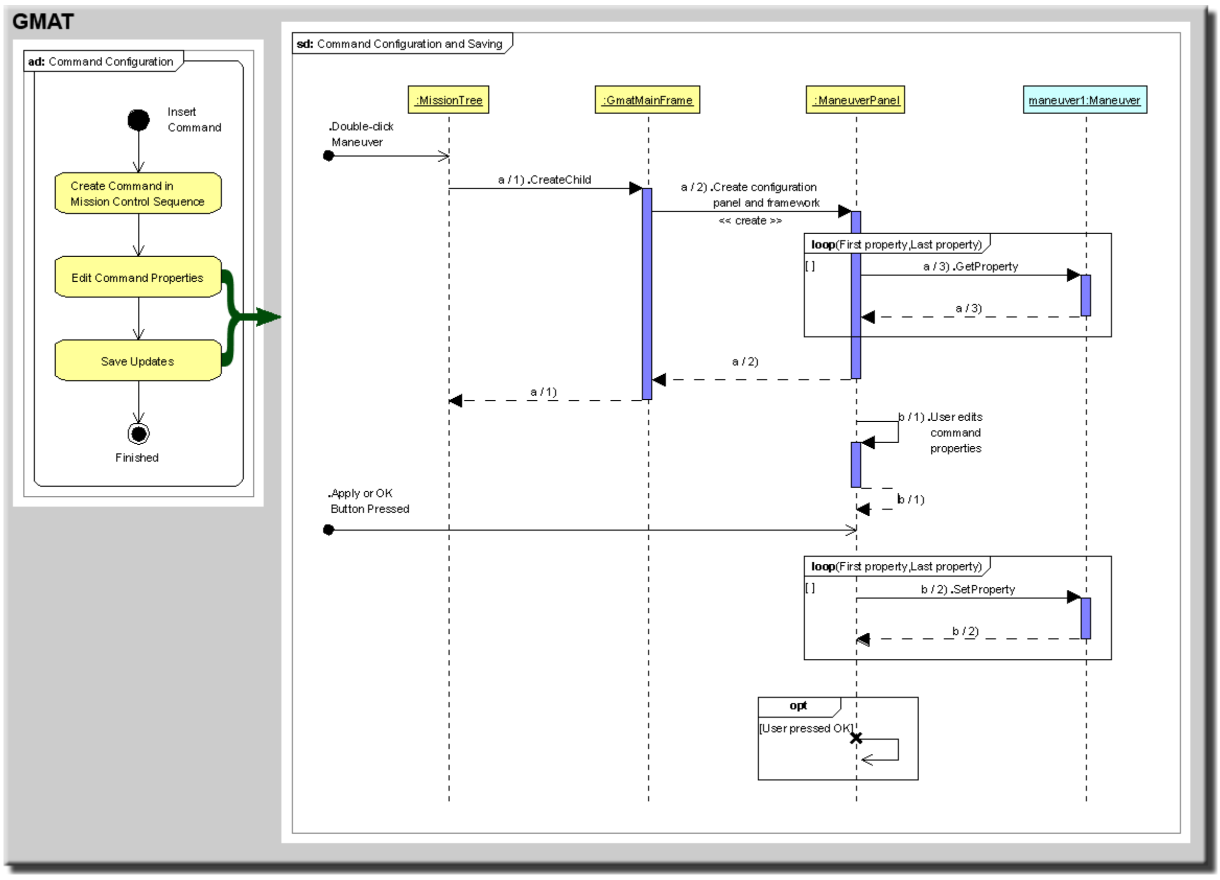
GMAT
ad: Command Configuration
Insert Command
Create Command in Mission Control Sequence
Edit Command Properties
Save Updates
Finished
sd: Command Configuration and Saving
:MissionTree
:GmatMainFrame
:ManeuverPanel
maneuver1:Maneuver
.Double-click Maneuver
a / 1) .CreateChild
a / 2) .Create configuration panel and framework
<< create >>
loop(First property,Last property)
[]
a / 3) .GetProperty
a / 3)
a / 2)
a / 1)
b / 1) .User edits command properties
b / 1)
.Apply or OK Button Pressed
loop(First property,Last property)
[]
b / 2) .SetProperty
b / 2)
opt
[User pressed OK]

Figure 3.15: Command Configuration Example: Configuring the Maneuver Command

called the GmatMainFrame, asking for a new child window configured to edit the properties of the command contained in the item data. The GmatMainFrame creates the child window and displays it for the user.

More concretely, if the user double clicks on the Maneuver command created in the preceding section, the tree item data for that maneuver command is passed from the MissionTree to the GmatMainFrame. The configuration window that should result from this action for display in the GUI needs to contain the panel designed to match the underlying object that is being configured – in this case, a Maneuver command. The GmatMainFrame uses the tree item data passed to it to determine the type of panel needed by the child window during its creation. For this example, the GmatMainFrame determines that the panel that is needed should be a ManeuverPanel because the tree item data includes a pointer to a Maneuver command. Accordingly, the GmatMainFrame creates an instance of the ManeuverPanel class, and passes that panel to the child window. The child window receives the panel and places it into the corresponding container in the window.

Finally, the child window uses the command pointer in the tree item data to access the command and determine the current values of its internal properties. These data are collected from the command and passed to the corresponding GUI components so that the user can see the current settings. Once these data fields have been populated, the child window is displayed on the GUI, giving the GUI a new window like that shown in Figure figure:ManeuverConfigPanel. This completes the top portion of the sequence shown in Figure 3.15.

Once the panel is shown on the GUI, the user makes changes to the settings for the command on the

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new panel. When the settings match the needs of the mission, the user clicks on either the "OK" or "Apply" button. This action makes the ManeuverPanel update the Maneuver command with the new settings. If the user pressed the OK button, the child window also passes a message to GMAT indicating that the user is finished with the window. When that message is processed, the child window is closed in the GUI.

3.2.4 Model and Mission Persistence: Script Files

GMAT saves configuration data in files referred to as script files. The details of the script file parsing can be found in Chapter 17. The following paragraphs provide an overview of these processes.

The GMAT script files can be thought of as a serialized text view of the configured objects and Mission Control Sequence constructed by the user to model spacecraft. GMAT provides a subsystem, controlled by the ScriptInterpreter, that manages reading and writing of these files. All of these script files are ASCII based files, so they can be edited directly by users.

```
% -------------------------------------------
%   Configure Resources
% -------------------------------------------
Create Spacecraft sat1
sat1.SMA = 10000.0
sat1.ECC = 0.25
sat1.INC = 78.5
sat1.RAAN = 45

Create ForceModel fm
fm.PrimaryBodies = {Earth}
fm.PointMasses = {Luna, Sun}

Create Propagator prop
prop.FM = fm

Create XYPlot posvel
posvel.IndVar = sat1.X
posvel.Add = sat1.VX
posvel.Add = sat1.VY
posvel.Add = sat1.VZ

% -------------------------------------------
%   The Mission Control Sequence
% -------------------------------------------
While sat1.ElapsedDays < 7
   Propagate prop(sat1)
EndWhile
```

Listing 3.1: A Basic GMAT Script File

Listing 3.1 shows a simple script that propagates a spacecraft for approximately 7 days, plotting the Cartesian components of the velocity against the spacecraft's X coordinate value. Details of all of these settings can be found in the User's Guide[UsersGuide]. This script just serves as an example for the discussion that follows.

All objects that are created as configured resources from the GUI are stored in the script files using the keyword "Create". In the script shown here, there are four resources: a Spacecraft named "sat1", a ForceModel named "fm", a Propagator (actually an instance of the PropSetup class) named "prop", and an XYPlot Subscriber named "posvel". Each of these resources is used when running the mission.

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In GMAT, each resource can have one or more data members that users can set. These resource properties are initialized to default settings. Users can override the values of these properties. In the GUI, this action is performed by editing data presented on the panels for the resources. Properties are changed in the script file by assigning new values to the properties by name; for example, in the sample script, the Spacecraft's semimajor axis is changed to 10000.0 km on the fifth line of script:

```
sat1.SMA = 10000.0
```

The script shown here is a script as it might be entered by a user. Only the lines that override default property values are shown, and the lines are written as simply as possible. The full set of object properties can be examined by writing this object to a script file. When a Spacecraft – or any other resource – is saved, all of the resource properties are written. In addition, the keyword "GMAT" is written to the file, and the full precision data for the numerical properties are written as well. The Spacecraft configured in the script file above is written to file as shown in Listing 3.2.

```
Create Spacecraft sat1;
GMAT sat1.DateFormat = TAIModJulian;
GMAT sat1.Epoch = 21545.000000000;
GMAT sat1.CoordinateSystem = EarthMJ2000Eq;
GMAT sat1.DisplayStateType = Keplerian;
GMAT sat1.SMA = 9999.999999999998;
GMAT sat1.ECC = 0.2499999999999999;
GMAT sat1.INC = 78.5;
GMAT sat1.RAAN = 45;
GMAT sat1.AOP = 7.349999999999972;
GMAT sat1.TA = 0.9999999999999002;
GMAT sat1.DryMass = 850;
GMAT sat1.Cd = 2.2;
GMAT sat1.Cr = 1.8;
GMAT sat1.DragArea = 15;
GMAT sat1.SRPArea = 1;
```

Listing 3.2: Script Listing for a Spacecraft

GMAT generates the scripting for resources and commands using a method, GetGeneratingString(), which is provided in the GmatBase class. This class provides the infrastructure needed to read and write object properties through a consistent set of interfaces. The GetGeneratingString() method uses these interfaces when writing most user objects and commands to script. Derived classes can override the method as needed to write out class specific information. When GMAT saves a model to a script file, it tells the ScriptInterpreter to write a script file with a given name. The ScriptInterpreter systematically calls GetGeneratingString() on each object in the configuration and sends the resulting serialized form of each object to the script file. Once all of the objects in the configuration have been saved, GMAT takes the first command in the Mission Control Sequence and calls its GetGeneratingString() method, writing the resulting text to the script file. It traverses the command list, writing each command in sequential order.

Script reading inverts this process. When a user tells GMAT to read a script, the name of the script file is passed to the ScriptInterpreter. The ScriptInterpreter then reads the file, one logical block[12] at a time, and constructs and configures the scripted objects following a procedure similar to that described above for actions taken from the GUI.

Details of script processing can be found in Chapter 17.

[12]A "logical block" of script is one or more lines of text sufficiently detailed to describe a single action taken in GMAT. Examples include creation of a resource, setting of a single parameter on a resource, or adding a command to the Mission Control Sequence.

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3.2.5 Running a Mission

Once a user has configured a model in GMAT, the model is ready to be run. The configuration has been populated with all of the resources needed for the run, and the resources have been configured to match the needs of the analyst. The Mission Control Sequence has been entered and configured to meet the needs of the mission. All that remains is the actual running of the model encoded in these elements.

Figure 3.16 shows the sequence followed when a mission is executed in GMAT. The figure shows the sequence as initiated in the GUI. The user chooses to run the mission by pressing the “Run” button on GMAT’s toolbar. This action sends a RunMission message to the GuiInterpreter, which then calls the Moderator’s RunMission() method (Step 1 in the figure).

The Moderator begins by clearing any stale data out of the Sandbox by calling the Sandbox’s Clear() method (Step 2). This action removes any local copies of objects in the Sandbox that may still exist from a previous run. Once the Sandbox has been cleared, the Moderator begins passing resources into the Sandbox.

The Moderator passes the current Solar System into the Sandbox, and then begins making calls to ConfigurationManager to get the current set of resources used in the model (Step 3). The Moderator passes these resources into the Sandbox (Step 4) by type, starting with coordinate systems, and proceeding until all of the resources have been passed into the Sandbox. The Sandbox receives each resource as it is passed in and makes a copy of that resource by calling its Clone() method (Steps 5 and 6). The Sandbox stores these local clones by name in its local object map. The local object map contains the objects that are manipulated during a run; the configured objects are not used when running the mission.

After the configured objects have been passed into the Sandbox, the Moderator sends the head node of the Mission Control Sequence to the Sandbox[13] (Step 7). This sets the Sandbox’s internal sequence pointer to the first command in the Mission Control Sequence (Step 8), completing steps needed to begin work in the Sandbox.

The Moderator has completed the bulk of its work for the run at this point. The next action taken is a call from the Moderator to the Sandbox, instructing it to initialize itself (Step 9). When the Sandbox receives this instruction, it begins initializing the local objects. Each object is queried for a list of referenced objects that need to be set, and the Sandbox finds these objects in the local object store and sets each one on the requesting object (Step 10, performed iteratively through all of the objects). After the object initialization, the Sandbox walks through the Mission Control Sequence node by node, passing each command a pointer to the local object map and then calling the Command’s Initialize method, giving each command the opportunity to set up data structures needed to execute the Mission Control Sequence (Step 11, performed iteratively through the Mission Control Sequence). If initialization fails at any point during this process, the Sandbox halts the initialization process and reports the error to the Moderator.

Once initialization is complete, the Sandbox reports successful initialization to the Moderator. At this point the Moderator sends an Execute() message to the Sandbox (Step 12). The Sandbox responds by calling the Execute() method on the first command in the Mission Control Sequence (Step 13). The command executes this method, manipulating objects in the local object map (Step 14) and sending data to GMAT’s Publisher (Step 15) based on the design of each command. When data is passed to the Publisher, it passes the data on to each Subscriber (Step 16), producing output that the user can view to monitor the mission as it executes, or to process after the mission has finished running.

When the first command completes execution, the Sandbox asks for the next node to execute in the Mission Control Sequence, and repeats this process on the second node. The process continues, calling node after node in the Mission Control Sequence until the final command has been executed.

[13]Commands are not cloned into the Sandbox at this writing. A future build of GMAT may require cloning of commands as well as resources, so that the system can support multiple Sandboxes simultaneously. The system is designed to allow this extensibility when needed.

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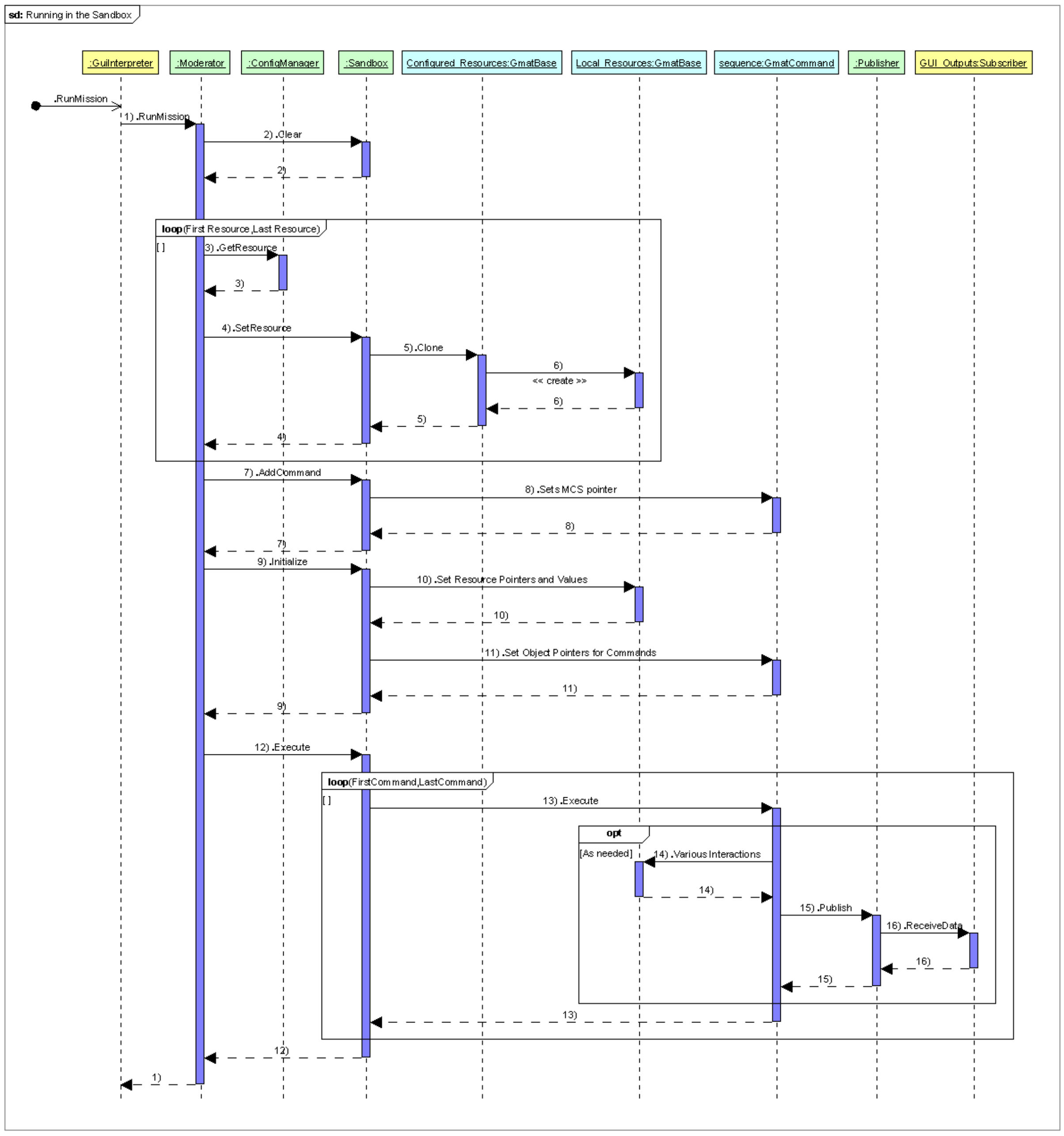

Figure 3.16: The Sequence followed to Run a Mission

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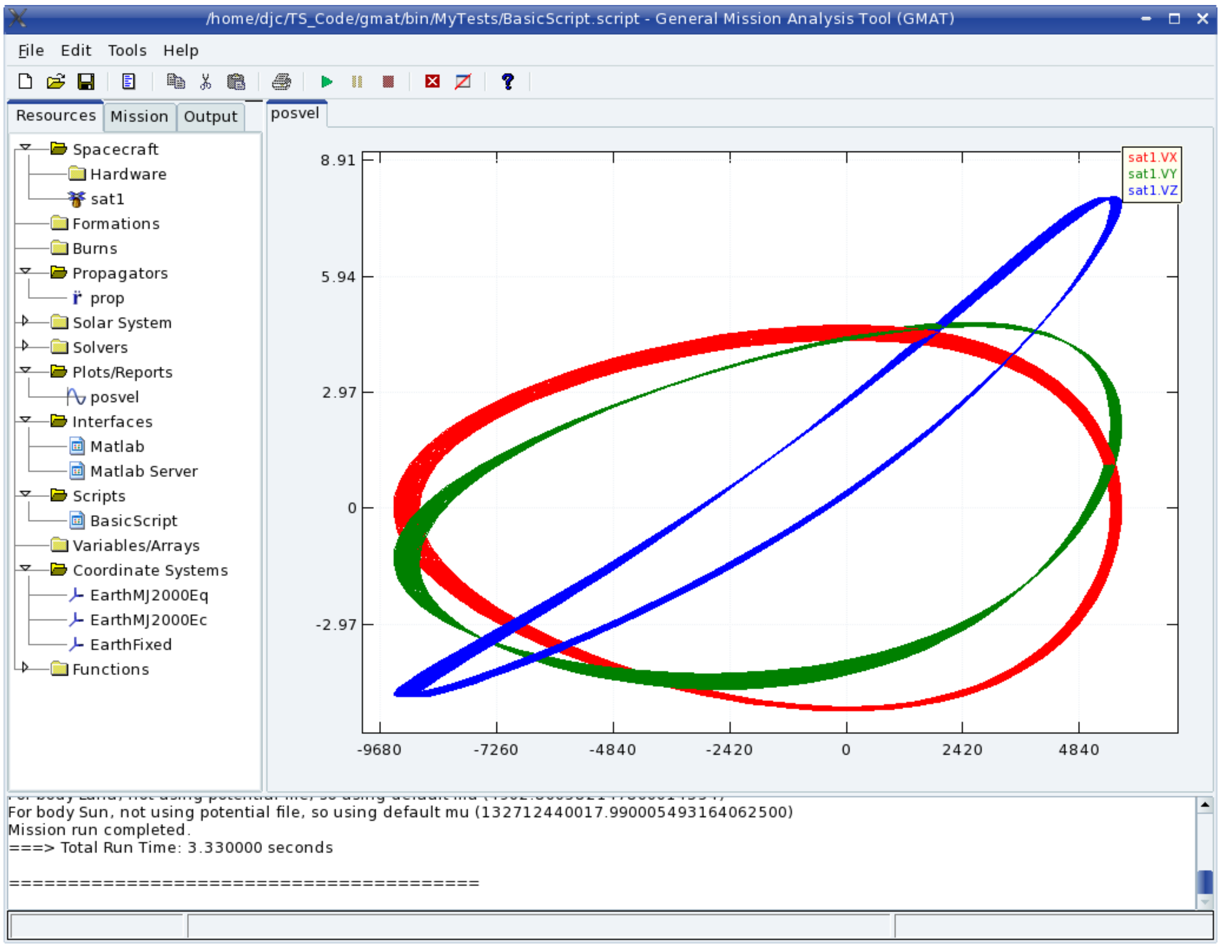

```
For body Sun, not using potential file, so using default mu (132712440017.990005493164062500)
Mission run completed.
===> Total Run Time: 3.330000 seconds

========================================
```

Figure 3.17: Results of the Script Example, Run on Linux

Once the final command has executed, the Sandbox sends a message to the Mission Control Sequence stating that the run has completed execution, and control is returned to the Moderator from the Sandbox. The Moderator returns control to the GuiInterpreter, which returns control, through the GUI, to the user, completing the mission run. Figure 3.17 shows the results of this sequence when executed for the script shown in Listing 3.1.

3.3 Summary

This completes the presentation of the overview of GMAT's architecture. In this chapter we have discussed the basic architecture for GMAT, presented an overview of the arrangement of the components of the system that we will build upon in upcoming chapters, and presented a programmatic description of the workflow of three common tasks performed in GMAT: Starting the system, Creating resources and comments for a spacecraft mission, and running that mission.

The next few chapters will present, in some detail, descriptions of each of the components of the Engine package, followed by sections describing the infrastructure used for the Resources and Commands, and then the design features of these elements.

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Part II

Engine Components

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Overview of Chapters 4 through 8

Mission modeling is performed in GMAT through the core numerical engine designed for the system. This part of the architectural specification describes the classes that make up the core engine components: the Moderator, the Factory Manager, the Configuration Manager, the Publisher, and Sandboxes. The purpose of each of these components is summarized in Table 3.1.

Table 3.1: Key Elements of the GMAT Engine

Component	Notes	Description
Moderator	Singleton	Controls the program flow in the Engine.
Factory Manager	Singleton	Responsible for the creation of objects and Mission Control Sequence commands used in the flight dynamics model.
Configuration Manager	Singleton	Stores and retrieves user objects created by the Factory Manager.
Publisher	Singleton	Passes data generated during a run to the Subscribers that present these data to users.
Sandbox	Multiple copies allowed[1]	The component that manages initialization and execution of the Mission Control Sequence when a mission is run.

Contents of the Chapters

Each component of the engine is described in a separate chapter, structured on the following outline:

Overview The introductory text for each chapter contains an overview of the component and its role in the GMAT engine.

Design Principles This section describes the motivation behind the component, along with the principles followed while designing it. It includes a description of patterns or other criteria used in the component design, the roles and responsibilities handled by the component, and other design features that will help you understand how the component fits into the GMAT engine.

Design The design section presents the design for the component. It starts with the class diagram for the component, followed by descriptions of representative methods and attributes of the class selected to help you understand its implementation. It also provides an explanation of how the class satisfies the roles and responsibilities identified in the preceding section, through the use of activity and sequence diagrams. Sometimes the details of these descriptions are better placed in other portions of the design specification; when that happens, a summary is provided in the chapter along with a reference to the detailed description.

Usage and Modification This section of the chapter provides additional tips about how to use or change the component, and includes text describing best practices for working with it.

[1]While GMAT is designed to allow more than one Sandbox, the current implementation only uses a single Sandbox.

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Chapter 4

The Moderator

The entry point into GMAT's engine is the Moderator. The Moderator controls program flow, creating components through the factory manager that are then managed in the configuration manager, and then using these components to model missions in a sandbox. The Moderator creates the engine components, manages those components when necessary, and controls the processes in GMAT's engine. It initializes the Sandbox prior to a run, and launches the run in the Sandbox. In other words, the Moderator is the central control element of GMAT, acting as the interface between users and the internal elements of the system, and facilitating communications between those internal elements.

The engine contains one component, the Publisher, that does not interact with the Moderator beyond initialization. The Publisher, described in Chapter 8, is the communications interface between the Sandbox objects and the Subscriber objects that present data to users. The following sections discuss interactions between engine components and the Moderator.With the exception of initialization, these interactions exclude the Publisher.

This chapter explains how the Moderator accomplishes its tasks.

4.1 Moderator Design Principles

Figure 3.3 shows a high level view into GMAT's architecture. That figure contains arrows showing all of the allowed communications paths in the engine. Figure 4.1 shows the portion of that diagram that corresponds to the Moderator's role in GMAT. The Moderator handles all communications between the Interpreters and the engine, and between the components of the engine used to set up and run a mission.

While the arrows in this figure show the information flow through the Moderator, they do not state explicitly what data or objects move along these paths. The Moderator is the manager for all of the tasks accomplished in the engine.

The Moderator design is built around two design patterns: the Singleton pattern and the Mediator pattern. The Mediator pattern is discussed in Section 4.1.2. The Moderator consolidates the management actions needed for GMAT into a central location. It is a singleton to ensure that this consolidation happens at only one place for the GMAT executable. Each instance of GMAT running in memory has exactly one Moderator managing the GMAT engine.

There are seven key actions that the Moderator is responsible for managing, described in the next section.

4.1.1 Moderator Responsibilities

The Moderator plays a central role in seven tasks:

1. **Engine Initialization:** The Moderator is responsible for initializing GMAT's engine when the system starts.

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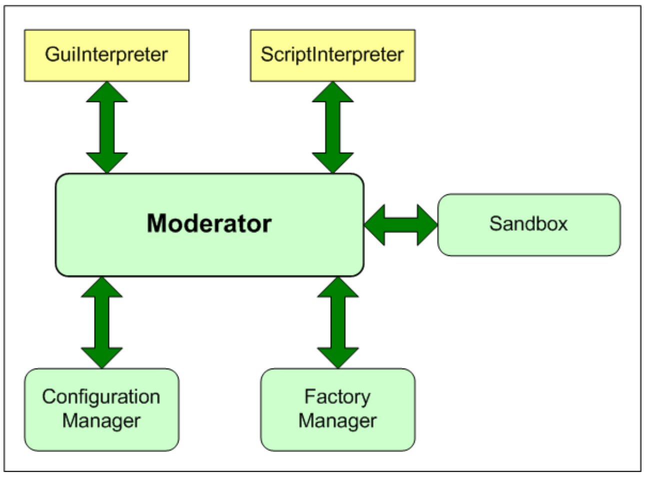

Figure 4.1: Program Flow and the Moderator

2. **Object Creation:** All object creation requests made by users are passed, through an Interpreter, to the Moderator. The Moderator starts this process by passing creation requests to the factory subsystem, and completes it by sending the created objects to their destinations.

3. **Object Configuration:** All object configuration requests made by users are passed, through an Interpreter, to the Moderator. The Moderator locates the object that needs configuration, and passes that object to the process that performs the configuration.

4. **Loading a Script:** The Moderator works with the Script Interpreter to manage the creation and configuration process performed when a script file is loaded into the system.

5. **Running a Mission:** The Moderator ensures that all of the elements needed to run a mission are provided to the Sandbox used in the run, and then passes the initialization and run control into that Sandbox. The Moderator then monitors the process in the background during the run, and handles the communications necessary when a user interrupts the run.

6. **Saving a Mission:** The Moderator acts as an intermediary between the objects configured in GMAT and the Interpreters when a mission is saved, locating and serving up the objects that need to be serialized as needed by the Interpreters.

7. **User Extension:** The Moderator provides the interfaces needed to extend GMAT using user libraries.

Each of these tasks involves communications between components of the engine that, were the Moderator absent, would be made directly between the engine components. While that approach may seem like a more efficient avenue at first, the resulting number and types of communications that it would necessitate would produce a much more tightly coupled system. As the number of engine components increases, the complexity of these component interactions would also increase. The Moderator reduces this communications complexity by consolidating the communications into a central component, using a design pattern called the Mediator pattern.

4.1.2 The Mediator Pattern Employed in the Moderator

The Moderator is designed to enforce loose coupling between the elements of GMAT's engine, and to simplify and standardize the communications between the other elements of the engine. It acts as an intermediary

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between user inputs passed in through the script and GUI interpreters, the factory subsystem used to build objects needed to simulate a mission, the configuration that stores these configured objects, and the sandboxes that actually run the simulation. It is built using the Mediator design pattern, as described in [GoF] and summarized in Appendix B. This pattern enforces the following features:

Loose Coupling The engine components communicate with each other through calls into the Moderator. This feature means that the other engine components do not need to know how to communicate with each other. Instead, they make all communications calls to the Moderator, which is responsible for routing these calls to the appropriate recipients. In other words, the Interpreters, Factory Manager, Configuration Manager, and Sandboxes do not know about each other. Instead, all of the interactions between these components is made through calls to and from the Moderator.

Maintainability All communications between the Interpreters, Factory Manager, Configuration Manager, and Sandboxes is performed through the Moderator. This consolidation of the information exchange between the components centralizes the location for communications mishaps, and simplifies the task of correcting these defects as they are detected. In addition, the interfaces in the Moderator are designed to be consistent, reducing the number of different calling protocols that a maintainer needs to learn and understand.

4.1.2.1 Implications

The design of the Moderator as a Mediator produces the following benefits:

Decouples Objects Since the internal communications between the components of the engine pass through the Moderator, the other elements of the engine do not need knowledge about each other.

Simplifies Object Protocols The Moderator simplifies objects by replacing direct communications between the engine components with communications through a central component.

Abstracts Object Communications Since the Moderator stands separate from the actions taken by the other engine components, work performed by the Moderator has the effect of reducing the interfaces in the engine components to the minimal set necessary to achieve these communications. This feature simplifies those interfaces, and encourages better encapsulation of the workings of the other components.

Centralizes Complexity All of the complexity involved in the communications between the engine components is captured in the Moderator. The interactions between the other engine components is greatly simplified through this design, making the engine easier to understand and maintain.

4.1.2.2 Summary

To summarize, the design of the Moderator reduces the interaction complexity in GMAT's engine; communications complexity resides in the Moderator, rather than in the interactions between the Interpreters and the elements of the engine. The other objects involved in these communications – the Script and GUI Interpreters, the Factory Manager, the Configuration Manager, and the Sandboxes – are less complex because they only communicate with the Moderator, rather than with each other. The Moderator is constructed to handle all of the interactions between the interpreters and amongst the engine components. You are unlikely to need to make any changes to the Moderator unless you are adding an unanticipated feature.

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4.2 Moderator Design

Figure 4.2 shows the Moderator, the classes it interacts with, and some of its internal structures. The interactions between the Moderator and other elements of GMAT's engine were presented in Chapter 3. The sequence diagrams presented there describe the interfaces to the Moderator and their usage when constructing and using a model. The methods shown in Figure 4.2 present representative examples of these interfaces in more detail.

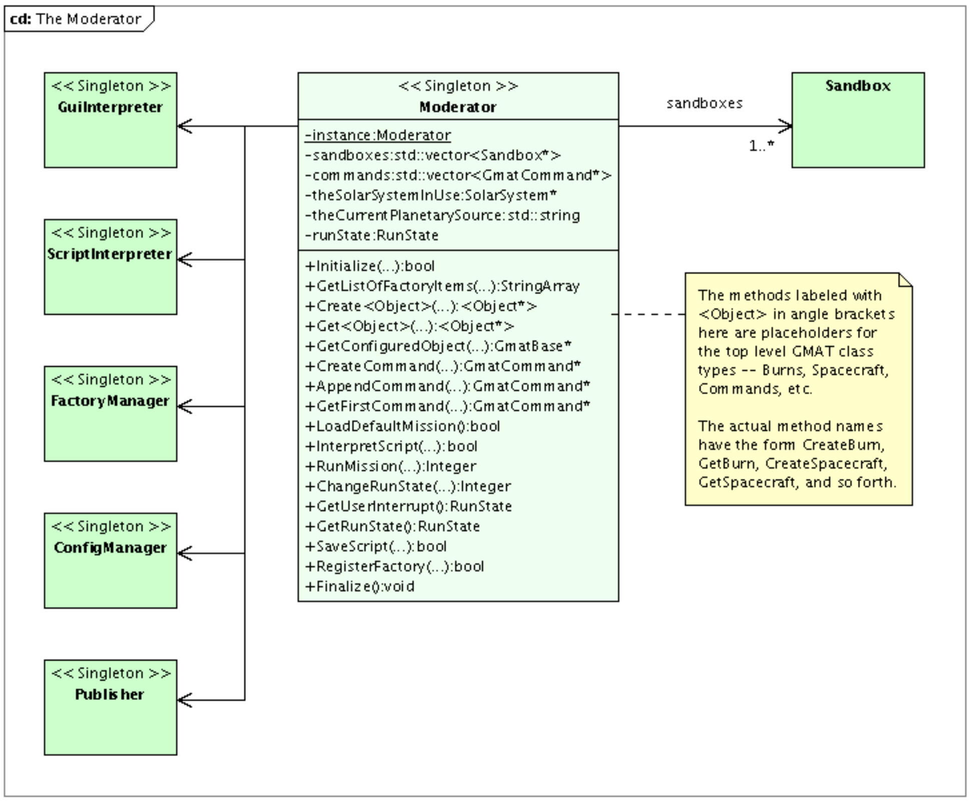
cd: The Moderator
<< Singleton >>
GuiInterpreter
<< Singleton >>
ScriptInterpreter
<< Singleton >>
FactoryManager
<< Singleton >>
ConfigManager
<< Singleton >>
Publisher
<< Singleton >>
Moderator
-instance:Moderator
-sandboxes:std::vector<Sandbox*>
-commands:std::vector<GmatCommand*>
-theSolarSystemInUse:SolarSystem*
-theCurrentPlanetarySource:std::string
-runState:RunState
+Initialize(...):bool
+GetListOfFactoryItems(...):StringArray
+Create<Object>(...):<Object*>
+Get<Object>(...):<Object*>
+GetConfiguredObject(...):GmatBase*
+CreateCommand(...):GmatCommand*
+AppendCommand(...):GmatCommand*
+GetFirstCommand(...):GmatCommand*
+LoadDefaultMission():bool
+InterpretScript(...):bool
+RunMission(...):Integer
+ChangeRunState(...):Integer
+GetUserInterrupt():RunState
+GetRunState():RunState
+SaveScript(...):bool
+RegisterFactory(...):bool
+Finalize():void
sandboxes
1..*
Sandbox
The methods labeled with <Object> in angle brackets here are placeholders for the top level GMAT class types -- Burns, Spacecraft, Commands, etc.
The actual method names have the form CreateBurn, GetBurn, CreateSpacecraft, GetSpacecraft, and so forth.

Figure 4.2: The Moderator in its Environment

4.2.1 Class Details

The following paragraphs describe the internal data members used by the Moderator and a brief discussion of how the methods shown in the figure are used to accomplish its tasks. Full details of the Moderator and its members can be found in the Doxygen documentation, generated by running Doxygen[doxygen] on GMAT's source code.

4.2.1.1 Class Attributes

There are several key data members that the Moderator uses to perform its assigned tasks. These members are

- **Moderator *instance**: The `instance` pointer in the Moderator is the singleton instance used throughout GMAT.

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- **std::vector<Sandbox*> sandboxes**: GMAT's Sandbox class is used to run missions simulating spacecraft in orbit. The Sandbox instances are the only key players in the engine which do not exist as singletons. Instead, the Sandbox instances are managed by the Moderator using the `sandboxes` vector.

- **std::vector<GmatCommand*> commands**: GMAT maintains a 1:1 mapping between the Sandbox instances and the Mission Control Sequences assigned to each Sandbox. The Moderator uses its `commands` vector to manage the first node of the command sequence linked list for the Mission Control Sequence of each Sandbox.

- **SolarSystem* theSolarSystemInUse**: GMAT's Solar System model (see Chapter 12) is an aggregated object configured to include all of the bodies, special points, and other environmental elements necessary for precision spacecraft modeling. The Moderator manages the Solar System used in the Sandboxes, and stores the current Solar System in the `theSolarSystemInUse` data member.

- **std::string theCurrentPlanetarySource**: This string identifies the source of the planetary ephemerides used in GMAT's environmental model.

- **RunState runState**: The Moderator keeps track of the current state of the Sandbox instances in order to facilitate communications about that status between the interpreters and user interfaces, the Publisher, and the Sandbox instances[1]. The `runState` member tracks this information for the Moderator.

Each of these class attributes plays a role in the seven tasks managed by the Moderator. Figure 4.2 also shows several methods used for these tasks. These methods and their roles in the Moderator's tasks are described next.

4.2.1.2 Initialization and Finalization Methods

The Moderator is responsible for starting the internal components of GMAT's engine, and for ensuring that those components exit gracefully when GMAT is closed. The start up process is described in some detail in section 3.2.1. Initialization and finalization are performed through the following two methods:

- **bool Initialize(bool isFromGui = false)**: The `Initialize` method creates the core engine components, parses the start up file and sets up the external file pointers for references contained in that file, and populates the Factory manager with the default factories. This method should be called before performing any other interactions with the GMAT engine. The input parameter, `isFromGui`, is used to determine if the default mission should be constructed during initialization.

- **void Finalize()**: The `Finalize` method is called as GMAT shuts down. This method frees memory that was allocated for use by the Moderator, and closes any open files managed in the Moderator.

4.2.1.3 Creation and Configuration Methods

The creation process, described in Section 3.2.2.1 for configured objects and in Section 3.2.3.1 for commands, allocates objects and stores them in GMAT's configuration database or the Mission Control Sequence, respectively. These objects can then be accessed by GMAT so that their attributes can be set as needed for the simulation, and, for the objects in the configuration database, so that they can be copied into a Sandbox prior to a mission run. The Moderator acts as the intermediary for the creation and object access processes, using methods tailored to these actions.

The full set of creation and access methods are best viewed in the Doxygen files. The following method descriptions are representative of the full set found there. The methods listed here use the Burn classes to

[1]The current implementation uses a single runState data member. This data structure will change to a vector when the multiple Sandbox features of GMAT are enabled.

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illustrate the objects that can be created in GMAT; other types of objects are created and configured using similar methods.

- **StringArray GetListOfFactoryItems(Gmat::ObjectType type)**: This method returns a list of all of the creatable types of objects of a given supertype, described by the `type` parameter. For example, if the `type` parameter is set to the `BURN` type, the returned string array contains the entries "ImpulsiveBurn" and "FiniteBurn".
- **Burn* CreateBurn(const std::string &type, const std::string &name)**: Creates a Burn object of the specified subtype, with the specified name. The Moderator contains creation methods for all of GMAT's core types. These methods are all similar in form to the method shown here; they specify the subtype and name of the requested object, and then return a pointer to the object if it was created successfully.
- **Burn* GetBurn(const std::string &name)**: Retrieves the Burn object with the specified name. Similar methods exist for all of GMAT's core types.
- **GmatBase* GetConfiguredObject(const std::string &name)**: Returns a base class pointer to the configured object of the specified name.
- **GmatCommand* CreateCommand(const std::string &type, const std::string &name, bool &retFlag)**: Creates a Mission Control Sequence command of the specified type.
- **GmatCommand* AppendCommand(const std::string &type, const std::string &name, bool &retFlag, Integer sandboxNum = 1)**: Creates a Mission Control Sequence command of the specified type, and passes it into the Mission Control Sequence associated with the specified Sandbox.
- **GmatCommand* GetFirstCommand(Integer sandboxNum = 1)**: Retrieves the first command in the Mission Control Sequence associated with the specified Sandbox. Since the Mission Control Sequence is a linked list, this method can be used to retrieve the entire Mission Control Sequence.

4.2.1.4 Reading or Saving a Mission

The processes followed when loading a mission into GMAT and when saving a mission from GMAT are managed by the Script Interpreter.

The read process is implemented as a sequence of object creations and configurations in the Script Interpreter. The Moderator passes requests for these processes to the Interpreter through several different methods, including these:

- **bool LoadDefaultMission()**: Clears the current configuration and Mission Control Sequence from memory, and then creates and configures the default GMAT mission.
- **bool InterpretScript(const std::string &filename, bool readBack = false, const std::string &newPath = "")**: Creates and configures all of the objects in a script file.

Each object defining a mission in GMAT includes the ability to serialize itself so that is can be passed to an external process or written to a file. The Moderator passes requests for this serialization to the Script Interpreter for processing. A representative example of the Moderator methods used for this process is the `SaveScript` method:

- **bool SaveScript(const std::string &filename, Gmat::WriteMode mode = Gmat::SCRIPTING)**: Builds scripts from the configured objects and commands, and write them to a file named by the `filename` parameter. The writeMode parameter is used to determine the style of the serialization; it can be set to either the default `SCRIPTING` style or to a style, `MATLAB_STRUCT`, compatible with MATLAB.

Details of the actual processes followed when reading or writing a script can be found in Chapter 17.

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4.2.1.5 Methods Used to Run a Mission

The process followed when GMAT runs a mission is described in Section 3.2.5. The process is relatively straightforward: the configured objects and Mission Control Sequence are loaded into the Sandbox instance, initialized to establish the connections between those objects, and then run in the Sandbox, as described in Section 3.2.5 and in Chapter 5. The Moderator supports these tasks through the following methods and through similar methods that can be examined in the Doxygen output.

- **Integer RunMission(Integer sandboxNum = 1)**: Loads objects into the specified Sandbox, initializes it, and starts the mission run in the Sandbox.
- **Integer ChangeRunState(const std::string &state, Integer sandboxNum = 1)**: Method used by the interpreters to update the run state information in the Moderator, so that the Sandbox can later check the Moderator's run state.
- **RunState GetUserInterrupt()**: Method called to determine if the user has requested a change in the run state. This method queries the interpreter for state changes before returning the run state, so that the interpreter code has an opportunity to update the state based on user actions.
- **RunState GetRunState()**: Returns the current run state of the Sandbox.

The Moderator keeps track of the state of execution in the Sandbox instance so that it can respond to messages from the interpreters that affect the system, like user commands to pause or terminate the run. The discussion in Section 3.2.5 presented the program flow exercised during a mission run. During the loop through the Mission Control Sequence shown in Figure 3.16, the Sandbox polls the Moderator for the execution state. This polling checks the Moderator's state variable and responds accordingly, as discussed in Chapter 5.

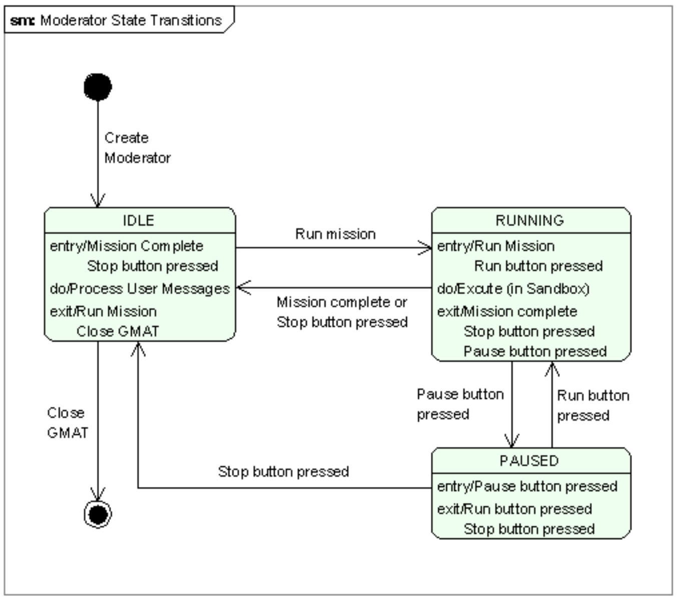

Figure 4.3: State Transitions in the Moderator

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State Transitions in the Moderator The Moderator tracks the current state of the system using a parameter named runState, which is set to a value in the RunState enumeration (see Table 9.8) defined in the Gmat namespace. The engine states tracked in the Moderator are the IDLE, RUNNING, and PAUSED states.

Figure 4.3 shows the run state transitions tracked by the Moderator. The Moderator is created with the run state set to the IDLE state. Most of the time, the Moderator remains in the IDLE state, processing messages from users and managing the internal components of the GMAT engine[2].

When a user executes a Mission Control Sequence, the Moderator transitions to the RUNNING state. In this state, the Moderator performs very limited processing while the control of the system is managed by the sandbox that is running the mission. The sandbox polls the Moderator for user activity at convenient points during the mission run. This polling allows the Moderator to respond to user actions that either terminate the mission early or pause the mission.

If the user presses the pause button on the GUI, the Moderator transitions into the PAUSED state when the sandbox polls for state status. This activity stops the mission run, but maintains data so that the run can be resumed from the point of the stop. The user tells the Moderator to resume the run by pressing the run button on the GUI. When the Moderator receives the run message, it transitions back into the RUNNING state and tells the sandbox to resume the run.

The user can terminate a run early by pressing the stop button on the GUI during a run. This action always causes the Moderator to transition from its current state - either RUNNING or PAUSED – into the IDLE state.

4.2.1.6 Support for Extending GMAT

GMAT employs a design pattern that allows the objects and commands used in simulations to be treated generically in the engine code. The system can be extended by creating a class or collection of classes, derived from one of GMAT's base classes, for each new feature that is added to the system, and then creating a Factory class that constructs instances of these new classes. This Factory is registered with GMAT's Factory Manager through the following call in the Moderator:

- **bool RegisterFactory(Factory* newFactory)**: Adds a Factory to the object creation subsystem managed by the Factory Manager.

Further details of the Factory subsystem can be found in Chapter 6.

4.3 Usage and Modification

The Moderator runs in the background for most of GMAT's programmatic tasks. You'll need to interact with it directly if you are working with the Factory Manager, Configuration Manager, or Sandbox code, or if you are adding a new interface to GMAT that requires a new Interpreter. Most programmatic tasks are not that extensive, and can be performed without changing the Moderator.

If you are adding a new user class to GMAT, you'll need to register the factory that creates instances of that class. These extensions are made through a call to the Moderator's `RegisterFactory` method, as described in Chapter 32. In addition, if the new class is not derived from a base class matching the set of Create and Get functions in the Moderator, you may need to add these methods to the Moderator code[3].

By design, the Moderator was written to support operations in GMAT's engine as it stands without the need for further extension. If you find a case that seems to need new functionality in the Moderator, please start a discussion regarding the change on GMAT's message forums at SourceForge[4].

[2]Many of the activities performed by the Moderator in the IDLE state are described in Chapter 3. Additional Moderator interactions with the other engine components are described in the appropriate sections of this document.

[3]The GMAT development team has this item noted as an issue that needs to be resolved.

[4]http://sourceforge.net/projects/gmat

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Chapter 5

The Sandbox

5.1 Design Principles

5.1.1 Sandbox Responsibilities

1. Clones configured objects for use during a run.
2. Connects local objects and commands together during initialization.
3. Runs the Mission Control Sequence.
4. Responds to interrupts from teh Moderator.
5. Passes output data to the Publisher.
6. Coordinates mission-run communications with outside processes.
7. Resets itself for new runs.

5.2 Design

5.2.1 Class Details

5.2.1.1 Class Attributes

5.2.2 The Late Binding Strategy

5.2.2.1 Sandbox Initialization Details

Figure 5.1 shows the steps taken to initialize a control sequence – either the Mission Control Sequence or a Function Control Sequence.

5.2.3 Interrupt Polling During a Run

5.3 Usage and Modification

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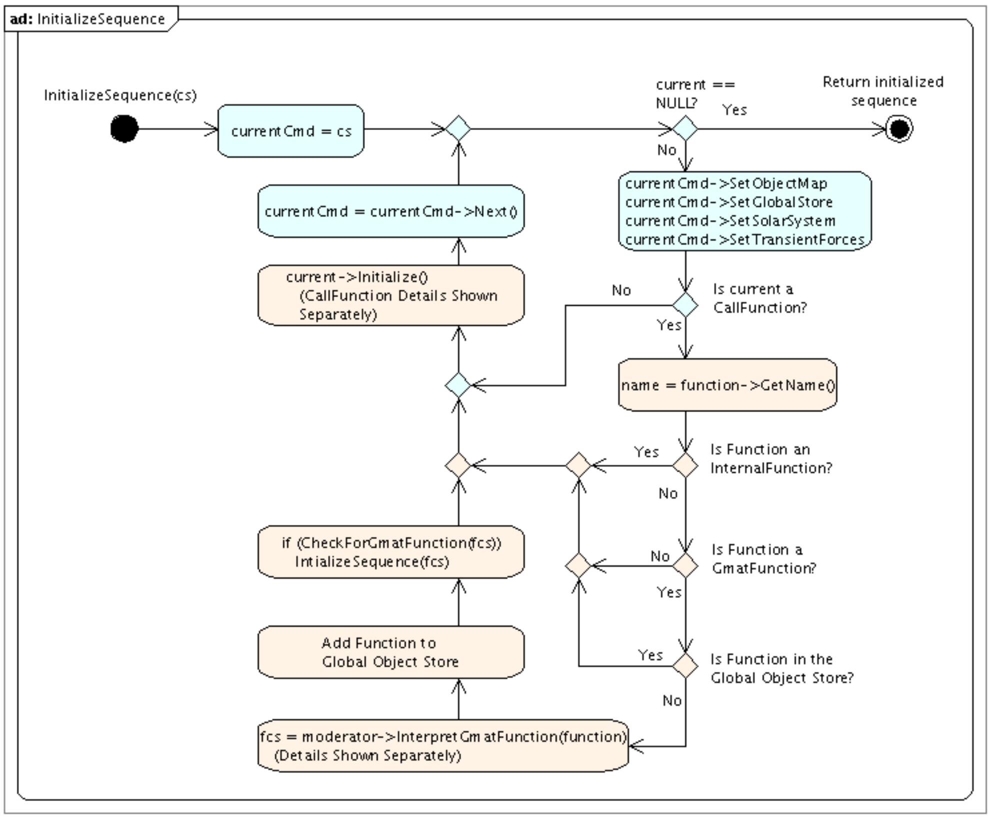
ad: InitializeSequence
InitializeSequence(cs)
currentCmd = cs
current == NULL?
Yes
Return initialized sequence
No
currentCmd->SetObjectMap
currentCmd->SetGlobalStore
currentCmd->SetSolarSystem
currentCmd->SetTransientForces
currentCmd = currentCmd->Next()
current->Initialize() (CallFunction Details Shown Separately)
No
Is current a CallFunction?
Yes
name = function->GetName()
Yes
Is Function an InternalFunction?
No
No
Is Function a GmatFunction?
Yes
if (CheckForGmatFunction(fcs)) IntializeSequence(fcs)
Add Function to Global Object Store
Yes
Is Function in the Global Object Store?
No
fcs = moderator->InterpretGmatFunction(function) (Details Shown Separately)

Figure 5.1: Initialization of a Control Sequence in the Sandbox

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Chapter 6

The Factory Manager

The Factory Manager uses Factory classes to create objects for GMAT's model. It takes creation messages from the Moderator, passes those messages into the Factory designed to create the specific type of object requested, and returns the created object to the Moderator.

This chapter describes the Factory Manager and introduces the Factory classes. The Factory Manager acts as the central junction into the Factory subsystem, managing Factories as they are created an d registered, and routint creation requests to the specific Factory that knows how to create a requested type of object.

Object creation is performed in a Factory derived from the Factory base class. An overview of the Factory infrastructure is provided in Section 11.1. Details about how you use the Factory classes to extend GMAT can be found in Chapter 32.

6.1 Design Principles

6.1.1 Factory Manager Responsibilities

1. Manages object creation for the engine.
2. Calls Factory classes to create objects.
3. Registers new Factories to support newly defined objects.
4. Provides a list of creatable object types.

6.1.2 The Abstract Factory Pattern, Factory Subclasses, and the Factory Manager

6.2 Design

6.2.1 Class Details

6.2.1.1 Class Attributes

6.2.2 Design of the Factory Classes

6.2.2.1 Factory Details

6.3 Usage and Modification

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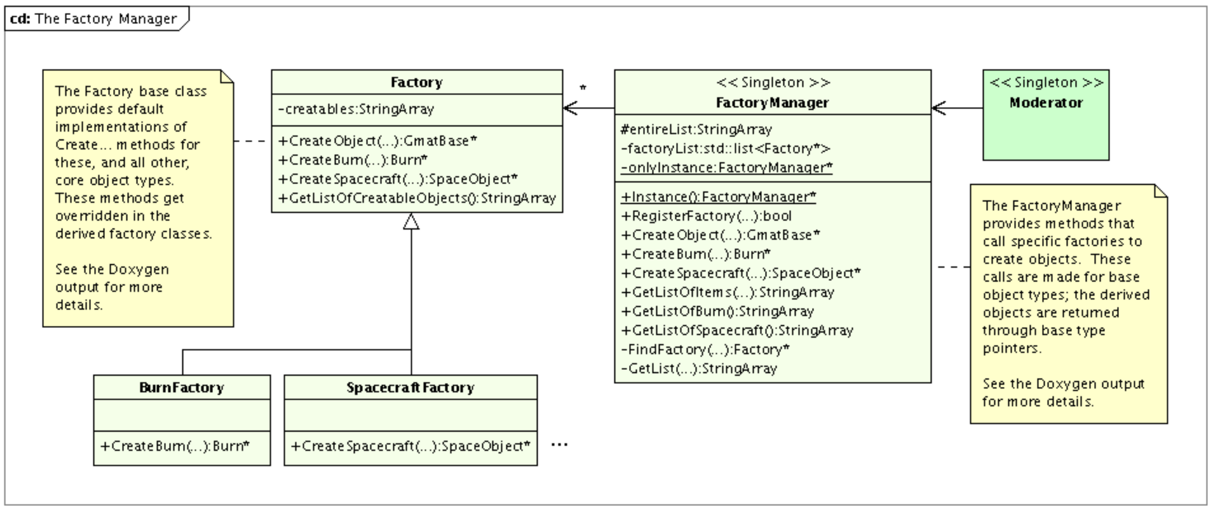
cd: The Factory Manager
Factory
-creatables:StringArray
+CreateObject(...):GmatBase*
+CreateBurn(...):Burn*
+CreateSpacecraft(...):SpaceObject*
+GetListOfCreatableObjects():StringArray
*
<< Singleton >>
FactoryManager
#entireList:StringArray
-factoryList:std::list<Factory*>
-onlyInstance:FactoryManager*
+Instance():FactoryManager*
+RegisterFactory(...):bool
+CreateObject(...):GmatBase*
+CreateBurn(...):Burn*
+CreateSpacecraft(...):SpaceObject*
+GetListOfItems(...):StringArray
+GetListOfBurn():StringArray
+GetListOfSpacecraft():StringArray
-FindFactory(...):Factory*
-GetList(...):StringArray
<< Singleton >>
Moderator
BurnFactory
+CreateBurn(...):Burn*
SpacecraftFactory
+CreateSpacecraft(...):SpaceObject*
...

The Factory base class provides default implementations of Create... methods for these, and all other, core object types. These methods get overridden in the derived factory classes.

See the Doxygen output for more details.

The FactoryManager provides methods that call specific factories to create objects. These calls are made for base object types; the derived objects are returned through base type pointers.

See the Doxygen output for more details.

Figure 6.1: The Factory Manager and Some Factories

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Chapter 7

The Configuration Manager

User created objects are stored in a vector of object pointers called the configuration. The Configuration Manager maintains this vector, provides access to the members, and adds new objects to teh vector as they are created. This chapter describes how the Configuration Manager performs these tasks.

7.1 Design Principles

The Configuration Manager Does not initiate communications with any other components of GMAT. It responds to requests from the Moderator to store or retrieve components of the GMAT model.

7.1.1 Configuration Manager Responsibilities

The Configuration Manager plays a central role in object storage and retrieval for the model elements. It performs the following tasks:

1. Maintain the collection of configured objects used in the model.
2. Add new objects to the collection when they are created, ensuring that the new objects have unique names.
3. Retrieve objects as they are needed.
4. Retrieve the list of stored objects, either by type or generically.
5. Clear the configuration in preparation for a new mission.

7.2 Design

7.2.1 Class Details

7.2.1.1 Class Attributes

7.3 Usage and Modification

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Chapter 8

The Publisher

8.1 Design Principles

8.1.1 Publisher Responsibilities

1. Registers data Subscribers that receive data during a mission run.
2. Receives published data during a run and passes it to Subscribers.
3. Flushes data streams when needed.
4. Passes messages indicating state changes and other run information to the Subscribers.
5. Manages the subscriber list, adding or removing Subscribers as needed.

8.2 Design

8.2.1 Class Details

8.2.1.1 Class Attributes

8.3 Usage and Modification

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Part III

Model Components

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Chapter 9

The GmatBase Class, Constants, and Defined Types

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This chapter documents GMAT's predefined data types, constants, and the core user classes used in GMAT to implement the flight dynamics model.

9.1 Defined Data Types

GMAT uses the C++ type definition mechanism to define the data types shown in Table 9.1. These definitions, found in the gmatdefs.hpp header file, provide a mechanism to generalize common data types and frequently used structures in the source code.

Table 9.1: Data Types Defined for GMAT

Defined typedef	Type Name	Description
double	Real	8 byte float
int	Integer	4 byte signed integer
unsigned char	Byte	1 byte character
unsigned int	UnsignedInt	4 byte unsigned integer
std::vector<Real>	RealArray	Vector of Reals
std::vector<Integer>	IntegerArray	Vector of signed integers
std::vector<UnsignedInt>	UnsignedIntArray	Vector of unsigned integers
std::vector<std::string>	StringArray	Vector of strings
std::vector<GmatBase*>	ObjectArray	Vector of GmatBase objects
std::vector<Gmat::ObjectType>	ObjectTypeArray	Vector of object type identifiers

9.2 Error Handling in GMAT

GMAT responds to critical anomalies in the configuration or other settings by throwing exceptions reporting the error. Every effort has been made to make GMAT's exception messages consistent and informative. Less

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serious anomalies may be reported through masseges passed as warnings to GMAT's messaging system. The classes implemented to support these two mechanisms are documented in Chapter 10.

9.3 GmatBase

The factory classes described in Chapter 11 are used to generate the resources and Mission Control Sequence commands needed to simulate flight dynamics models. The objects that are generated in GMAT corresponding to these model elements are all instances of classes derived from a base class named GmatBase. The GmatBase class defines a common set of interfaces used to build, configure, maintain, and store these elements. This commonality of the interfaces into user defined objects enforces consistency, simplifying common tasks that are performed on these objects.

Since understanding of the GmatBase is key to understanding how to work with the source code for the model, this section of the document is written to thoroughly capture the contents of the class. We'll begin by examining the class features in the following sections, and then provide some information about how GMAT uses these features to set properties while reading and to serialize model objects while writing objects to a text stream.

9.3.1 GmatBase Attributes and Methods

The features of GmatBase are broken into the class attributes and methods. The method descriptions are categorized into ??? subsections: (1) Constructors, Destructor, and Static Methods, (2) Object Management Interfaces, (3) Interfaces Used for Scripting, the GUI, and External Communications, (4) Class Attributes for Referenced and Owned Objects, (5) Class Attribute Management interfaces, and (6 – 9) sections for the interfaces into Reals, Integers, Strings, and other attribute types.

9.3.1.1 *Class Attributes*

GmatBase contains data structures designed to manage the common elements shared by all of the derived classes. Configurable pieces of the derived classes are referred to as "parameters" in the GmatBase code; hence the Integer attribute "parameterCount" reports the number of parameters that can be accessed for instances of the derived class. The attributes of GmatGase are described here:

- **static Integer instanceCount**: Count of the number of GmatBase objects currently instantiated.
- **Integer parameterCount**: Count of the accessible parameters.
- **std::string typeName**: Script string used or this class.
- **std::string instanceName**: Name of the object – empty if it is nameless.
- **Gmat::ObjectType type**: Enumerated base type of the object.
- **Integer ownedObjectCount**: Number of owned objects that belong to this instance.
- **std::string generatingString**: Script string used to build the object.
- **ObjectTypeArray objectTypes**: The list of generic types that this class extends.
- **StringArray objectTypeNames**: The list types that this class extends, by name.
- **ObjectTypeArray refObjectTypes**: The list of object types referenced by this class.
- **StringArray refObjectNames**: The list of object names referenced by this class.
- **bool callbackExecuting**: Flag indicating whether or not a Callback method is currently executing.

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- **std::string errorMessageFormat**: The format string used when throwing error messages for named objects.
- **std::string errorMessageFormatUnnamed**: The format string used when throwing error messages for unnamed objects.
- **bool inMatlabMode**: Flag used to deterine if the current write is in Matlab mode.
- **std::string commentLine**: String used to hold the comment line.
- **std::string inlineComment**: String used to hold inline comment.
- **StringArray attributeCommentLines**: String array used to hold the attribute comments.
- **StringArray attributeInlineComments**: String array used to hold the attribute inline comments.

9.3.1.2 *Constructor, Destructor, and Static Methods*

GmatBase implements methods that override the default compiler-generated construction and destruction capabilities, along with several class level utilities, as described below.

Default Methods C++ automatically defines four methods when a class is defined in code: a default constructor, a copy constructor, a destructor, and an assignment operator. Every user class in GMAT overrides these methods to prevent generation of the default compiler versions.

- **GmatBase(Gmat::ObjectType typeId, const std::string &typeStr, const std::string &nomme = "")**: This is the default constructor for all GmatBase objects.
- **virtual GmatBase() = 0**: The base class destructor. The destructor is set as abstract, but it does have an implementation; designating it as abstract ensures that the compiler will not allow GmatBase base class instances.
- **GmatBase(const GmatBase &a)**: The copy constructor.
- **GmatBase& operator=(const GmatBase &a)**: The assignment operator.

Static Methods The GmatBase class provides a mechanism to count object instances, provide numerical precision setting data, and find object types and names through the following static class methods:

- **static Integer GetInstanceCount()**: Method to return the current number of instantiated objects.
- **static Integer GetDataPrecision()**: Returns the current precision setting used when converting Real numbers into strings.
- **static Integer GetTimePrecision()**: Returns the current precision setting used when converting epoch data into strings.
- **static std::string GetObjectTypeString(Gmat::ObjectType type)**: Method for getting GMAT object type string.
- **static Gmat::ObjectType GetObjectType(const std::string &typeString)**: Method for getting GMAT object type.

9.3.1.3 *Object Management Interfaces*

GmatBase provides interfaces that are used to identify the object so that it can be accessed, and so that other objects can find and connect to it. These interfaces are described in this section.

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Base Class Property Interfaces We'll begin by listing the interfaces that are used to retrieve information about the current object.

- **virtual Gmat::ObjectType GetType() const**: Retrieves the core type of the object.
- **inline std::string GetTypeName() const**: Retrieves the test description used for the object type.
- **inline std::string GetName() const**: Retrieves teh object's name. Names in GMAT are used to access objects in the Configuration; each user defined object that is stored in the configuration is given a unique name.
- **virtual bool SetName(const std::string &who, const std::string &oldName = "")**: Renames the object.
- **virtual Integer GetParameterCount() const**: Returns the number of parameters that can be accessed for the object using the parameter interfaces, discussed below.
- **bool IsOfType(Gmat::ObjectType ofType)**: Checks the object to see if it is derived from the specified ObjectType.
- **bool IsOfType(std::string typeDescription)**: Checks the object to see if it is derived from the specified named type.

Overridable Interfaces The interfaces listed next are interfaces that are overrridden in the derived classes to provide functionality as needed.

- **virtual GmatBase* Clone() const = 0**: Every GmatBase derived class that can be instantiated must implement the Clone() method. Clone() is used to copy objects from the configuration into the Sandbox prior to the execution of the Mission Control Sequence.
- **virtual void Copy(const GmatBase*)**: The Copy() method is provided so that objects that need to copy data from other objects of the same class type can do so even when referenced through GmatBase pointers.
- **virtual bool Initialize()**: Objects that need to preform specific initialization tasks override this method to perform those tasks. The Sandbox calls the Initialize() method as part of the Sandbox initialization process.
- **virtual void SetSolarSystem(SolarSystem *ss)**: Objects that need access to GMAT's current SolarSystem object override this method to set their SolarSystem pointer.
- **virtual bool RequiresJ2000Body()**: Classes that need location data in the model use a referenced body – referred to as the J2000 body – as the origin for spatial conversions. Classes that require this body override the RequiresJ2000Body method to return true from this call.
- **virtual bool TakeAction(const std::string &action, const std::string &actionData = "")**: TakeAction() is a utility method that derived classes override to provide functionality that cannot be implemented through basic parameter setting calls[1].
- **virtual void FinalizeCreation()**: Performs initialization of GmatBase properties that depend on the features of the derived classes. Derived classes can touch some of the base class properties – the parameterCount, for example. This method is called after the object creation process is complete, so that any of the object's base-class properties can be updated to reflect the object's actual properties.

[1]One example of the use of the TakeAction() can be found in the Spacecraft class. The Spacecraft class uses TakeAction() to manage attached tank and thruster objects. Tanks and Thrusters are attached by name to the Spacecraft instances during configuration, but the actual member objects are set during Sandbox initialization through a call, "TakeAction("SetupHardware");", made to the Spacecraft object.

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- **virtual std::string GetErrorMessageFormat()**: Returns the error message format string used by the object.
- **virtual void SetErrorMessageFormat(const std::string &fmt)**: Updates the error message format string used by the object.

9.3.1.4 *Interfaces Used for Scripting, the GUI, and External Communications*

The interfaces used for scripting and callbacks are described in the following paragraphs.

General Purpose Interfaces All of the objects used in GMAT's model have the ability to produce text descriptions – aka script blocks – sufficient to reproduce themselves and to incorporate text comments that help document the intent of the setting selected by the user. These interfaces are described here:

- **virtual const std::string GetCommentLine() const**: Returns the comment lines that occur before the object definition or command line.
- **virtual void SetCommentLine(const std::string &comment)**: Sets the comment lines that occur before the object definition or command line.
- **virtual const std::string GetInlineComment() const**: Returns the comment that occurs inline at the end of the object definition or command line.
- **virtual void SetInlineComment(const std::string &comment)**: Sets the comment that occurs inline at the end of the object definition or command line.
- **virtual const std::string GetAttributeCommentLine(Integer index)**: Returns any comment that occurs before an attribute setting line.
- **virtual void SetAttributeCommentLine(Integer index, const std::string &comment)**: Sets a comment that occurs before the attribute setting line.
- **virtual const std::string GetInlineAttributeComment(Integer index)**: Returns the comment that occurs at the end of an attribute setting line.
- **virtual void SetInlineAttributeComment(Integer index, const std::string &comment)**: Sets the comment that occurs at the end of an attribute setting line.
- **virtual const std::string& GetGeneratingString(Gmat::WriteMode mode = Gmat::SCRIPTING, const std::string &prefix = "", const std::string &useName = "")**: Returns a text string that can be used to regenerate the object. See Section 9.3.3.1 for an explanation of the write modes.
- **virtual StringArray GetGeneratingStringArray(Gmat::WriteMode mode = Gmat::SCRIPTING, const std::string &prefix = "", const std::string &useName = "")**: Returns a string array that can be used to regenerate the object. See Section 9.3.3.1 for an explanation of the write modes.
- **void CopyParameters(const GmatBase &a)**: Copies the attributes from one object into the current object.
- **virtual void WriteParameters(Gmat::WriteMode mode, std::string &prefix, std::stringstream &stream)**: Writes the parameter details for an object. This method is called by the GetGeneratingString methods to build the individual attribute lines needed to write configured objects.
- **void WriteParameterValue(Integer id, std::stringstream &stream)**: Formats and writes the attribute value portion of the attribute line.
- **virtual void PrepCommentTables()**: A private method used to configure teh comment tables so that they are sized correctly for the owning object.

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Callback Interfaces Some GMAT classes are designed to communicate with external process through a basic callback method. These classes override the following methods to implement callbacks.

- **virtual bool ExecuteCallback()**: The method called from the external process to execute a task in GMAT.
- **virtual bool IsCallbackExecuting()**: Monitoring function used to determine if the object is executing its callback method.
- **virtual bool PutCallbackData(std::string &data)**: Sends data from GMAT to the process that is using the callback.
- **virtual std::string GetCallbackResults()**: Retrieves the results of the callback.

9.3.1.5 *Class Attributes: Referenced and Owned Objects*

Many of the user created objects need to interact with other model objects to correctly model the spacecraft mission. When an object uses the interfaces for a second named object that is stored in the configuration, the second object is called a "referenced object" in this document. Occasionally an object will have, as a wholly owned, encapsulated member, another object. These internal member objects are called "owned objects." The methods listed here are implemented to work with the owned and referenced objects.

- **virtual std::string GetRefObjectName(const Gmat::ObjectType type) const**: Returns the name of a referenced object of a specified type, of the object uses that type of referenced object.
- **virtual const ObjectTypeArray& GetRefObjectTypeArray()**: Returns an array of the reference object types used by the current object. Derived classes set the types in the refObjectTypes attribute, which is returned from this call.
- **virtual const StringArray& GetRefObjectNameArray(const Gmat::ObjectType type)**: Returns the reference object names used by the current object. Derived classes override this method to return the correct values.
- **virtual bool SetRefObjectName(const Gmat::ObjectType type, const std::string &name)**: Sets the name of a referenced object.
- **virtual bool RenameRefObject(const Gmat::ObjectType type, const std::string &oldName, const std::string &newName)**: Resets the reference object name when the reference object is renamed elsewhere.
- **virtual GmatBase* GetRefObject(const Gmat::ObjectType type, const std::string &name)**: Returns the current reference object of specified type and name.
- **virtual GmatBase* GetRefObject(const Gmat::ObjectType type, const std::string &name, const Integer index)**: Returns the current reference object when there are multiple objects of a given type. The referenced object is specified by type, name, and index.
- **virtual bool SetRefObject(GmatBase *obj, const Gmat::ObjectType type, const std::string &name = "")**: Passes a referenced object's pointer into the object.
- **virtual bool SetRefObject(GmatBase *obj, const Gmat::ObjectType type, const std::string &name, const Integer index)**: Passes a referenced object's pointer into the object for use in an array of referenced objects.
- **virtual ObjectArray& GetRefObjectArray(const Gmat::ObjectType type)**: Retrieves an array of referenced objects by type.

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- **virtual ObjectArray& GetRefObjectArray(const std::string& typeString)**: Retrieves an array of referenced objects by type name.
- **virtual Integer GetOwnedObjectCount()**: Retrieves the number of owned objects contained in the object.
- **virtual GmatBase* GetOwnedObject(Integer whichOne)**: Retrieves teh owned objects by index into the owned object array.

9.3.1.6 *Class Attribute Accessors: Parameter Management*

All of the attributes of the GmatBase classes that are accessible directly by users have associated descriptions, ID numbers, and types. When attributes have these features, they will be referred to as parameters in this chapter. Classes can have other attributes that are not directly accessible by users.

The parameters that are reported when an object is serialized are identified and read and write enabled parameters; those that are not contained in the serialization are nominally identified as read only, though the base class does not enforce read-only nature on those parameters. Classes that need strict read-only enforcement implement that nature in the parameter access methods.

The parameter management interfaces are described here:

- **virtual std::string GetParameterText(const Integer id) const**: Returns the text string associated with the parameter ID input into the method.
- **virtual Integer GetParameterID(const std::string &str) const**: Returns the ID associated with a parameter's description.
- **virtual Gmat::ParameterType GetParameterType(const Integer id) const**: Returns the parameter type for the specified ID.
- **virtual std::string GetParameterTypeString(const Integer id) const**: Returns the parameter type string for the input parameter ID.
- **virtual bool IsParameterReadOnly(const Integer id) const**: Returns true if the parameter, identified by parameter ID, is read-only. Derived classes override this method to identify read-only parameters.
- **virtual bool IsParameterReadOnly(const std::string &label) const**: Returns true if the parameter, identified by parameter name, is read-only. Derived classes override this method to identify read-only parameters.

9.3.1.7 Static Members Used with Attributes

GmatBase includes several class-level (static) members used to simplify parameter access methods. These members are specified in the following tables.

String Definitions for Attributes The arrays shown in Table 9.2 provide text strings for each of GMAT's defined data types and object types. These strings are used to identify types in a human readable format.

Table 9.2: Arrays Holding Defined Type Names

Type	Array Name	Purpose
static const std::string	PARAM_TYPE_STRING[]	String mappings for the GMAT data types
static const std::string	OBJECT_TYPE_STRING[]	String mappings for the GMAT object types

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Constants for Undefined Values Occasionally GMAT objects need an initial value for attribute initialization when that value is not yet available. The static constants shown in Table 9.3 provide these initial values.

Table 9.3: Constants Holding Undefined Values

Type	Variable Name	Value
const Real	REAL_PARAMETER_UNDEFINED	-987654321.0123e-45
const Integer	INTEGER_PARAMETER_UNDEFINED	-987654321
const UnsignedInt	UNSIGNED_INT_PARAMETER_UNDEFINED	987654321
const std::string	STRING_PARAMETER_UNDEFINED	"STRING_PARAMETER-_UNDEFINED"
const Rvector	RVECTOR_PARAMETER_UNDEFINED	A 1-element Rvector, initialized to REAL_PARAMETER-_UNDEFINED
const Rmatrix	RMATRIX_PARAMETER_UNDEFINED	A 1-by-1 Rmatrix, initialized to REAL_PARAMETER-_UNDEFINED

The following sections describe the interfaces used to access the parameters. These methods are type specific; the parameter has to have the type accosiated with teh method in order to return a valid value.

9.3.1.8 *Class Attributes: Real Number Interfaces*

GmatBase objects support the following interfaces into Real number attributes:

- **virtual Real GetRealParameter(const Integer id) const**: Retrieves the Real value of the parameter with the specified ID.
- **virtual Real SetRealParameter(const Integer id,const Real value)**: Sets the Real value of the parameter with the specified ID.
- **virtual Real GetRealParameter(const Integer id, const Integer index) const**: Retrieves the Real value of a parameter stored in a vector, where the vector is identified by the specified ID, and the requested element has the specified index.
- **virtual Real GetRealParameter(const Integer id, const Integer row, const Integer col) const**: Retrieves the Real value of a parameter stored in an array, where the array is identified by the specified ID, and the requested element is located in the specified row and column.
- **virtual Real SetRealParameter(const Integer id, const Real value, const Integer index)**: Sets the Real value of a parameter stored in a vector, where the vector is identified by the specified ID, and the requested element has the specified index.
- **virtual Real SetRealParameter(const Integer id, const Real value, const Integer row, const Integer col)**: Sets the Real value of a parameter stored in an array, where the array is identified by the specified ID, and the requested element is located in the specified row and column.
- **virtual Real GetRealParameter(const std::string &label) const**: Retrieves the Real value of the parameter with the text label.

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- **virtual Real SetRealParameter(const std::string &label, const Real value)**: Sets the Real value of the parameter with the specified text label.
- **virtual Real GetRealParameter(const std::string &label, const Integer index) const**: Retrieves the Real value of a parameter stored in a vector, where the vector is identified by the specified text label, and the requested element has the specified index.
- **virtual Real SetRealParameter(const std::string &label, const Real value, const Integer index)**: Sets the Real value of a parameter stored in a vector, where the vector is identified by the specified text label, and the requested element has the specified index.
- **virtual Real GetRealParameter(const std::string &label, const Integer row, const Integer col) const**: Retrieves the Real value of a parameter stored in an array, where the array is identified by the specified text label, and the requested element is located in the specified row and column.
- **virtual Real SetRealParameter(const std::string &label, const Real value, const Integer row, const Integer col)**: Sets the Real value of a parameter stored in an array, where the array is identified by the specified text label, and the requested element is located in the specified row and column.
- **virtual const Rvector& GetRvectorParameter(const Integer id) const**: Retrieves a vector of Real data, contained in an Rvector instance, with the specified ID.
- **virtual const Rvector& SetRvectorParameter(const Integer id, const Rvector &value)**: Sets a vector of Real data, contained in an Rvector, with the specified ID.
- **virtual const Rmatrix& GetRmatrixParameter(const Integer id) const**: Retrieves an array of Real data, contained in an Rmatrix instance, with the specified ID.
- **virtual const Rmatrix& SetRmatrixParameter(const Integer id, const Rmatrix &value)**: Sets an array of Real data, contained in an Rmatrix instance, with the specified ID.
- **virtual const Rvector& GetRvectorParameter(const std::string &label) const**: Retrieves a vector of Real data, contained in an Rvector instance, with the specified text label.
- **virtual const Rvector& SetRvectorParameter(const std::string &label, const Rvector &value)**: Sets a vector of Real data, contained in an Rvector, with the specified text label.
- **virtual const Rmatrix& GetRmatrixParameter(const std::string &label) const**: Retrieves an array of Real data, contained in an Rmatrix instance, with the specified text label.
- **virtual const Rmatrix& SetRmatrixParameter(const std::string &label, const Rmatrix &value)**: Sets an array of Real data, contained in an Rmatrix instance, with the specified text label.

9.3.1.9 *Class Attributes: Integer Interfaces*

The access methods used for integer parameters – both signed and unsigned – are listed here:

- **virtual Integer GetIntegerParameter(const Integer id) const**: Retrieves the Integer value of the parameter with the specified ID.
- **virtual Integer SetIntegerParameter(const Integer id, const Integer value)**: Sets the Integer value of the parameter with the specified ID.
- **virtual Integer GetIntegerParameter(const Integer id, const Integer index) const**: Retrieves the Integer value of a parameter stored in a vector, where the vector is identified by the specified ID, and the requested element has the specified index.

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- **virtual Integer SetIntegerParameter(const Integer id, const Integer value, const Integer index)**: Sets the Real value of a parameter stored in a vector, where the vector is identified by the specified ID, and the requested element has the specified index.

- **virtual UnsignedInt GetUnsignedIntParameter(const Integer id) const**: Retrieves the unsigned Integer value of the parameter with the specified ID.

- **virtual UnsignedInt SetUnsignedIntParameter(const Integer id, const UnsignedInt value)**: Sets the unsigned Integer value of the parameter with the specified ID.

- **virtual UnsignedInt GetUnsignedIntParameter(const Integer id, const Integer index) const**: Retrieves the unsigned Integer value of a parameter stored in a vector, where the vector is identified by the specified ID, and the requested element has the specified index.

- **virtual UnsignedInt SetUnsignedIntParameter(const Integer id, const UnsignedInt value, const Integer index)**: Sets the unsigned Integer value of a parameter stored in a vector, where the vector is identified by the specified ID, and the requested element has the specified index.

- **virtual const UnsignedIntArray& GetUnsignedIntArrayParameter(const Integer id) const**: Retrieves an array of unsigned Integers identified by the specified ID.

- **virtual Integer GetIntegerParameter(const std::string &label) const**: Retrieves an Integer parameter identified by the specified text label.

- **virtual Integer SetIntegerParameter(const std::string &label, const Integer value)**: Sets an Integer parameter identified by the specified text label

- **virtual Integer GetIntegerParameter(const std::string &label, const Integer index) const**: Retrieves the Integer value of a parameter stored in a vector, where the vector is identified by the specified text label and the requested element has the specified index.

- **virtual Integer SetIntegerParameter(const std::string &label, const Integer value, const Integer index)**: Sets the Integer value of a parameter stored in a vector, where the vector is identified by the specified text label and the requested element has the specified index.

- **virtual UnsignedInt GetUnsignedIntParameter(const std::string &label) const**: Retrieves the unsigned Integer value of a parameter identified by a text label.

- **virtual UnsignedInt SetUnsignedIntParameter(const std::string &label, const UnsignedInt value)**: Sets the unsigned Integer value of a parameter identified by a text label.

- **virtual UnsignedInt GetUnsignedIntParameter(const std::string &label, const Integer index) const**: Retrieves the unsigned Integer value of a parameter stored in a vector, where the vector is identified by a text label, and the requested element has the specified index.

- **virtual UnsignedInt SetUnsignedIntParameter(const std::string &label, const UnsignedInt value, const Integer index)**: Sets the unsigned Integer value of a parameter stored in a vector, where the vector is identified by a text label, and the requested element has the specified index.

- **virtual const UnsignedIntArray& GetUnsignedIntArrayParameter(const std::string &label) const**: Retrieves an array of unsigned Integers identified by a text label.

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9.3.1.10 *Class Attributes: String Interfaces*

String interfaces are used to set reference object names, along with other textual data used inside of the GmatBase objects. The string interfaces into GmatBase parameters are described here:

- **virtual std::string GetStringParameter(const Integer id) const**: Retrieves the string value of the parameter with the specified ID.
- **virtual bool SetStringParameter(const Integer id, const std::string &value)**: Sets the string value of the parameter with the specified ID.
- **virtual std::string GetStringParameter(const Integer id, const Integer index) const**: Retrieves a string from a vector of strings, where the vector has the specified ID and the retrieved string is in the vector element identified by index.
- **virtual bool SetStringParameter(const Integer id, const std::string &value, const Integer index)**: Sets a string in a vector of strings, where the vector has the specified ID and the input string is placed in the vector element identified by index.
- **virtual std::string GetStringParameter(const std::string &label) const**: Retrieves the string value of the parameter with the specified text label.
- **virtual bool SetStringParameter(const std::string &label, const std::string &value)**: Sets the string value of the parameter with the specified text label.
- **virtual std::string GetStringParameter(const std::string &label, const Integer index) const**: Retrieves a string from a vector of strings, where the vector has the specified text label and the retrieved string is in the vector element identified by index.
- **virtual bool SetStringParameter(const std::string &label, const std::string &value, const Integer index)**: Sets a string in a vector of strings, where the vector has the specified text label and the input string is placed in the vector element identified by the specified index.
- **virtual const StringArray& GetStringArrayParameter(const std::string &label) const**: Retrieves a vector of strings stored in the vector associated with a text label.
- **virtual const StringArray& GetStringArrayParameter(const std::string &label, const Integer index) const**: Retrieves a vector of strings from a vector of string arrays identified by a text label. The retrieved vector is identified by index into the vector of string arrays.
- **virtual const StringArray& GetStringArrayParameter(const Integer id) const**: Retrieves a vector of strings stored in the parameter associated with an ID.
- **virtual const StringArray& GetStringArrayParameter(const Integer id, const Integer index) const**: Retrieves a vector of strings from a vector of string arrays identified by ID. The retrieved vector is identified by index into the vector of string arrays.

9.3.1.11 *Class Attributes: Boolean Interfaces*

GmatBase supports two types of boolean parameters: standard C++ bool values and a sttring version of boolean data, set to either the string “On” or “Off.” The interfaces implemented into these parameters is presented here:

- **virtual bool GetBooleanParameter(const Integer id) const**: Retrieves the boolean value of the parameter with the specified ID.

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- **virtual bool SetBooleanParameter(const Integer id, const bool value)**: Sets the boolean value of the parameter with the specified ID.
- **virtual bool GetBooleanParameter(const Integer id, const Integer index) const**: Retrieves a boolean from a vector of booleans, where the vector has the specified ID and the retrieved boolean is in the vector element identified by index.
- **virtual bool SetBooleanParameter(const Integer id, const bool value, const Integer index)**: Sets a boolean into a vector of booleans, where the vector has the specified ID and the input boolean is in the vector element identified by index.
- **virtual bool GetBooleanParameter(const std::string &label) const**: Retrieves the boolean value of the parameter with the specified text label.
- **virtual bool SetBooleanParameter(const std::string &label, const bool value)**: Sets the boolean value of the parameter with the specified text label.
- **virtual bool GetBooleanParameter(const std::string &label, const Integer index) const**: Retrieves a boolean from a vector of booleans, where the vector has the specified text label and the retrieved boolean is in the vector element identified by index.
- **virtual bool SetBooleanParameter(const std::string &label, const bool value, const Integer index)**: Sets a boolean into a vector of booleans, where the vector has the specified text label and the input boolean is in the vector element identified by index.
- **virtual std::string GetOnOffParameter(const Integer id) const**: Retrieves the state value (“On” or “Off”) of the parameter with the specified ID.
- **virtual bool SetOnOffParameter(const Integer id, const std::string &value)**: Sets the state value (“On” or “Off”) of the parameter with the specified ID.
- **virtual std::string GetOnOffParameter(const std::string &label) const**: Retrieves the state value (“On” or “Off”) of the parameter with the specified text label.
- **virtual bool SetOnOffParameter(const std::string &label, const std::string &value)**: Sets the state value (“On” or “Off”) of the parameter with the specified text label.

9.3.2 Setting GmatBase Properties

The somewhat tedious descriptions provided above show the interfaces into parameters for the configured objects in a static format. The next two sections show in a bit more detail how these interfaces are used to set parameters and to construct a serialized version of a GmatBase object. We'll begin with an example setting several properties on an ImpulsiveBurn object. The class hierarchy for ImpulsiveBurns is shown in Figure 9.1.

```
Create ImpulsiveBurn Burn1;

Burn1.Origin = Earth;
Burn1.Axes = VNB;
Burn1.VectorFormat = Cartesian;
Burn1.Element1 = 3.16;
Burn1.Element2 = 0;
Burn1.Element3 = 0;
```

Listing 9.1: Script Listing for an ImpulsiveBurn

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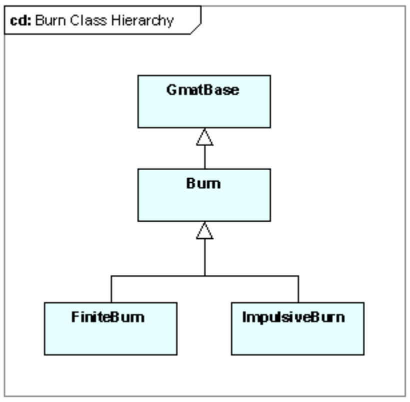

Figure 9.1: Class Hierarchy for Gmat's Burn Resources

The serialized text – that is, the scripting – for an ImpulsiveBurn object is shown in Listing 9.1. As can be seen on lines 3 – 8 in this listing, ImpulsiveBurn objects have six accessible parameters that users can manipulate: the Origin of the burn ("Origin"), the Axes used to orient the burn in space ("Axes"), a format defining how the burn is written relative to these axes ("VectorFormat"), and the three components necessary to define the delta-V that this burn models ("Element1", "Element2", and "Element3").

When GMAT reads a script containing these lines, it creates a new ImpulsiveBurn object named Burn1 and sets the values found in the script into the associated parameters on the object. The object creation process was described in Section 3.2.2.1. Figure 9.2 shows the calls made to the new object to set the parameter values. The steps shown in this figure are straightforward:

1. **Call Burn1->GetParameterType("Origin")** Determines that the "Origin" parameter is a string.

2. **Call Burn1->SetStringParameter("Origin", "Earth")** Sets the "Origin" parameter to the string "Earth".

3. **Call Burn1->GetParameterType("Axes")** Determines that the "Axes" parameter is a string.

4. **Call Burn1->SetStringParameter("Axes", "VNB")** Sets the "Axes" parameter to the string "VNB", denoting that the burn is specified in the Velocity-Normal-Binormal representation.

5. **Call Burn1->GetParameterType("VectorFormat")** Determmines that the "VectorFormat" parameter is a string.

6. **Call Burn1->SetStringParameter("VectorFormat", "Cartesian")** Sets the "VectorFormat" parameter to the string "Cartesian".

7. **Call Burn1->GetParameterType("Element1")** Determines that the "Element1" parameter is a Real number.

8. **Call Burn1->SetRealParameter("Element1", 3.16)** Sets the "Element1" parameter to the value 3.16.

9. **Call Burn1->GetParameterType("Element2")** Determines that the "Element2" parameter is a Real number.

10. **Call Burn1->SetRealParameter("Element2", 0)** Sets the "Element2" parameter to the value 0.0.

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11. **Call Burn1->GetParameterType("Element3")** Determines that the "Element3" parameter is a Real number.
12. **Call Burn1->SetRealParameter("Element3", 0)** Sets the "Element3" parameter to the value 0.0.

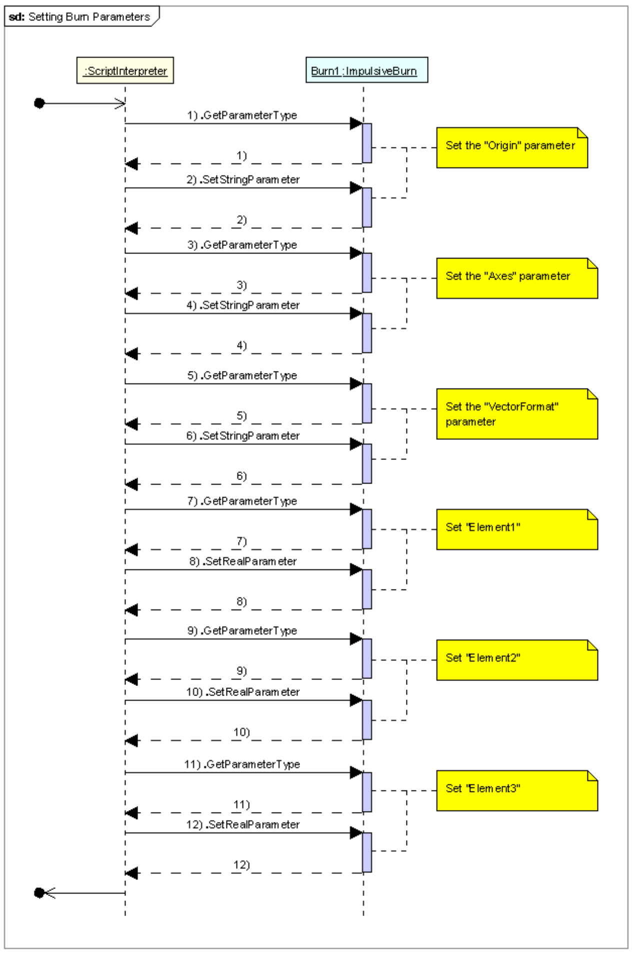

Figure 9.2: Parameter Setting for Listing 9.1

9.3.3 Serializing GmatBase Objects

Objects are written to text using the GetGeneratingString() method. GetGeneratingString can serialize objects this way for several purposes: to write an object to a script file, to pass the object to MATLAB or a MATLAB compatible external process, or in some cases to generate data used for the generation of an ephemeris file. The mode used for the serialization is determined using a setting on the call to GetGeneratingString(). That setting, the write mode, is set using the WriteMode enumeration.

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The following paragraphs describe the process followed when performing serialization of GmatBase objects. We begin with a brief description of the WriteMode enumeration, followed by a detailed description of the call to GetGeneratingString that serializes an object for scripting purposes, and conclude with a description of the differences encountered when serializing an object for MATLAB.

9.3.3.1 The WriteMode Enumeration

Table 9.4 shows the modes available to the GetGeneratingString methods for serialization of objects in GMAT. These modes are defined in an enumeration, WriteMode, contained in the Gmat namespace. GMAT uses the SCRIPTING mode as the default write mode, generating text strings that are designed to work with the script interpreter classes when saving a model to a script file.

Table 9.4: The WriteMode Enumeration

Identifier	Description
SCRIPTING	The mode used when writing an object as it appears in GMAT's script files.
SHOW_SCRIPT	Similar to the SCRIPTING mode, the SHOW_SCRIPT mode serializes an object as it would appear in a script file. The SHOW_SCRIPT mode does not guarantee that the resulting text is indented as it would be in a written script.
OWNED_OBJECT	OWNED_OBJECT mode is used to serialize the objects owned by an object that is being written to the text stream.
MATLAB_STRUCT	Generates the serialed object as a MATLAB structuire, so that the object can be passed into MATLAB for external processing.
EPHEM_HEADER	Generates a string used in GMAT's output ephemeris headers.

9.3.3.2 Writing to Script

Figure 9.3 shows the procedure followed when the GetGeneratingString() method is called on a configured object to write that object in script format[2]. The process starts by clearing the current generatingString attribute, and then writing the initial Create line to it. Objects without any parameters or owned objects are finished at this point, and simply return the resulting string, following the path shown in green in the figure.

If the object's parameter count is not zero, then the GetGeneratingString() method calls the WriteParameters() method, which adds text lines to the generatingString for each parameter that is writable. This process is shown in yellow in the figure. The process starts by initializing an index into the parameter list for the object. This index is used to loop through the parameters for the object. For each parameter, the code calls the IsParameterReadOnly() method to determine if the parameter should be written to teh generating string. If the parameter is not read only, the current value of the parameter is sent into a string in the WriteParameterValue() method. The WriteParameterValue method determines the type of the parameter, and calls the corresponding access method to retrieve the value and place it into a string. This string is returned to the WriteParameters() method for use as the right hand side of the text string setting the parameter's value. The parameter setting string is then build, using a call to GetParameterText() for the left side of the parameter setting string and the string returned from the call to WriteParameterValue() for the right side of the parameter setting string. The resulting string is added to the generating string, and the parameter index is incremented to move to the next parameter.

[2]GetGeneratingString() can be overridden by the derived classes. The description provided here is the default behavior. Command classes, in particular, always override this method so that the command specific scripting can be generated.

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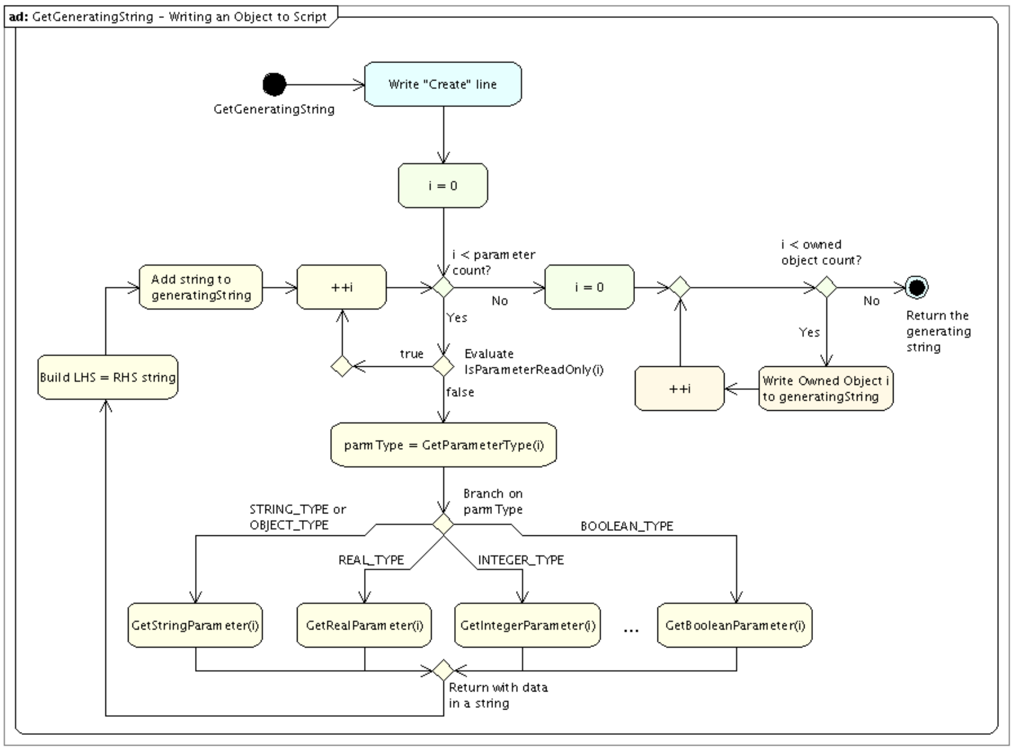

Figure 9.3: Flow in the GetGeneratingString() Method

Once the parameter index has iterated through all of the parameters, the call to WriteParameters() returns control to the GetGeneratingString() method. GetGeneratingString() resets its index, and then checks for owned objects. If there are any owned objects, each owned object writes its data to the generating string, following the process shown in orange in the figure. Owned objects write their data through calls to their GetGeneratingString() methods, with the write mode set to teh OWNED_OBJECT mode. After all of the owned objects have been written, the generating string is returned to the caller, completing the serialization process.

Listing 9.2 shown an example of the output generated when a coordinate system is written to script.

```
Create CoordinateSystem SunPointingCS;
GMAT SunPointingCS.Origin = DefaultSC;
GMAT SunPointingCS.Axes = ObjectReferenced;
GMAT SunPointingCS.UpdateInterval = 60;
GMAT SunPointingCS.OverrideOriginInterval = false;
GMAT SunPointingCS.XAxis = R;
GMAT SunPointingCS.ZAxis = N;
GMAT SunPointingCS.Primary = DefaultSC;
GMAT SunPointingCS.Secondary = Sun;
```

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Listing 9.2: Script Listing for a Coordinate System

9.3.3.3 Writing to MATLAB

The process followed when an object is serialized for export to MATLAB is the same as that shown in the sequence diagram for writing to script, Figure 9.3. The key differences between the processes are contained in the details of the strings generated. When an object is serialized for MATLAB, the Create line is omitted. The "GMAT" preface used for parameter strings in SCRIPTING mode is also omitted, and strings are enclosed in single quotes to conform to MATLAB's syntax. Listing 9.3 shows the resulting serailized version of the same coordinate system as was shown in the script serialization example, above.

```
SunPointingCS.Origin = 'DefaultSC'
SunPointingCS.Axes = 'ObjectReferenced'
SunPointingCS.UpdateInterval = 60
SunPointingCS.OverrideOriginInterval = false
SunPointingCS.XAxis = 'R'
SunPointingCS.ZAxis = 'N'
SunPointingCS.Primary = 'DefaultSC'
SunPointingCS.Secondary = 'Sun'
```

Listing 9.3: MATLAB Listing for a Coordinate System

9.3.4 GmatBase Derivatives

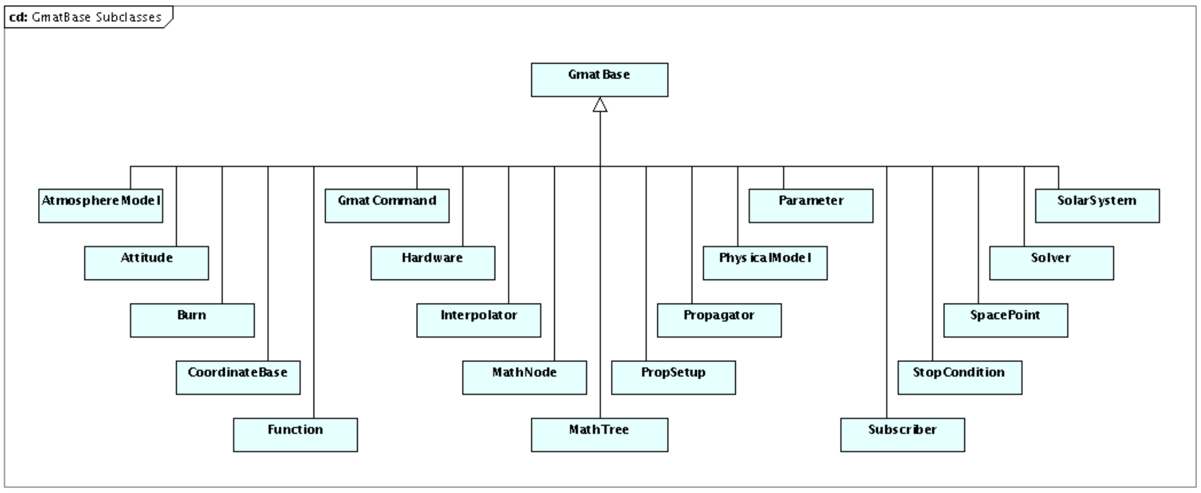

Figure 9.4: Classes Derived from GmatBase

Figure 9.4 shows the classes derived from GmatBase. These classes are presented more fully in other chapters of this document. Here is a brief description of each, with cross references to the chapters that provide the detailed descriptions:

AtmosphereModel Models the Atmosphere for bodies in the SolarSystem. The AtmosphereModel classes are used to determine atmospheric densities in GMAT's Drag models. Force modeling is described in Chapter 24.

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Attitude The base class for attitude modeling in GMAT. Attitude modeling is described in Chapter 16.

Burn The base class for burn modeling. The Burn class contains the elements common to finite and impulsive burns. The burn classes and other components used in maneuver modeling are described in Chapter 25.

CoordinateBase The base class for coordinate system modeling. GMAT provides a quite extensive system of coordinate system models, described in Chapter 13.

Function The base class for internal and external functions, described in Chapter 31.

GmatCommand The base class for the commands in the Mission Control Sequence. Commands are described in Chapters 26 and 27.

Hardware The base class for hardware elements that can be attached to other objects. Fuel tanks, thrusters, sensors, and antennae are all derived from this class. THe Hardware classes are described in Chapter 15.

Interpolator The base class for the numerical interpolaters. The interpolators are described in Chapter 10.

MathNode GMAT supports mathematics performed as part of the Mission Control Sequence. Mathematical expressions are decomposed into a tree structure for evaluation. The MathNode class is used for the nodes in this tree structure, as is described in Chapter 30.

MathTree MathTree objects are used as containers for inline mathematicas in GMAT's Mission Control Sequence, as is described in Chapter 30.

Parameter GMAT can calculate many different properties that are useful for analyzing spacecraft missions. The code that implements these calculations is derived from the Parameter class, described in Chapter 20.

PhysicalModel The PhysicalModel class is the base class for all of the forces used in GMAT's propagators. Force mdodeling is described in Chapter 24.

Propagator The Propagator class is the base class for the numerical integrators and analytic propagators[3] in GMAT. Propagators are described in Chapter 22.

PropSetup The PropSetup class is a container class that connects propagators to force models. When a user creates a "Propagator" in GMAT, the object that is created is really a PropSetup instance. The PropSetup class description is in Chapter 22.

SolarSystem The SolarSystem class is the container class used to hold all of the elements of the space environment: stars, planets, moons, other celestial bodies, calculated points, and any other entities that are used in the environment model. The SolarSystem instances include specification of global sources for the model as well – for example, identification of the planetary ephemeris souce used. These elements are described in Chapter 12.

Solver Solver classes are used to drive targeting, optimization, and parametric analysis tasks. The Solvers are described in Chapter 28.

SpacePoint All objects that have a physical location in the solar system are derived from the SpacePoint class. This class is the base class for everything from elements of the solar system to the spacecraft and groundstations. The SpacePoint class is described in Chapter 12.

[3]GMAT does not currently contain any analytic propagators; when such propagators are added to the system, they will be derived from the Propagator class.

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StopCondition GMAT's integrators can stop when any of a large set of conditions is met. This ability to stop is provided through the stopping condition class, described in Chapter 20.

Subscriber Subscribers are the recipients of data in GMAT's publish and subscribe subsystem, introduced in Chapter 8. The Subscriber base class, used for all subscribers, is described in Chapter 11.

9.4 Namespaces

GMAT uses several namespaces defined for specific purposes. The "Gmat" namespace is used to define program specific enumerations defining the types of objects users can configure in GMAT, the types of data structures commonly used in the system, and more specialized enumerations used by some of GMAT's subsystems.

9.5 Enumerations

GMAT uses enumerations to identify some of the key types of objects and parameters in the system, the current state of the system, and to track modes for some of the system processes. The remainder of this chapter tabulates the enumerations that are not listed in other places in this document.

9.5.1 The ParameterType Enumeration

GmatBase includes a method, GetParameterType(id), which returns an integer identifier for the type of the parameter with the ID input to the function. The return value is a member of the ParameterType enumeration, defined in the Gmat namespace. This enumeration is described in Table 9.5.

Table 9.5: The ParameterType Enumeration

Identifier	Description
INTEGER_TYPE	Integer parameters
UNSIGNED_INT_TYPE	Unsigned integer paramneters.
UNSIGNED_INTARRAY_TYPE	Arrays of unsigned integers.
REAL_TYPE	Real numbers.
REAL_ELEMENT_TYPE	A Real number accessed from an array.
STRING_TYPE	A string.
STRINGARRAY_TYPE	A vector of strings.
BOOLEAN_TYPE	A boolean value that evaluates to tru or false.
RVECTOR_TYPE	An Rvector
RMATRIX_TYPE	An Rmatrix
TIME_TYPE	A Real used to represent time.
OBJECT_TYPE	An object.
OBJECTARRAY_TYPE	A vector of objects.
ON_OFF_TYPE	A boolean that evaluates to either "On" or "Off"
TypeCount	The totla number of ParameterTypes available.
UNKNOWN_PARAMETER_TYPE	Unknown parameter types. Set to -1.

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9.5.2 The WrapperDataType Enumeration

Some components of GMAT need to access data elements in a generic fashion. These components, most notably including the Command subsystem, use a class of wrapper objects that take the disparate types and present a common interface into those types. The WrapperDataType enumeration is used to identify the type of underlying object presented by the wrapper classes. More information about this object can be found in Section 26.4.3. The defined wrapper types used in this enumeration are shown in Table 9.6.

Table 9.6: The WrapperDataType Enumeration

Identifier	Description
NUMBER	a Real or Integer value entered explicitly into the command
STRING	a text string with no associated object
OBJECT_PROPERTY	an internal data member of an object, accessible using the GmatBase parameter accessor methods (GetRealParameter(), GetIntegerParameter(), etc)
VARIABLE	an instance of the Variable class
ARRAY	an instance of the Array class
ARRAY_ELEMENT	an element of an Array object
PARAMETER_OBJECT	any other object derived from the Parameter class

9.5.3 The ObjectType Enumeration

GMAT has an enumeration in the Gmat namespace designed to provide ID values for each of the core types used in the system. Table 9.7 shows the identifiers for each entry in this enumeration, along with a brief description of the type of object the entry identifies.

9.5.4 The RunState Enumeration

The GMAT engine is always maintained in a specific state while the system is running, as is described in Section 4.2.1.5. The RunState enumeration, tabulated in Table 9.8 is used to track these states.

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Table 9.7: The ObjectType Enumeration

Identifier	Objects Identified	Notes & References
SPACECRAFT	Spacecraft	Initialized to 1001 Chapter 14
FORMATION	Formations	Chapter 14
SPACEOBJECT	Spacecraft and Formations	Chapter 14
GROUND_STATION	Groundstations	Not yet used
BURN	Burn objects for finite and impulsive maneuvers	Chapter 25
COMMAND	Commands in the Mission Control Sequence	Chapters 26 and 27
PROPAGATOR	Propagators and Integrators	Chapter 22
FORCE_MODEL	Force Models	Chapter 24
PHYSICAL_MODEL	Individual Forces	Chapter 24
TRANSIENT_FORCE	Forces that are dynamically added or removed	Chapter 25
INTERPOLATOR	Interpolators	Chapter 10
SOLAR_SYSTEM	Solar System	Chapter 12
SPACE_POINT	Objects that have physical locations in the Solar System	Chapter 12
CELESTIAL_BODY	Stars, Planets, and Moons	Chapter 12
CALCULATED_POINT	Barycenters and Libration Points	Chapter 12
LIBRATION_POINT	Libration Points	Chapter 12
BARYCENTER	Barycenters	Chapter 12
ATMOSPHERE	Atmosphere Models	Chapter 24
PARAMETER	Calculated Parameters, Variables, and Arrays	Chapter 20
STOP_CONDITION	Stopping Conditions	Chapter 20
SOLVER	Targeters, Optimizers, and Scanners	Chapter 28
SUBSCRIBER	Subscribers	Chapter 11
PROP_SETUP	PropSetups	Chapter 22
FUNCTION	Internal or External Functions	Chapter 31
FUEL_TANK	Fuek Tanks	Chapter 15
THRUSTER	Thrusters	Chapter 15
HARDWARE	Tanks, Thrusters, Antennae, Sensors, etc.	Chapter 15
COORDINATE_SYSTEM	Coordinate Systems	Chapter 13
AXIS_SYSTEM	Axis Systems	Chapter 13
ATTITUDE	Attitude	Chapter 16
MATH_NODE	Elements of Equations	Chapter 30
MATH_TREE	Parsed Mathematical Equations	Chapter 30
UNKNOWN_OBJECT	Objects that are not otherwise identified	Objects without one of the types listed above

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Table 9.8: The RunState Enumeration

Identifier	Description
IDLE	Initialized to 10000. The IDLE state indicates that GMAT's engine is waiting for instructions from the user.
RUNNING	GMAT enters the RUNNING state when the user starts a mission run.
PAUSED	When the user presses the Pause button on the GUI, GMAT enters the PAUSED state.
TARGETING	GMAT enters the TARGETING state when the Mission Control Sequence enters a Target loop.
OPTIMIZING	GMAT enters the TARGETING state when the Mission Control Sequence enters an Optimize loop.
SOLVING	GMAT enters the TARGETING state when the Mission Control Sequence enters other solver loops.
WAITING	GMAT defines the WAITING state for use when waiting for completion of an external process. The current code does not use the WAITING state.

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Chapter 10

Utility Classes and Helper Functions

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This chapter documents the classes and functions that are used by GMAT to support program functionality.

10.1 The MessageInterface

10.2 Exception Classes

10.3 Mathematical Utilities

10.3.1 The Rvector and Rmatrix Classes

10.3.2 Interpolators

10.4 The GmatStringUtil Namespace

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Chapter 11

Factories and Subscribers

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Chapter 4 through 8 discussed the components of GMAT's engine that are used to drive the flight dynamics model. This chapter discusses two elements used by the engine to construct and view the model during a run of the model: the Factory classes and the Subscribers.

11.1 The Factory Classes

The object factory components are responsible for creating instances of the classes registered with GMAT for use in a run. Each factory is configured as a node in a list. The factory classes include links to owned factories as well, allowing the creation of a tree structure for the factory system.

Each Factory maintains a list of core classes that it knows how to instantiate. All of the core classes are derived from a base class, GmatBase, which provides basic structure for the created objects. Each of the core objects has a group ID used to identify what type of object it is, the name of the object's type (e.g. RungeKutta89, Drag, Spacecraft, Groundstation, etc), and the instance's name. The GmatBase class also provides a mechanism to find the parameter list for instantiated objects, so that the list of available parameters can be built through calls to an instance of a class that is being configured.

The Moderator builds lists of the recognized objects on request. This feature allows a user interface to make a call through the User Action Interpreter to get a list of the available objects by class. The Moderator can be asked for all of the objects configured in the system or all objects of a specified type (e.g. Propagators). This list can be used to populate selection lists in the UI. Once a user selects a specific type of object for configuration, the UI can make a call through the Moderator to obtain an instance of the corresponding Atom. That Atom is then instantiated, and the UI makes calls to the created instance to get the list of available parameters, and to set the values for each parameter.

The Moderator creates instances of each registered Factory during the initialization sequence. GMAT starts with a set of core factories that are always instantiated when the system starts. Users can create additional Factories and add them to GMAT dynamically. User created factories are placed in shared libraries compiled for the platform running GMAT – for Windows, user created Factories are built into DLLs; under Linux and OS X, they are built into shared libraries.

11.1.1 Factory Attributes and Interfaces

Each Factory fills in the table of creatable objects and implements code to call the constructors for the creatable types. The following lists describe the attributes and methods in the base class that provide these functions.

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Class Attributes The current factories are tailored to support a single core type in each factory, represented by the itsType member. All current factories are case sensitive as well. The factory attribute list is presented here:

- **Gmat::ObjectType itsType**: The type supported by the Factory.
- **StringArray creatables**: The list of creatable objects.
- **bool isCaseSensitive**: A flag indicating if the type name is case sensitive for the factory.

Methods The Factory instances implement

- **virtual GmatBase* CreateObject(const std::string &ofType, const std::string &withName = "")**: Creates an object of the specified type with the specified name, and returns the object as a GmatBase pointer.
- **virtual SpaceObject* CreateSpacecraft(const std::string &ofType, const std::string &withName = "")**: Creates a SpaceObject object of the specified type with the specified name, and returns the object as a SpaceObject pointer.
- **virtual Propagator* CreatePropagator(const std::string &ofType, const std::string &withName = "")**: Creates a propagtor object of the specified type with the specified name, and returns the object as a Propagator pointer.
- **virtual ForceModel* CreateForceModel(const std::string &ofType, const std::string &withName = "")**: Creates a ForceModel object of the specified type with the specified name, and returns the object as a ForceModel pointer.
- **virtual PhysicalModel* CreatePhysicalModel(const std::string &ofType, const std::string &withName = "")**: Creates a Force used in a ForceModel of the specified type with the specified name, and returns the object as a PhysicalModel pointer.
- **virtual PropSetup* CreatePropSetup(const std::string &ofType, const std::string &withName = "")**: Creates a PropSetup object of the specified type with the specified name, and returns the object as a PropSetup pointer.
- **virtual Parameter* CreateParameter(const std::string &ofType, const std::string &withName = "")**: Creates a calculated parameter object of the specified type with the specified name, and returns the object as a Parameter pointer.
- **virtual Burn* CreateBurn(const std::string &ofType, const std::string &withName = "")**: Creates a burn object of the specified type with the specified name, and returns the object as a Burn pointer.
- **virtual StopCondition* CreateStopCondition(const std::string &ofType, const std::string &withName = "")**: Creates a stopping condition object of the specified type with the specified name, and returns the object as a StopCondition pointer.
- **virtual CalculatedPoint* CreateCalculatedPoint(const std::string &ofType, const std::string &withName = "")**: Creates a calculated point SpacePoint of the specified type with the specified name, and returns the object as a CalculatedPoint pointer.
- **virtual CelestialBody* CreateCelestialBody(const std::string &ofType, const std::string &withName = "")**: Creates a celestial body object of the specified type with the specified name, and returns the object as a CelestialBody pointer.

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- **virtual SolarSystem* CreateSolarSystem(const std::string &ofType, const std::string &withName = "")**: Creates a SolarSystem object of the specified type with the specified name, and returns the object as a SolarSystem pointer.
- **virtual Solver* CreateSolver(const std::string &ofType, const std::string &withName = "")**: Creates a Solver object of the specified type with the specified name, and returns the object as a Solver pointer.
- **virtual Subscriber* CreateSubscriber(const std::string &ofType, const std::string &withName = "", const std::string &fileName = "")**: Creates a subscriber object of the specified type with the specified name, and returns the object as a Subscriber pointer.
- **virtual GmatCommand* CreateCommand(const std::string &ofType, const std::string &withName = "")**: Creates a Command for use in the Mission Control Sequence of the specified type with the specified name, and returns the object as a GmatCommand pointer.
- **virtual AtmosphereModel* CreateAtmosphereModel(const std::string &ofType, const std::string &withName = "", const std::string &forBody = "Earth")**: Creates an atmosphere model of the specified type with the specified name, and returns the object as a AtmosphereModel pointer.
- **virtual Function* CreateFunction(const std::string &ofType, const std::string &withName = "")**: Creates a user defined function of the specified type with the specified name, and returns the object as a Function pointer.
- **virtual Hardware* CreateHardware(const std::string &ofType, const std::string &withName = "")**: Creates a hardware object of the specified type with the specified name, and returns the object as a Hardware pointer.
- **virtual AxisSystem* CreateAxisSystem(const std::string &ofType, const std::string &withName = "")**: Creates an axis system as used in the coordimate system classes, of the specified type with the specified name, and returns the object as an AxisSystem pointer.
- **virtual CoordinateSystem* CreateCoordinateSystem(const std::string &ofType, const std::string &withName = "")**: Creates a coordinate system object of the specified type with the specified name, and returns the object as a CoordinateSystem pointer.
- **virtual MathNode* CreateMathNode(const std::string &ofType, const std::string &withName = "")**: Creates a node for use in a mathematical expression, of the specified type with the specified name, and returns the object as a MathNode pointer.
- **virtual Attitude* CreateAttitude(const std::string &ofType, const std::string &withName = "")**: Creates an attitude object of the specified type with the specified name, and returns the object as a Attitude pointer.
- **StringArray GetListOfCreatableObjects() const**: Returns the list of object types that can be created by this Factory.
- **bool SetListOfCreatableObjects(StringArray newList)**: Resets the list of creatable objects.
- **bool AddCreatableObjects(StringArray newList)**: Extends the list of creatable objects.
- **Gmat::ObjectType GetFactoryType() const**: Returns the type of the factory.
- **bool IsTypeCaseSensitive() const**: Returns true if the creatable object type names are case sensitive, false otherwise.

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11.1.2 An example: The BurnFactory

Listing 11.1 shows the complete code implementing the BurnFactory class[1]. At this writing, GMAT supports two Burn classes, named ImpulsiveBurn and FiniteBurn. The CreateBurn() method is used to build instances of these classes, as can be seen on lines 5 through 15. Each of the constructors for the Factory needs to register the types of objects that can be created. This registration of accomplished by adding the string describing the supported object to the creatables StringArray attrinute. An example of this is shown on lines 22 through 26.

```
 1  #include "BurnFactory.hpp"
 2  #include "ImpulsiveBurn.hpp"
 3  #include "FiniteBurn.hpp"
 4
 5  // Creation method
 6  Burn* BurnFactory::CreateBurn(const std::string &ofType,
 7                                const std::string &withName)
 8  {
 9     if (ofType == "ImpulsiveBurn")
10        return new ImpulsiveBurn(withName);
11     else if (ofType == "FiniteBurn")
12        return new FiniteBurn(withName);
13
14     return NULL;   // doesn't match any known type of burn
15  }
16
17
18  // Default constructor
19  BurnFactory::BurnFactory() :
20     Factory     (Gmat::BURN)
21  {
22     if (creatables.empty())
23     {
24        creatables.push_back("ImpulsiveBurn");
25        creatables.push_back("FiniteBurn");
26     }
27  }
28
29  // Support for secondary base class constructor
30  BurnFactory::BurnFactory(StringArray createList) :
31     Factory     (createList, Gmat::BURN)
32  {
33  }
34
35  // Copy constructor
36  BurnFactory::BurnFactory(const BurnFactory &fact) :
37      Factory     (fact)
38  {
39     if (creatables.empty())
40     {
41        creatables.push_back("ImpulsiveBurn");
```

[1] Comments and extra space have been removed from this listing to make it as short as possible.

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```
        creatables.push_back("FiniteBurn");
    }
}

// Assignment operator for the BurnFactory base class.
BurnFactory& BurnFactory::operator=(const BurnFactory &fact)
{
    Factory::operator=(fact);
    return *this;
}

// Destructor for the BurnFactory class.
BurnFactory::~BurnFactory()
```

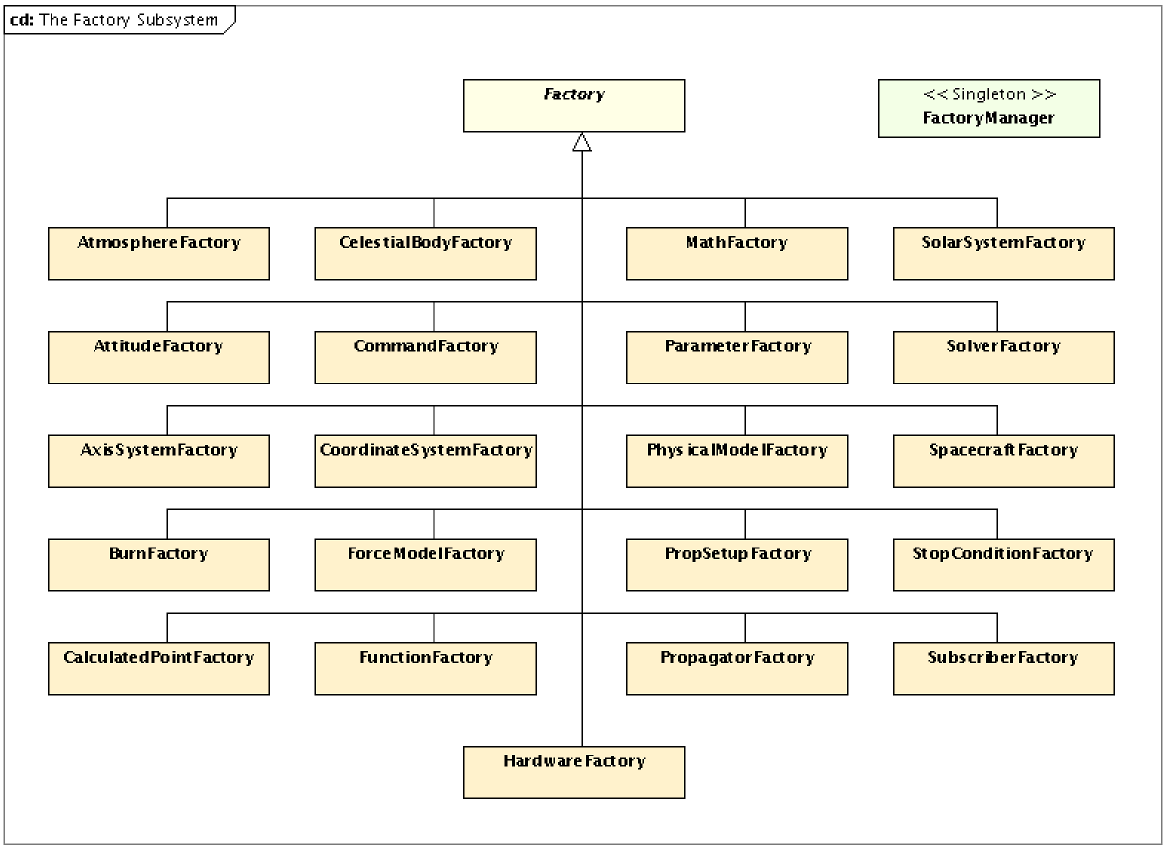

Figure 11.1: Class Hierarchy for 21 GMAT Factories

GMAT contains twenty-one factories at this writing, all implemented in a similar manner to that shown in the previous section. These factories are shown in Figure 11.1.

11.1.4 Extending GMAT

Factories are a key element of GMAT's extensibility strategy. A developer adds a new user component to GMAT by taking the following steps:

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1. Design the new component based on GMAT's architecture.
2. Code the new component, using GmatBase or one of its derivatives as the base class for the component.
3. Compile and debug the component as a stand-alone object (as much as possible).
4. Create a new Factory that creates instances of the new component, or add the component to an existing Factory[2].
5. Either build a new shared library that contains the Factory and the class or classes defining the new component, or incorporate the new classes and Factory in a GMAT build.
6. Register the new Factory with the Factory Manager.
7. Test the new component in GMAT.
8. Start using the new component.

Note that step 5 lists two possible ways to build the new code. Chapter 32 provides a more thorough introduction to adding new classes to GMAT, and includes a discussion of registering new components either at runtime or linked in at compile time.

11.2 Subscribers

During a Mission Control Sequence run data is sent from the Sandbox to GMAT's Publisher. The Publisher routes this data to two and three dimensional plots on the user's display, to report files, and to any other output objects configured by the user prior to the run. These output objects are instances of classes derived from the Subscriber base class, shown in Figure 11.2.

11.2.1 Structure of the Subscribers

The Subscribers all implement methods and structures designed to work as recipients of the data delivered from GMAT's Publisher. These members include several flags used to track the state of a Mission Control Sequence run, wrappers used for published data, and methods used to pass the data into the Subscribers and manage Subscriber processing. The class members are describewd below.

Class Attributes

- **std::string mSolverIterations**: Sets the behavior of the Subscriber when a Solver is finding a solution. The current options are "All" and "None".
- **const char *data**: A pointer used in the ReceiveData method to set the input buffer that is processed.
- **CoordinateSystem *internalCoordSystem**: A coordinate system available for conversions when needed.
- **bool active**: Flag specifying if the Subscriber is currently processing data.
- **bool isEndOfReceive**: Flag indicating that the current set of data has finished being sent.
- **bool isEndOfRun**: Flag indicating that the current Mission Control Sequence has finished running.
- **Gmat::RunState runstate**: The current run state of the Mission Control Sequence.

[2]Factories can support many classes at once; if a convenient Factory already exists for the developer, the new class can be added to that Factory without any loss of functionality

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- **Integer currentProvider**: The ID of the current data privider.
- **StringArray wrapperObjectNames**: The list of data wrappers used by the Subscriber.
- **std::vector<ElementWrapper*> depParamWrappers**: The data wrappers used for dependent parameters.
- **std::vector<ElementWrapper*> paramWrappers**: The data wrappers used for parameters.

Methods

- **virtual bool Initialize()**: Sets all internal pointers needed to use the Subscriber.
- **virtual bool ReceiveData(const char* datastream)**: Receives character data from the Publisher. The data passed in is a standard C/C++ string, terminated with a NULL ('
  0') character.
- **virtual bool ReceiveData(const char* datastream, const Integer len)**: Receives character data from the Publisher. The data passed in fills a buffer of the indicated length.
- **virtual bool ReceiveData(const Real* datastream, const Integer len = 0)**: Receives Real number data from the Publisher. The data passed inis in a C/C++ array of the indicated length.
- **virtual bool FlushData()**: Method called to tell the Subscriber to process all received data immediately.
- **virtual bool SetEndOfRun()**: Tells the Subscriber that a Mission Control Sequence run has been complted, so the Subscriber should process all unprocessed data.
- **virtual bool SetRunState(Gmat::RunState rs)**: Updates the run state so the subscriber can act based in state changes.
- **void Activate(bool state = true)**: Changes the active flag to the input setting. Subscribers can use this setting to toggle on or off the processing on input data.
- **bool IsActive()**: Returns the value of the active flag.
- **virtual void SetProviderId(Integer id)**:
- **virtual Integer GetProviderId()**:
- **virtual void SetInternalCoordSystem(CoordinateSystem *cs)**:
- **virtual const StringArray& GetWrapperObjectNameArray()**:
- **virtual bool SetElementWrapper(ElementWrapper* toWrapper, const std::string &name)**:
- **virtual void ClearWrappers()**: Deletes and sets all wrapper pointers to NULL but leaves size unchanged.
- **static Integer GetSolverIterOptionCount()**:
- **static const std::string* GetSolverIterOptionList()**:
- **bool SetWrapperReference(GmatBase *obj, const std::string &name)**:
- **virtual bool Distribute(Integer len) = 0**:
- **virtual bool Distribute(const Real *dat, Integer len)**:

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Deprecated Attributes and Methods Subscribers were initially prototyped in a linked list structure. Some artifacts of that design remain in the current code, but will be removed in a later release. These pieces are listed below.

- **Subscriber *next**: The pointer to the next Subscriber in the list.
- **Subscriber* Next()**: Retrieves the next Subscriber for the current list.
- **bool Add(Subscriber *s)**: Adds a Subscriber at the end of the list.
- **bool Remove(Subscriber *s, const bool del)**: Removes a Subscriber from the list.

11.2.2 Subscriber Initialization and Execution

11.2.2.1 Defining and Initializing Subscribers

Each Subscriber in GMAT has an associated GmatBase derived object that is stored in the configuration and cloned into the Sandbox prior to a run. These objects are the connection points between operations occuring in the Sandbox and the data presented to the user, either graphically or in text form.

11.2.2.2 Subscriber Usage During Mission Execution

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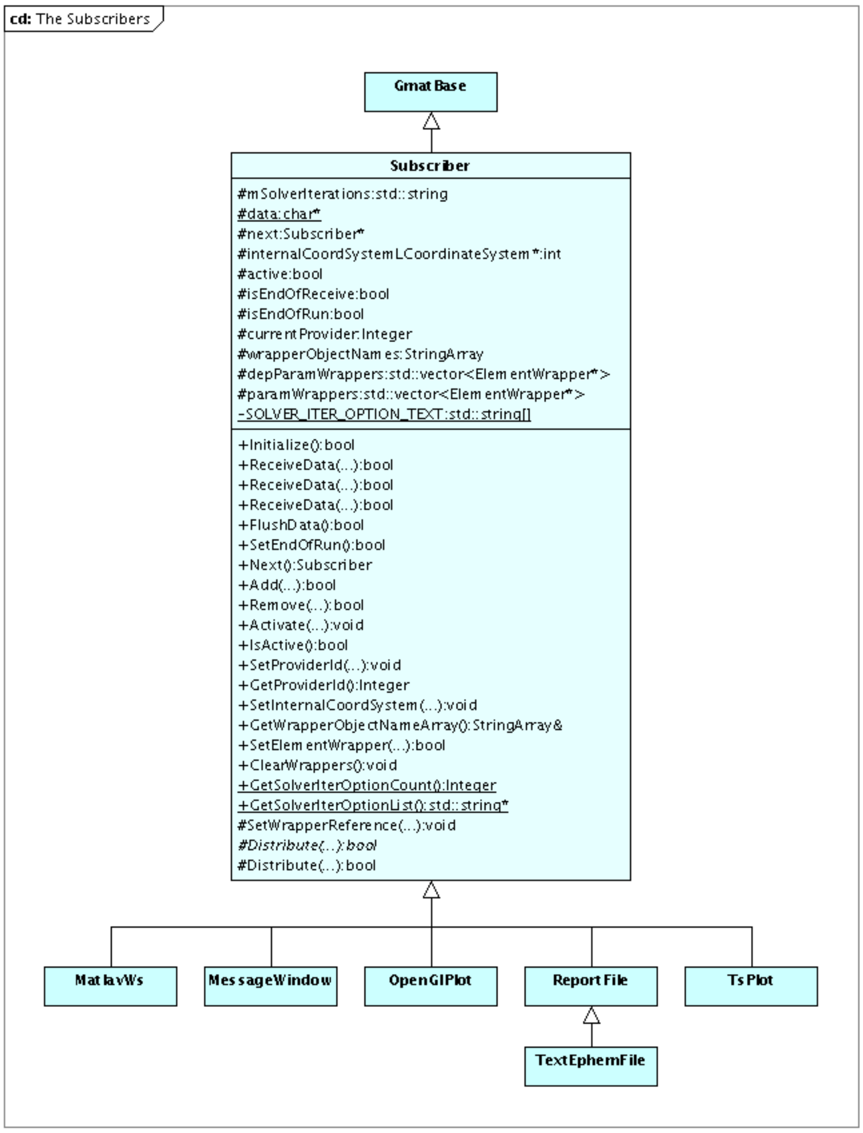

Figure 11.2: The Subscriber Class

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Chapter 12

The Space Environment

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The core purpose of GMAT is to perform flight dynamics simulations for spacecraft flying in the solar system. There are many different components that users interact with to produce this model. In this chapter, the architecture for the elements that comprise the model is introduced. The elements that are not directly manipulated in the model – specifically, the Sun, planets, moons, and related points that comprise the stage on which the spacecraft and related objects perform their actions – are described in some detail in the chapter. Descriptions for the other objects – most specifically spacecraft and formations – introduced here appear in chapters for those components. References for those chapters are provided when the objects are introduced.

12.1 Components of the Model

The environmental elements that have a spatial location and evolve over time in the GMAT model are all derived from the SpacePoint class. The class hierarchy, shown in Figure 12.1, includes classes that model the objects and special locations in GMAT's solar system – referred to as "background" objects because their evolution is modeled through precalculated ephemerides or computations performed off of these precalculated data – along with the pieces that are directly manipulated in the mission control sequence and that evolve through numerical integration using GMAT's propagation subsystem. In the figure, the classes used to model background objects are shown in purple; those that evolve through direct modeling in GMAT using the propagation subsystem are shown in blue, and other elements that will be incorporated in the future, in red.

The space environment as defined in this document consists of the elements that, while dynamic, are automatically updated as the model evolves, based on epoch data generated for the model. These elements are the gravitating bodies in the model – that is, the Sun and the planets and their moons – and points with specialized significance in flight dynamics, like the Lagrange points and gravitational barycenters. All of these elements are managed in an instance of the SolarSystem class. SolarSystem acts as a container, and manages both the objects in the space environment and the resources needed to calculate ephemerides for these objects. The bulk of this chapter provides details about the classes and objects comprising this space environment.

A key feature of GMAT is the ability to model spacecraft and formations of spacecraft as they move through the space environment. These elements of the model are configured in detail by GMAT users, and evolve through time using precision numerical integrators configured by the users. The Spacecraft and Formation classes, along with their base SpaceObject class, are discussed in detail in Chapter 14. The numerical integrators and associated force model components are presented in Chapter 22.

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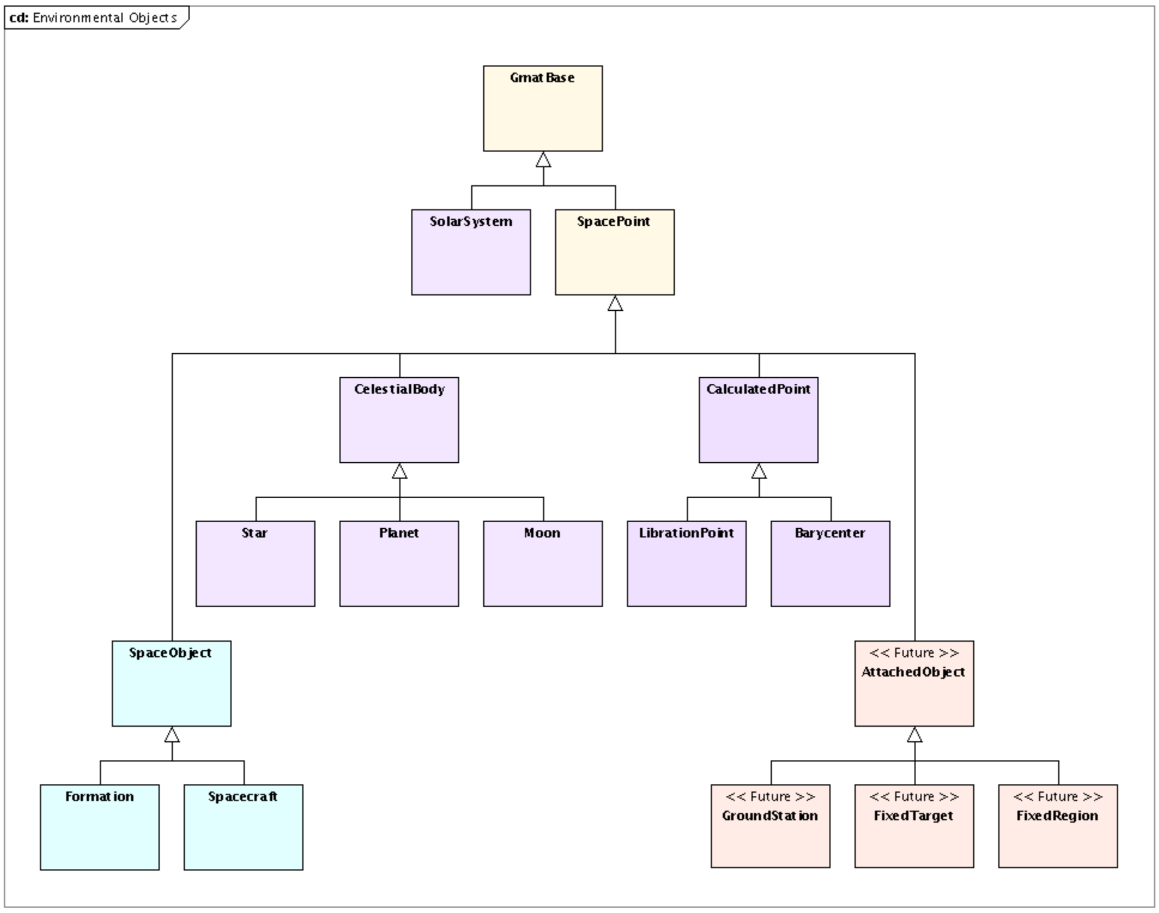

Figure 12.1: Objects in the GMAT Model.
The elements shown in purple are core constituents of GMAT's solar system. Classes shown in yellow are GMAT base classes. Elements shown in blue are the key components studied in GMAT's model: Spacecradft and Formations of Spacecraft. Those shown in red are future enhancements, primarily focussed on contact analysis with different types of objects.

The class hierarchy includes provisions for future model elements attached to components of the space environment. These classes, FixedObject and the derived GroundStation, FixedTarget and FixedRegion classes, will be documented at a later date in preparation for implementation.

Before proceeding with a detailed description of GMAT's space environment, the base class used for all of the model elements needs some explanation. Those details are provided in the next section.

12.2 The SpacePoint Class

All spatially modeled components need some common data in order to define the positions of objects in the model. These data are collected in the SpacePoint base class. This base class provides the foundation for objects used to define coordinate systems (see Chapter 13), for the user configured Spacecraft and Formations (see Chapter 14), and for other specialized points and objects in the space environment.

Figure 12.2 shows the elements of the SpacePoint class. In order for GMAT to accurately model flight

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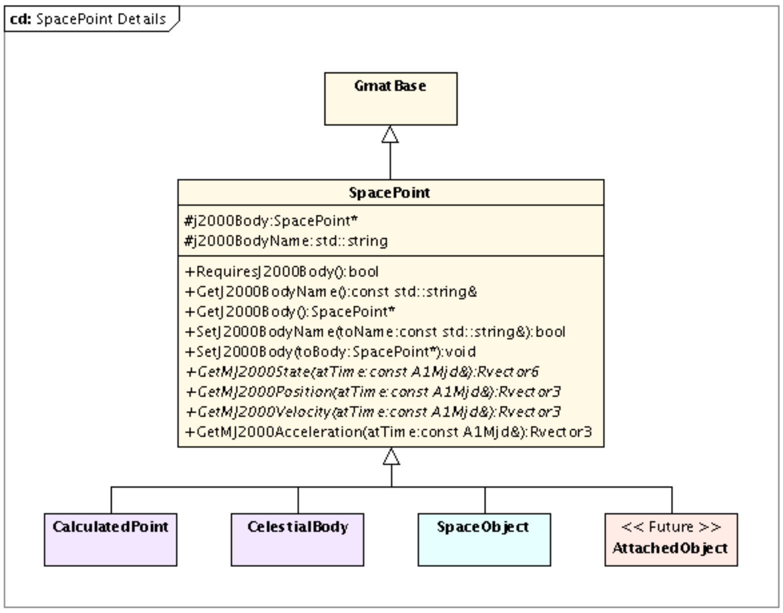
cd: SpacePoint Details
GmatBase
SpacePoint
#j2000Body:SpacePoint*
#j2000BodyName:std::string
+RequiresJ2000Body():bool
+GetJ2000BodyName():const std::string&
+GetJ2000Body():SpacePoint*
+SetJ2000BodyName(toName:const std::string&):bool
+SetJ2000Body(toBody:SpacePoint*):void
+GetMJ2000State(atTime:const A1Mjd&):Rvector6
+GetMJ2000Position(atTime:const A1Mjd&):Rvector3
+GetMJ2000Velocity(atTime:const A1Mjd&):Rvector3
+GetMJ2000Acceleration(atTime:const A1Mjd&):Rvector3
CalculatedPoint
CelestialBody
SpaceObject
<< Future >>
AttachedObject

Figure 12.2: The SpacePoint Class

dynamics problems, the GMAT space model needs to specify an internal origin and coordinate system orientation used as a reference for computations. SpacePoint defines one object, the J2000 body, which is used to define that origin. GMAT uses the Mean-of-J2000 Earth Equatorial axis system as the orientation for all such calculations.

Class Attributes SpacePoint defines two data members to track the J2000 body:

- **SpacePoint* j2000Body**: The body used to define the coordinate origin for the SpacePoint.
- **std::string j2000BodyName**: The name of the body defining the coordinate origin.

Methods All classes derived from SpacePoint inherit the implementation of six methods used to set and access the J2000 body. Five of these methods are used specifically for the internal data members; the sixth, GetMJ2000Acceleration(), provides a default implementation so that derived classes that do not have acceleration data do not need to provide an implementation

- **bool RequiresJ2000Body()**: Returns a boolean used to determine if the SpacePoint requires a J2000 body.
- **const std::string& GetJ2000BodyName()**: Returns the name of the J2000 body for the SpacePoint.
- **SpacePoint *GetJ2000Body()**: Returns the pointer to the J2000 body for the SpacePoint.
- **bool SetJ2000BodyName(const std::string &toName)**: Sets the name of the J2000 body for the SpacePoint.
- **void SetJ2000Body(SpacePoint *toBody)**: Sets the pointer to the J2000 body for the SpacePoint.

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- **Rvector3 GetMJ2000Acceleration(const A1Mjd &atTime)**: Returns the Cartesian acceleration of the SpacePoint relative to its J2000 body at the specified epoch. The default implementation returns [0.0, 0.0, 0.0]; derived classes that contain acceleration data should override this method.

Abstract Methods Each subclass of SpacePoint implements three pure virtual methods defined in the class, using computations specific to that subclass. THese abstract methods have the following signatures:

- **virtual Rvector6 GetMJ2000State(const A1Mjd &atTime) = 0**: Returns the Cartesian state of the SpacePoint relative to its J2000 body at the specified epoch.
- **virtual Rvector3 GetMJ2000Position(const A1Mjd &atTime) = 0**: Returns the Cartesian location of the SpacePoint relative to its J2000 body at the specified epoch.
- **virtual Rvector3 GetMJ2000Velocity(const A1Mjd &atTime) = 0**: Returns the Cartesian velocity of the SpacePoint relative to its J2000 body at the specified epoch.

12.3 The Solar System Elements

GMAT provides a container class, SolarSystem, that is used to manage the objects modeling the space environment.

12.3.1 The SolarSystem Class

12.3.1.1 Members and Methods

12.3.1.2 Ephemeris Sources

12.3.2 The CelestialBody Class Hierarchy

12.3.2.1 Stars

12.3.2.2 Planets

12.3.2.3 Moons

12.4 The PlanetaryEphem Class

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Chapter 13

Coordinate Systems

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NOTE: This chapter currently contains the original design spec for the coordinate systems. It needs to be reviewed against the current GMAT system, the figures need to be recreated, and some of the text needs to be fitted into the rest of the design document.

This chapter presents design guidelines for the coordinate system classes in the Goddard Mission Analysis Tool (GMAT). It describes how the GMAT software implements the coordinate system math described in the GMAT Mathematical Specifications[MathSpec]. This description includes the initial design for the classes that provide coordinate system support in GMAT. The interactions between these classes and the rest of the GMAT system are also described.

13.1 Introduction

The Goddard Mission Analysis Tool (GMAT) is a multi-platform orbit simulator designed to support multiple spacecraft missions flying anywhere in the solar system. GMAT is written in C++ and runs on Windows, Macintosh and Linux computer systems. The tool provides an integrated interface to MATLAB, a high level computing environment from the Mathworks, Inc[matlab]. The GMAT graphical user interface (GUI) is written using the wxWidgets GUI Toolkit[wx], an open source library that compiles and runs under all of the target operating systems.

GMAT is an object-oriented system, using the full extent of the C++ language to implement the object model that provides GMAT's functionality. The first three builds of GMAT provided capabilities to model orbits in the vicinity of the Earth, including detailed force modeling, impulsive maneuvers, and parameter targeting using a differential corrector. All of these capabilities can be controlled either using either the GMAT graphical user interface or a custom scripting language designed to simplify GMAT and MATLAB interactions. The fourth build of the system generalizes the capabilities of GMAT modeling for other orbital regimes.

In order to model spacecraft trajectories in these regimes, GMAT needs to be able to represent the spacecraft state and related quantities in coordinate systems that are convenient to each regime. This document describes how these coordinate systems are implemented in the GMAT code.

13.2 Coordinate System Classes

Figure 13.1 shows the core C++ classes (drawn using Poseidon[poseidon]) added to GMAT to provide support for coordinate systems in Build 4. The coordinate system capabilities are provided by the incorporation of

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these classes into the GMAT base subsystem[1].

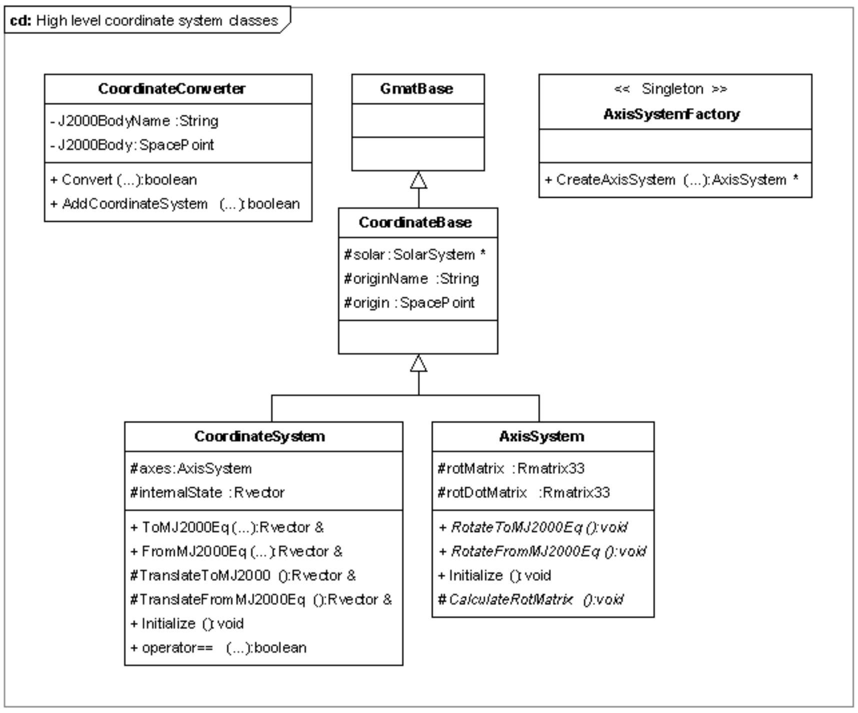

Figure 13.1: Coordinate System Classes in GMAT

The coordinate system classes consist of a CoordinateSystem class that acts as the interface between the conversions and the rest of GMAT, an AxisSystem base class with a derived hierarchy used for rotational conversions, a CoordinateConverter class that manages conversions between different coordinate systems, and a factory constructed as a singleton that create the AxisSystem objects. The CoordinateSystem class is the component that is instantiated when a user "Creates" a coordinate system object.

Previous builds of GMAT included classes that model spacecraft, formations, and celestial objects. These classes were derived from a core base class named GmatBase. A new intermediate class, SpacePoint, is implemented in GMAT to make access to position, velocity, and rotational data available to the coordinate system classes when needed. Section 13.2.4 describes this class.

13.2.1 The CoordinateSystem Class

The CoordinateSystem class is a configured component that implements the functionality needed to convert into and out of a specified coordinate system. Internally, GMAT performs computations in a Mean of J2000 Earth Equatorial coordinate system, centered at one of the celestial bodies in the GMAT solar system (i.e. the Sun, a planet, or a moon) or at a barycenter or libration point. Each CoordinateSystem instance provides methods to transform into and out of these J2000 coordinate systems. It contains the data necessary for translation calculations, along with a member object pointer that is set to an AxisSystem instance for coordinate systems whose principle axes are not parallel to the Mean of J2000 Earth Equatorial axes, or to NULL for coordinate systems that are oriented parallel to these axes.

[1]The GMAT code base consists of a set of classes that provide the core functionality of the system, the "base" subsystem, and classes that comprise the graphical user interface, the "gui" subsystem. All of the classes described in this document are members of the base subsystem, with the exception of the recommendations for changes to the panels on the GUI.

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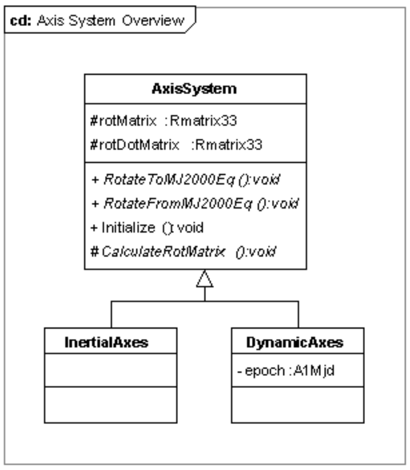

Figure 13.2: Top level AxisSystem Derived Classes

The AxisSystem class provides the methods needed to rotate the coordinate system into and out of the Mean of J2000 Earth Equator frame. The AxisSystem is set for a given CoordinateSystem by setting the axes member to an AxisSystem instance.

GMAT uses a late binding scheme to provide interconnections between objects used when modeling an analysis problem. Individual components are configured from either the grapical user interface or a script file describing the objects that need to be modeled. Connections between these objects are defined using the names of the objects, but the actual object instances used in the model are not set until the simulation is run. Upon execution, the configured objects are copied into the analysis workspace, called the Sandbox, and the connections between the configured objects are established immediately prior to the run of the simulation. The Initialize method in the CoordinateSystem class implements this late binding for the connection between the coordinate system instance and the related SpacePoints.

13.2.2 The AxisSystem Class Hierarchy

GMAT is capable of supporting numerous coordinate system orientations. These orientations are defined through the AxisSystem class; each unique axis orientation is implemented as a separate class derived from the AxisSystem base class. Figure 13.2 shows an overview of the AxisSystem class hierarchy, and identifies the top level classes in this hierarchy.

The orientations of the coordinate systems in GMAT fall into two broad categories: axes that change orientation over time, and those that remain fixed in orientation. The latter category requires computation of the rotation matrices one time, at initialization, in order to perform the rotations into and out of the coordinate system. Figure 13.3 shows the six inertial axis systems supported in GMAT. These systems support equatorial and ecliptic versions of Mean of J2000, Mean of Epoch, and True of Epoch transformations.

Coordinate systems that are not fixed in orientation over time are derived from the DynamicAxes class, as is shown in Figure 13.4. These coordinate systems include equatorial and ecliptic versions of the mean of date and true of date axes, along with axes that evolve with the polar motion of the body's rotational axis (implemented in the EquatorAxes class) and axes that are fixed on the body's prime meridian (the BodyFixedAxes class). All of these classes require recomputation of the orientation of the axes as the epoch of the model evolves.

One additional class in Figure 13.4 bears discussion here. GMAT supports numerous coordinate systems that reference bodies that are not celestial objects – specifically coordinate systems that use Lagrange points,

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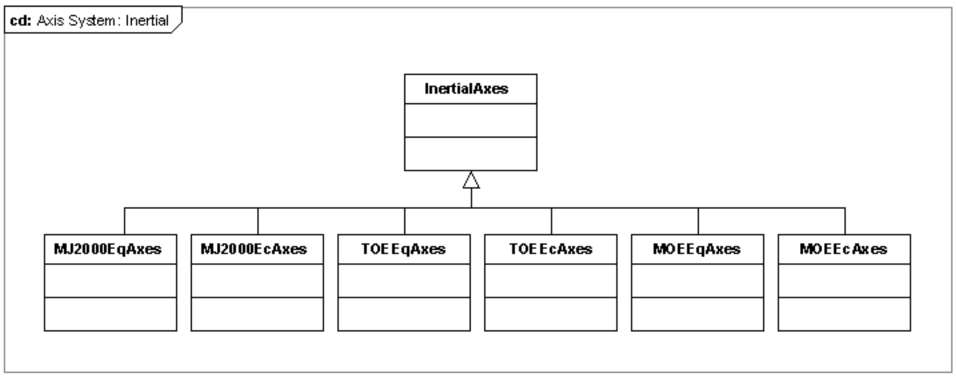

Figure 13.3: Inertial Axis Classes

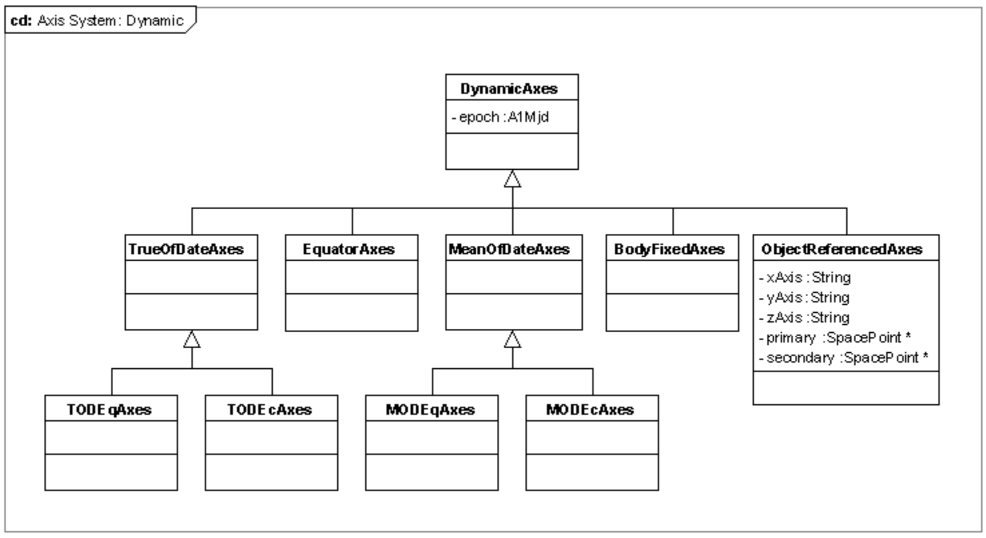

Figure 13.4: Dynamic Axis Classes

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barycenters, spacecraft, and formations to define the coordinate origins and axes. These coordinate systems use the ObjectReferencedAxes class to construct the coordinate basis and rotation matrices. The GMAT Mathematical Specifications[MathSpec] provide detailed descriptions of how this class operates.

13.2.3 CoordinateSystem and AxisSystem Collaboration

The GMAT Mathematical Specification[MathSpec] includes a flow chart that describes the process of transforming between coordinate systems. This process is performed in the GMAT code using the Coordinate-Converter class and the public methods of the CoordinateSystem class. When GMAT needs a conversion from one coordinate system to another, the method `CoordinateConverter::Convert` is called with the epoch, input state, input coordinate system, output state, and output coordinate system as parameters. The converted state vector is stored in the output state parameter.

The Convert method calls the conversion method `CoordinateSystem::ToMJ2000Eq` on the input coordinate system, followed by `CoordinateSystem::FromMJ2000Eq` on the output coordinate system. `ToMJ2000Eq` calls the `AxisSystem::RotateToMJ2000Eq` method followed by the `CoordinateSystem::TranslateToMJ2000Eq` method, converting the input state from the input coordinate system into Mean of J2000 Equatorial coordinates. Similarly, `FromMJ2000Eq` calls the `CoordinateSystem::TranslateFromMJ2000Eq` method and then the `AxisSystem::RotateFromMJ2000Eq` method, converting the intermediate state from Mean of J2000 Equatorial coordinates into the output coordinate system, completing the transformation from the input coordinate system to the output coordinate system. Each of the conversion routines takes a SpacePoint pointer as the last parameter in the call. This parameter identifies the J2000 coordinate system origin to the conversion routine. If the pointer is NULL, the origin is set to the Earth.

The following paragraphs provide programmatic samples of these conversions.

13.2.3.1 Code Snippets for a Conversion

Figure 13.5, generalized from the GMAT mathematical specification, illustrates the procedure used to implement a transformation from one coordinate system to another. The following paragraphs provide code snippets with the corresponding function arguments for this process.

When GMAT needs to convert from one coordinate system to another, this method is called:

```
   if (!coordCvt->Convert(epoch, instate, inputCS, outstate, outputCS))
   throw CoordinateSystemException("Conversion from " +
      inputCS->GetName() + " to " + outputCS->GetName() + " failed.");
```

This method invokes the calls listed above, like this:

```
   // Code in CoordinateConverter::Convert
if (!inputCS->ToMJ2000Eq(epoch, instate, internalState, J2000Body))
   throw CoordinateSystemException("Conversion to MJ2000 failed for " +
      inputCS->GetName());

if (!outputCS->FromMJ2000Eq(epoch, internalState, outState, J2000Body))
   throw CoordinateSystemException("Conversion from MJ2000 failed for " +
      outputCS->GetName());
```

The conversion code from the input state to Mean of J2000 Equatorial Coordinates is accomplished using the calls

```
   // Code in CoordinateSystem::ToMJ2000Eq
if (axes)      // axes == NULL for MJ2000Eq orientations
   if (!axes->RotateToMJ2000Eq(epoch, instate, internalState, J2000Body))
      throw CoordinateSystemException("Rotation to MJ2000 failed for " +
```

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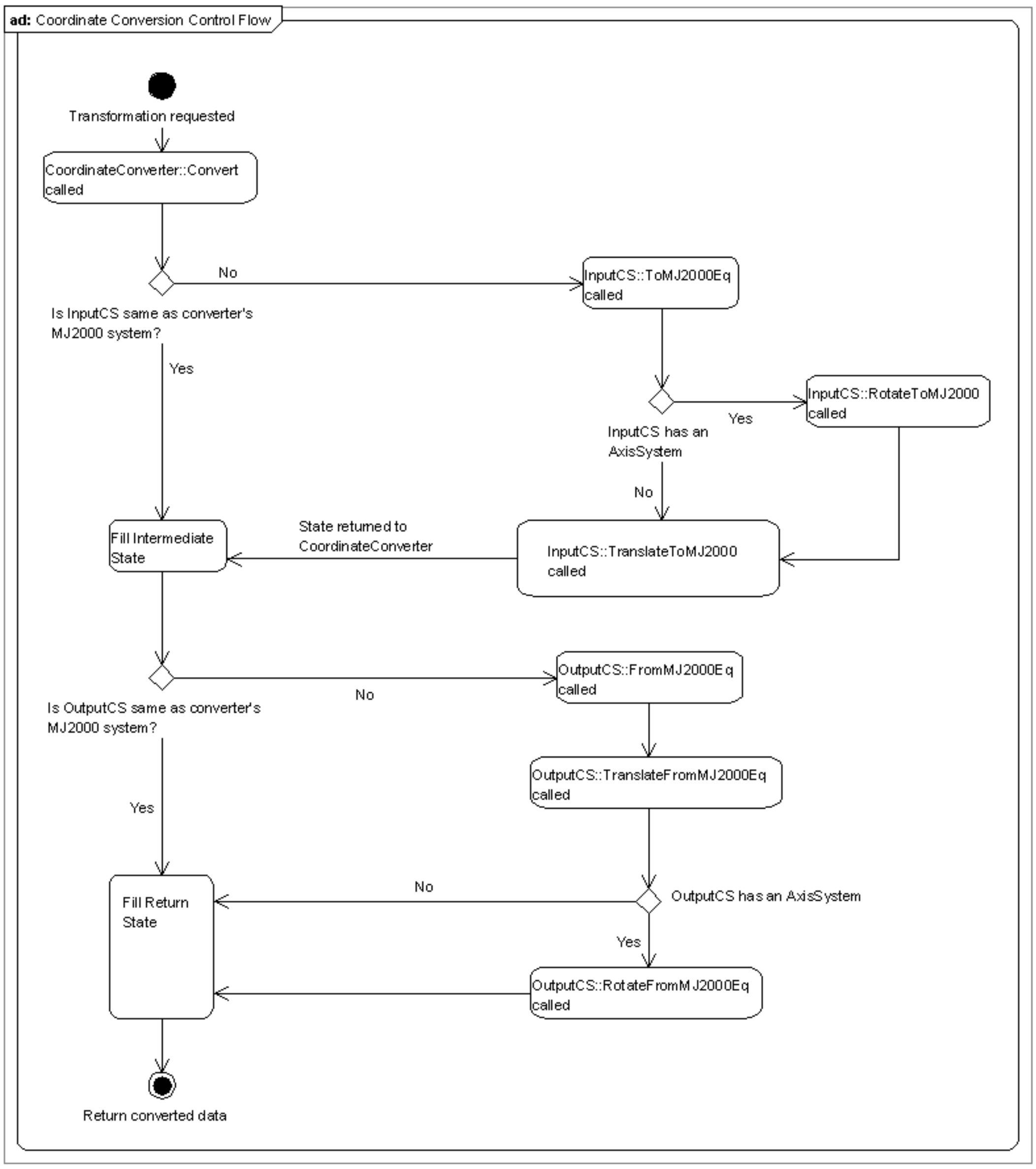
ad: Coordinate Conversion Control Flow
Transformation requested
CoordinateConverter::Convert called
No
Is InputCS same as converter's MJ2000 system?
Yes
InputCS::ToMJ2000Eq called
InputCS::RotateToMJ2000 called
Yes
InputCS has an AxisSystem
No
Fill Intermediate State
State returned to CoordinateConverter
InputCS::TranslateToMJ2000 called
OutputCS::FromMJ2000Eq called
No
Is OutputCS same as converter's MJ2000 system?
OutputCS::TranslateFromMJ2000Eq called
Yes
Fill Return State
No
OutputCS has an AxisSystem
Yes
OutputCS::RotateFromMJ2000Eq called
Return converted data

Figure 13.5: GMAT Procedure for a Generic Coordinate Transformation

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```
            instanceName);
   else           // Set the intermediate state to the input state
      internalState = instate;

   if (!TranslateToMJ2000Eq(epoch, internalstate, internalState, J2000Body))
      throw CoordinateSystemException("Translation to MJ2000 failed for " +
         instanceName);
```

and the conversion from Mean of J2000 Equatorial Coordinates to the output state is performed using these calls:

```
      // Code in CoordinateSystem::FromMJ2000Eq
   if (!TranslateFromMJ2000Eq(epoch, internalstate, internalState, J2000Body))
      throw CoordinateSystemException("Translation from MJ2000 failed for " +
         instanceName);

   if (axes)      // axes == NULL for MJ2000Eq orientations
      if (!axes->RotateFromMJ2000Eq(epoch, internalState, outstate, J2000Body))
         throw CoordinateSystemException("Rotation from MJ2000 failed for " +
            instanceName);
   else           // Set the output state to the intermediate state
      outstate = internalState;
```

13.2.4 The SpacePoint Class

In general, coordinate systems are defined in reference to locations and directions in space. Many of the coordinate systems used in GMAT have the direction fixed based on an external reference – for example, the MJ2000Eq system has the z-axis pointed along the Earth's rotation axis at the J2000 epoch and the x-axis aligned with the vernal equinox at the same epoch. GMAT also supports coordinate systems constructed in reference to objects internal to the GMAT – typically a planet, the Sun, a moon, or a spacecraft can be used, as can special points in space like Lagrange points or the barycenter of a multi-body system. The coordinate system classes need to be able to access position and velocity data about these objects in a generic fashion. GMAT has a class, SpacePoint, that provides this access. SpacePoint is the base class for all of the objects that model location data in the solar system, as is shown in Figure 13.6. The SpacePoint class is described in more detail in Chapter 12.

13.3 Configuring Coordinate Systems

13.3.1 Scripting a Coordinate System

The script commands used to create a coordinate system object in GMAT are defined in the GMAT Mathematical Specifications[MathSpec]. Coordinate System scripting is performed using the following lines of script:

```
      Create CoordinateSystem csName
   GMAT csName.Origin = <SpacePoint name>;
   GMAT csName.Axes = <Axis type>;
   GMAT csName.Primary = <Primary SpacePoint name, if needed>;
   GMAT csName.Secondary = <Secondary SpacePoint name, if needed>;
   GMAT csName.Epoch.<Format> = <Epoch data, if needed>;

   % Only two of these three can exist for a given coordinate system;
```

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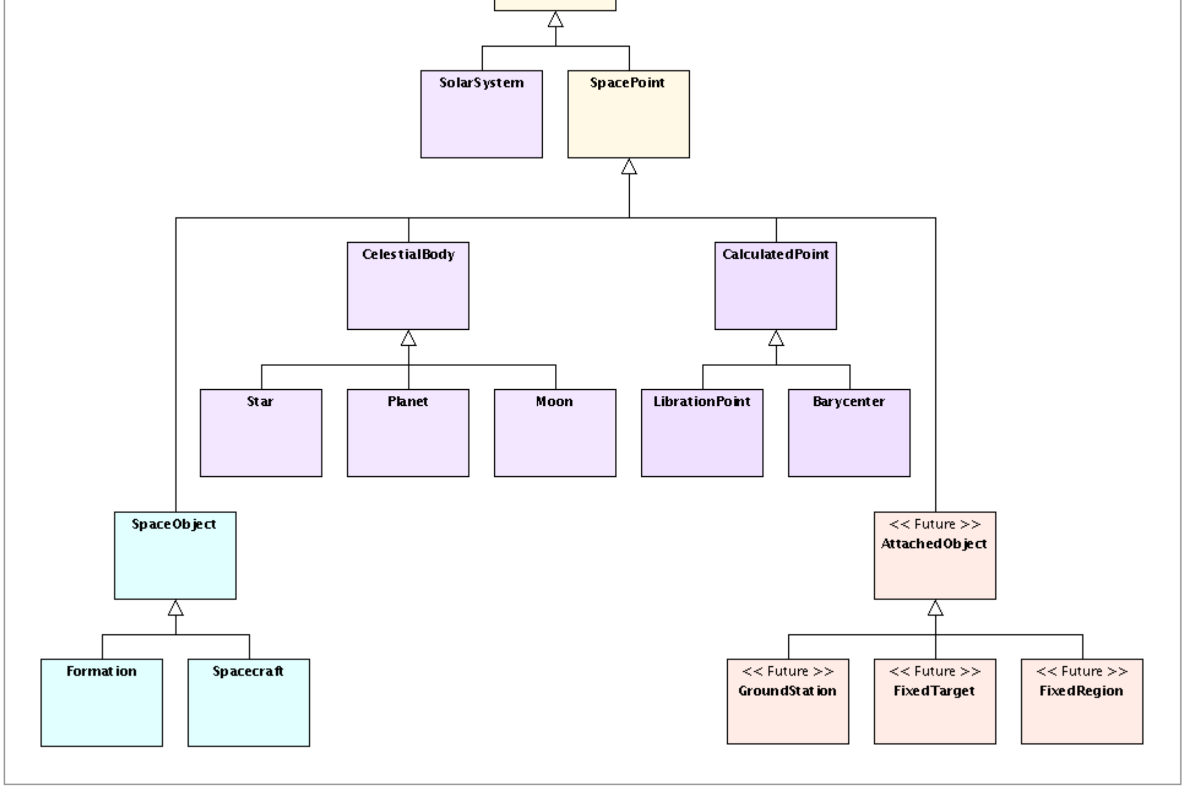

Figure 13.6: The SpacePoint Class Hierarchy

```
% see the coordinate system table for more information
GMAT csName.XAxis = <$\pm$R, $\pm$V, or $\pm$N>;
GMAT csName.YAxis = <$\pm$R, $\pm$V, or $\pm$N>;
GMAT csName.ZAxis = <$\pm$R, $\pm$V, or $\pm$N>;
```

The fields in angle brackets are used to set the parameters that define the coordinate system. Table 13.1 provides a brief description of these fields; more details are available in [MathSpec].

In the following paragraphs, the interactions between the script interpreter subsystem and the coordinate system classes are described.

13.3.1.1 Script Interpreter Actions

In GMAT, the ScriptInterpreter reads each line of script and sets up the corresponding objects. The lines of script above map to calls made in the ScriptInterpreter code, as described in the following text.

The Create line causes the ScriptInterpreter to call the CoordinateSystemFactory and requests a CoordinateSystem instance:

```
   // In the Interpreter subsystem
GmatBase *csInstance = moderator->CreateCoordinateSystem("CoordinateSystem", "csName");
```

The resulting coordinate system is registered with the configuration manager.

The Origin line sets the originName parameter on this instance:

```
   // First determine that the parm is a string
Gmat::ParameterType type = csInstance->GetParameterType({}‘‘Origin’’);

// Here type is a string, so this is called:
csInstance->SetStringParameter({}‘‘Origin’’, <SpacePoint name>);
```

The Axes line creates an instance of the AxisSystem and passes it to the coordinate system:

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Table 13.1: Coordinate System Parameters

Parameter	Required/ Optional	Allowed Values	Description
Origin	Required	Any Named SpacePoint	Defines the location of the coordinate system origin.
Axes	Required	Equator, MJ2000Ec, MJ2000Eq, TOEEq, MOEEq, TODEq, MODEq, TOEEc, MOEEc, TODEc, MODEc, Fixed, ObjectRefernced	Defines the orientation of the coordinate axes in space.
Primary	Optional	Any Named SpacePoint	Defines the primary body used to orient axes for systems that need a primary body.
Secondary	Optional	Any Named SpacePoint	Defines the secondary body used to orient axes for systems that need a secondary body.
Epoch	Optional	Any GMAT Epoch	Sets the reference epoch for systems that need a reference epoch.
XAxis	Optional	±R, ± V, ± N	Used for ObjectReferences axes only; two of the three axes are set, and one must reference $\pm N$.
YAxis	Optional	±R, ± V, ± N	Used for ObjectReferences axes only; two of the three axes are set, and one must reference $\pm N$.
ZAxis	Optional	±R, ± V, ± N	Used for ObjectReferences axes only; two of the three axes are set, and one must reference $\pm N$.

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```
   // First determine that the parm is an internal object
Gmat::ParameterType type = csInstance->GetParameterType({}‘‘Axes’’);

// Here type is an object, so this is called:
GmatBase {*}axesInstance = moderator->CreateAxisSystem(<Axis type>, {}‘‘’’);

// Then the object is set on the coordinate system
csInstance->SetRefObject(axesInstance);
```

The Primary line sets the primary body on the AxisSystem instance. This is done by passing the data through the CoordinateSystem object into the AxisSystem object:

```
   // First determine that the parm is a string
Gmat::ParameterType type = csInstance->GetParameterType({}‘‘Primary’’);

// Pass the string to the coordinate system
csInstance->SetStringParameter({}‘‘Primary’’, <SpacePoint name>);

...

// In CoordinateSystem, this parameter is passed to the AxisSystem:
axes->SetStringParameter({}‘‘Primary’’, <SpacePoint name>);
```

The Secondary line is treated similarly to the primary line:

```
   // First determine that the parm is a string
Gmat::ParameterType type = csInstance->GetParameterType({}‘‘Secondary’’);

// Pass the string to the coordinate system
csInstance->SetStringParameter({}‘‘Secondary’’, <SpacePoint name>);

...

// In CoordinateSystem, this parameter is passed to the AxisSystem:
axes->SetStringParameter({}‘‘Secondary’’, <SpacePoint name>);
```

The Epoch line is handled like in the Spacecraft object, and the XAxis, YAxis and ZAxis lines are treated as string inputs, like the Primary and Secondary lines, above.

13.3.2 Default Coordinate Systems

GMAT defines several coordinate systems by default when it is initialized. These systems are listed in Table 13.2.

13.4 Coordinate System Integration

Sections 13.2 and 13.3 describe the internal workings of the GMAT coordinate systems, but do not explain how the coordinate system code interacts with the rest of GMAT. This section outlines that information.

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Table 13.2: Default Coordinate Systems defined in GMAT

Name	Origin	Axis System	Comments
EarthMJ2000Eq	Earth	MJ2000 Earth Equator	The default coordinate system for GMAT
EarthMJ2000Ec	Earth	MJ2000 Ecliptic	
EarthFixed	Earth	Body Fixed	The Earth fixed system is used by the gravity model for full field modeling
BodyFixed	Other celestial bodies	Body Fixed	Fixed systems used by the gravity model for full field modeling at other bodies

13.4.1 General Considerations

GMAT uses coordinate systems in several general areas: for the input of initial state data, internally in the impulsive and finite burn code, force models and propagation code, in the calculation of parameters used to evaluate the behavior of the model being run, and in the graphical user interface (GUI) to display data as viewed from a coordinate system based perspective.

13.4.2 Creation and Configuration

13.4.2.1 Coordinate System Creation

Coordinate systems are created through a series of interactions between the GMAT interpreters, the Moderator, and the Factory system. Figure 13.7 shows the sequence followed by the ScriptInterpreter when a coordinate system is configured from a script. The procedure is similar when the GUI configures a coordinate system, with one exception. The ScriptInterpreter translates a script file a line at a time, so it needs to look up the CoordinateSystem object each time it is referenced in the script. The GUI configures the coordinate system from a single panel, so the coordinate system object does not need to be found each time a parameter is accessed.

13.4.2.2 Startup Considerations

When a user starts GMAT, the executable program creates a singleton instance of the Moderator. The Moderator is the core control module in GMAT; it manages the creation and deletion of resources, the interfaces between the core components of the system and the external interfaces (including the GUI and the scripting engines), and the execution of GMAT simulations. When the Moderator is created, it creates a variety of default resources, including the default factories used to create the objects in a simulation. The factories that get created include the CoordinateSystemFactory.

After it has created the factories and constructed the default solar system, the Moderator creates the default coordinate systems listed in Table 13.2, following a procedure like the one shown in Figure 13.7. These coordinate systems are registered with the Configuration Manager using the names in the table. Users can use these coordinate systems without any taking any additional configuration actions.

13.4.3 Sandbox Initialization

When a user runs a mission sequence, the Moderator takes the following sequence of actions [2]:

1. Send the current SolarSystem to the Sandbox for cloning

[2]The description here references a Sandbox for the run. The Moderator can be configured to manage a collection of Sandboxes; in that case, the actions described here are applied to the current Sandbox from that collection.

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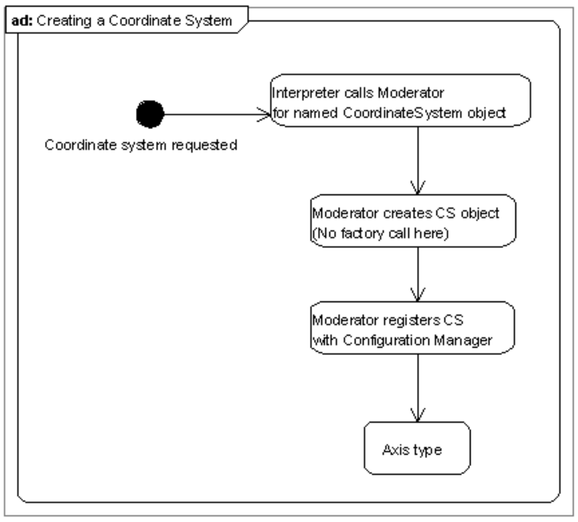
ad: Creating a Coordinate System
Coordinate system requested
Interpreter calls Moderator for named CoordinateSystem object
Moderator creates CS object (No factory call here)
Moderator registers CS with Configuration Manager
Axis type

Figure 13.7: Coordinate System Creation and Configuration Sequence

2. Load the configured objects one at a time into the Sandbox. These objects are cloned [3] into the Sandbox.
3. The Sandbox is initialized.
4. The Mission is executed.

The critical piece for successful execution of a GMAT mission is the third step. When the Sandbox is initialized, the following actions are executed:

1. The local solar system object is set for all of the objects that need it.
2. Reference object pointers are set on objects that use them.
3. The objects are initialized.
4. Parameters are configured.
5. The command sequence is configured.
   (a) The object table is passed to each command.
   (b) The solar system is passed to each command.
   (c) The command is initialized.

The coordinate system objects are fully initialized and ready for use by the end of the step 3. Commands that use the coordinate system objects have the object associations set in step 5c.

13.4.4 Initial States

Users need to set the locations and initial motion of spacecraft, ground stations, and other physical entities modeled in GMAT using a coordinate system that makes this data simple to specify. For this reason, GMAT lets users select all or a portion of the coordinate system needed for these objects.

[3]The current build of GMAT does not fully implement cloning for the configured objects. This issue is being corrected.

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13.4.4.1 Spacecraft

The initial state for a spacecraft is expressed as an epoch and six numerical quantities representing the spacecraft's location and instantaneous motion. These quantities are typically expressed as either six Cartesian elements – the x, y, and z components of the position and velocity, six Keplerian elements – the semimajor axis, eccentricity, inclination, right ascension of the ascending node, argument of pariapsis, and the anomaly in one of three forms (true, mean, or eccentric), or one of several other state representations. The element representation depends on the coordinate system used. Some representations cannot be used with some coordinate systems – for example, the Keplerian representation requires a gravitational parameter, $\mu = GM$, in order to calculate the elements, so coordinate systems that do not have a massive body at the origin cannot be used for Keplerian elements. For these cases, GMAT reports an error if the element type is incompatible with the coordinate system.

13.4.4.2 Ground Stations and Other Body Fixed Objects

Ground station objects and other objects connected to physical locations on a body are expressed in terms of the latitude, longitude, and height above the mean ellipsoid for the body. The coordinate system used for these objects is a body fixed coordinate system. Users can specify the central body when they configure these objects. The body radius and flattening factor for that body are used to calculate the mean ellipsoid. Latitude is the geodetic latitude of the location, and longitude is measured eastwards from the body's prime meridian.

GMAT does not currently support ground stations or other body fixed objects. This section will be updated when this support is added to the system.

13.4.5 Forces and Propagators

Internal states in GMAT are always stored in a Mean of J2000 Earth-Equator coordinate system. The origin for this system is set to either a celestial body (i.e. the Sun, a planet, or a moon), a barycenter between two or more bodies, or a Lagrange point. The propagation subsystem in GMAT allows the user to specify this origin, but no other coordinate system parameters. Propagation is performed in the Mean of J2000 Earth-Equator frame located at the specified origin.

Individual forces in the force model may require additional coordinate system transformations. These transformations are described in the next section.

13.4.5.1 Coordinate Systems Used in the Forces

GMAT contains models for point mass and full field gravity from both a central body and other bodies, atmospheric drag, solar radiation pressure, and thrust from thrusters during finite maneuvers. Table 13.3 identifies the coordinate system used for each force. Users set the point used as the origin for the force model. This point is labeled $\mathbf{r_o}$ in the table. Forces that require a central body reference that body as $\mathbf{r_{cb}}$ in the table. Users also specify the coordinate system used for finite maneuvers. All other coordinate systems are set up internally in the force model code, and managed by the constituent forces.

13.4.5.2 Transformations During Propagation

GMAT's propagators consist of a numerical integrator and an associated force model. Each force model is a collection os individual forces that get added togehter to determine the net acceleration applied to the object that is propagated. The preceding section defined the coordinate systems used by each of these forces. Figure 13.8 shows the procedure that is followed each time the force model calculates the acceleration applied to an object.

The force model calls each force in turn. As a force is called, it begins by transforming from the internal Mean of J2000 equatorial coordinate system into the coordinate system required for that force. The acceleration from the force is then calculated.

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Table 13.3: Coordinate Systems Used by Individual Forces

Force	Coordinate System	Notes
Point Mass Gravity	$\mathbf{r_o}$ centered MJ2000 Earth Equator	Point mass forces use the default representations
Full Field Gravity	$\mathbf{r_{cb}}$ centered Body Fixed	Full field models use the body fixed system to calculate latitude and longitude data, and calculate accelerations in the MJ2000 frame based on those values.
Drag	$\mathbf{r_{cb}}$ centered MJ2000 Earth Equator	Drag forces set the atmosphere to rotate with the associated body, so the reference frame remains inertial (i.e. MJ2000 based).
Solar Radiation Pressure	$\mathbf{r_o}$ centered MJ2000 Earth Equator	Solar Radiation Pressure calculations are performed in MJ2000 coordinates
Finite Maneuver Thrust	Any Defined Coordinate System, user specified	Finite maneuvers determine the thrust direction based on the thrust vector associated with the engines. The spacecraft are aligned with this coordinate system. A future build will add an additional transformation to allow specification of the spacecraft's attitude in this frame.

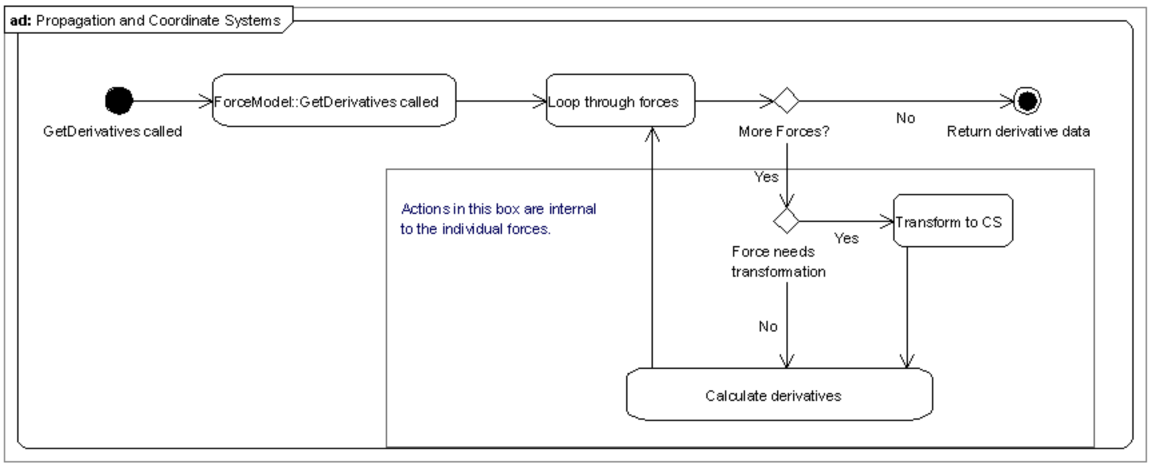
ad: Propagation and Coordinate Systems
GetDerivatives called
ForceModel::GetDerivatives called
Loop through forces
More Forces?
No
Return derivative data
Yes
Actions in this box are internal to the individual forces.
Transform to CS
Yes
Force needs transformation
No
Calculate derivatives

Figure 13.8: Control Flow for Transformations During Propagation

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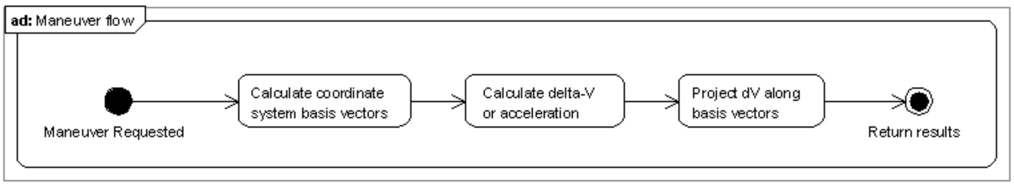
ad: Maneuver flow
Maneuver Requested
Calculate coordinate system basis vectors
Calculate delta-V or acceleration
Project dV along basis vectors
Return results

Figure 13.9: Calculating the Direction Used for Maneuvers

13.4.6 Maneuvers

The impulsive and finite burn models are used to simulate thruster actions on a spacecraft. Maneuvers are applied either as an impulsive delta-V or as an acceleration in the force model. In either case, the coordinate system related operations in the maneuver object are the same: the basis vectors for the coordinate system are calculated in the MJ2000 frame, the magnitude of the change in the velocity is calculated for the maneuver (resulting in a delta-V magnitude for impulsive maneuvers, or the time rate of change of velocity for finite maneuvers), and the resultant is projected along the basis vectors using attitude data in the maneuver object. Figure 13.9 illustrates this flow.

13.4.7 Parameters

Many of the parameters that GMAT can calculate are computed based on the coordinate system of the input data; in some cases this dependency uses the full coordinate system, and in other cases, it uses the origin or central body of the coordinate system. The Parameter subsystem contains flags for each parameter taht are used to indicate the level of coordinate system information required for that parameter. These flags indicate if the parameter is specified independently from the coordinate system, depends only on the origin of a coordinate system, or depends on a fully specified coordinate system.

13.4.8 Coordinate Systems and the GUI

13.4.8.1 OpenGL ViewPoints

The OpenGL visualization component in the first three GMAT builds set the Earth at the center of the display view and allowed users to move their Earth-pointing viewpoint to different locations. The incorporation of coordinate systems into the code opens GMAT to a greatly expanded visualization capability in this component. Users can set the viewing direction to point towards any SpacePoint or an offset from that direction. Users can also set the viewpoint location to either a point in space, to the origin of any defined coordinate system, or to locations offset from any specified SpacePoints. The latter capability allows the OpenGL view to follow the motion of the entities modeled in GMAT.

13.4.8.2 New Panels

GMAT needs a new GUI panel used to configure coordinate system objects.

13.4.8.3 Panel Changes

Several of the existing GUI panels in GMAT will change once the Coordinate System classes are functional. Both the report file and the X-Y plot components use parameter data to produce output. The configuration panels for these elements needs the ability to specify either the coordinate system or the origin for the calculated data that requires these elements. One way to add this capability to the GUI is shown in Figure 13.10.

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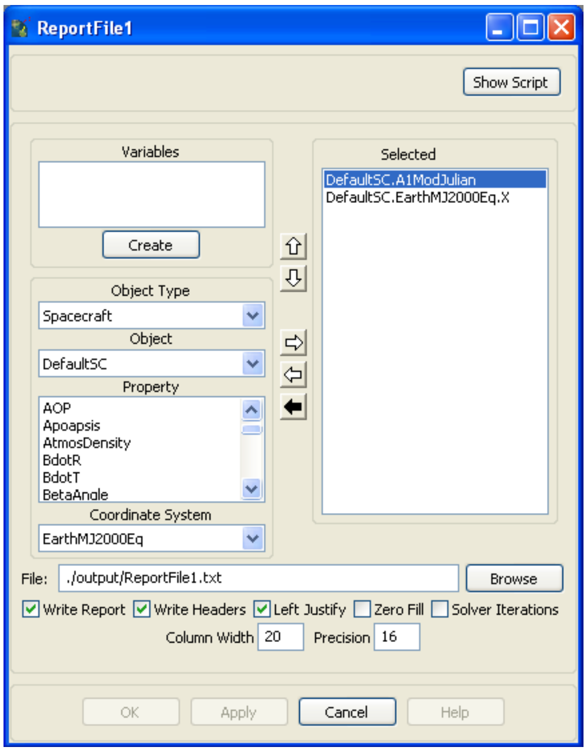

Selected: DefaultSC.A1ModJulian, DefaultSC.EarthMJ2000Eq.X

Object Type: Spacecraft

Object: DefaultSC

Property: AOP, Apoapsis, AtmosDensity, BdotR, BdotT, BetaAngle

Coordinate System: EarthMJ2000Eq

File: ./output/ReportFile1.txt

✓ Write Report ✓ Write Headers ✓ Left Justify ☐ Zero Fill ☐ Solver Iterations

Column Width 20 Precision 16

Figure 13.10: The Updated Parameter Subpanel

As different parameters are selected, the "Coordinate System" and "Coordinate Origin" comboboxes become active or disabled ("grayed out"), depending on the needs of the selected parameter.

The propagator subsystem needs information about the global origin for the forces in a force model. Figure 13.11 shows one way to add this data to the panel.

The OpenGL panel needs to be updated to allow configuration of the capabilities described in Section 13.4.8.1. Users can use the settings on this panel to specify both the coordinate system used to plot the mission data and the location and orientation of the viewpoint used to observe these data. In some cases, the viewpoint will not be a fixed point in space – for example, users will be able to view a spacecraft's environment in the simulation by specifying the location and orientation of the viewpoint relative to the spacecraft in a spacecraft centered coordinate system, and thus observe how other objects move in relation to that spacecraft.

13.5 Validation

In this section, several tables are presented that show the data for a single state in several different coordinate systems. GMAT tests will be run that transform between these systems and validates that the conversions are in agreement with the data in the tables to an acceptable level of precision. The test data were generated in Astrogator by GSFC, Code 595. This output should be in agreement with GMAT results to at least one part in 10^{12}. (Subject to change once tests are run – seems like a good value as a starting point.)

13.5.1 Tests for a LEO

Table 13.4 lists the expected state data for a spacecraft orbiting near the Earth.

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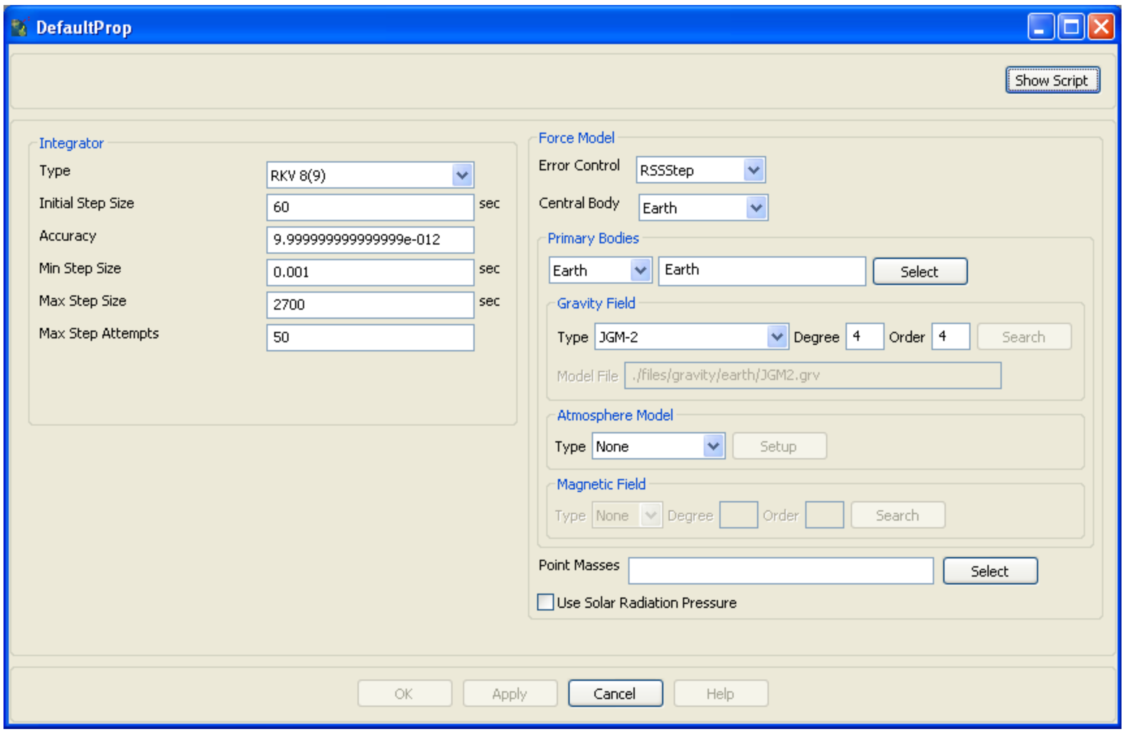

Integrator

Type: RKV 8(9)
Initial Step Size: 60 sec
Accuracy: 9.999999999999999e-012
Min Step Size: 0.001 sec
Max Step Size: 2700 sec
Max Step Attempts: 50

Force Model

Error Control: RSSStep
Central Body: Earth

Primary Bodies: Earth | Earth

Gravity Field
Type: JGM-2 Degree: 4 Order: 4
Model File: ./files/gravity/earth/JGM2.grv

Atmosphere Model
Type: None

Magnetic Field
Type: None Degree: Order:

Point Masses:

☐ Use Solar Radiation Pressure

Figure 13.11: Addition of the Propagation Origin

Table 13.4: Coordinate Conversions for an orbit near the Earth

A LEO State						
poch:	UTC Gregorian		UTC Julian		Ephemeris Time	
	1 Jan 2005 12:00:00.00		2453372		2453372.00074287	
oordinate System	**X**	**Y**	**Z**	V_x	V_y	V_z
rth Centered Mean 000 Equator	15999.999999999998	0.0000000000000	0.0000000000000	0.0000000000000	3.8662018270519716	3.866201827
rth Centered Fixed	3100.7006422193112	15696.674760971226	7.54822029656669	-2.6485022470204602	0.5213224286561129	3.866343176
rth Centered Mean liptic of Date	15999.988100569937	19.513619701949061	0.0163246416692983	-0.0062037647908650	5.0850309969931660	2.009341784
rth Centered Mean liptic of J2000	15999.999999999998	0.0000000000000	0.0000000000000	0.0000000000000	5.0850575916827729	2.009284057
rth Centered Mean of te	15999.9881005699370	17.8969907643261870	7.7768465297859297	-0.0062037647908650	3.8661983573941092	3.866200319

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Table 13.5: Coordinate Conversions for an orbit near the Earth/Moon-Sun L2 Point

A L2 State						
poch:	UTC Gregorian		UTC Julian		Ephemeris Time	
	25 Sep 2003 16:22:47.94		2452908.18249931		2452908.18324218	
oordinate Sys- em	**X**	**Y**	**Z**	V_x	V_y	V_z
arth Centered Mean 2000 Equator	1152413.9609139508	164482.90400985131	-270853.37069837836	-0.0237491328055502	0.5463496092937017	0.18969527053
un-Earth/Moon arycenter L1	2659568.8530356660	-467.97516783879695	-314259.10186388291	-0.0062197634008832	0.3610507604664427	-0.04258067111
un-Earth L2	-352659.29964214563	-0.0002161438986659	-313927.71991658572	0.0027515868356648	0.3488514802312706	-0.04329161797
olar System Barycen- er Mean J2000 Earth quator	151524360.68432158	4848014.2434389694	1751879.7152567047	-1.6146582474186386	27.776726415749529	11.9956571743

13.5.2 Tests for a Libration Point State

Table 13.5 lists the expected state data for a spacecraft flying near the Earth-Sun.

13.5.3 Tests for an Earth-Trailing State

Table 13.6 lists the expected state data for a deep space object trailing behind the Earth.

13.6 Some Mathematical Details

This section will probably appear in some form in the mathematical specifications. I'm leaving it here until I can confirm that assumption.

A spatial coordinate system is fully specified by defining the origin of the system and two orthogonal directions. Given these pieces of data, space can be gridded into triplets of numbers that uniquely identify each point. The purpose of this section is to provide some guidance into how to proceed with the definition of the coordinate system axes once the origin and two directions are specified.

13.6.1 Defining the Coordinate Axes

The coordinate system axes are defined from the two orthogonal directions in the system specification. These directions are given two of the three labels $\hat{X}$, $\hat{Y}$, and $\hat{Z}$. These labels are used to define the corresponding directions for the coordinate system. The third axis is calculated by taking the inner product of the other two axes, using

$$\begin{aligned}\hat{X} &= \hat{Y}\times\hat{Z}\\ \hat{Y} &= \hat{Z}\times\hat{X}\\ \hat{Z} &= \hat{X}\times\hat{Y}\end{aligned} \tag{13.1}$$

13.6.2 Setting Directions in GMAT

The principal directions for a coordinate system are set in GMAT by specifying a primary direction and a secondary direction. The specified secondary axis need not be orthogonal (i.e. perpendicular) to the primary

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Table 13.6: Coordinate Conversions for an Earth-Trailing state

An Earth-Trailing State						
poch:	UTC Gregorian		UTC Julian		Ephemeris Time	
	1 Jan 2012 00:00:00.00		2455927.5		2455927.50074287	
oordinate Sys-m	**X**	**Y**	**Z**	V_x	V_y	V_z
rth Centered Mean 00 Equator	18407337.2437560	146717552.364272	2436998.6080801622	-29.85775713588113	3.7988731566283533	-0.088353532
rth Centered Mean iptic of Date	18010745.506277718	135634904.81496251	-56121251.238084592	-29.8677194647804920	3.3629312165175098	-1.592147103
rth Centered Mean iptic of J2000	18407337.2437560	135580104.86024788	-56124988.196549937	-29.8577571358811300	3.4502529604822207	-1.592167741
ar System Barycen- Mean J2000 Earth uator	-7095223.559007301	279535881.30854195	60015670.739229225	-59.6890476068945470	-0.969033406060170	-2.154998010
n Centered Earth uator Mean J2000	-6610248.770514084	279718577.50517684	60095016.884433664	-59.6964420074725410	-0.9617072219755838	-2.151661882
nus Centered Fixed	234671807.87997022	-184530264.43020287	-49090196.384031780	87.7042809962516540	130.412316317457850	-3.65239585
on Centered Fixed	-28218680.593746454	-133515637.46513638	-56782561.270103499	-325.9434285713376800	70.716401043687014	-2.326936112
on Centered Inertial on Equator	18009331.473252095	146686558.45310178	2386670.4083221816	-29.7707871076046790	2.8992895961634191	-0.443005995
piter Centered Iner- Jupiter Equator	-562256455.23257434	-225513430.99244595	-25746106.471387718	-50.5813599808322610	-13.854862630504574	-0.555533610
rs Centered Inertial rs Equator	207783148.71266919	-43368297.655312374	13161295.341311477	-19.7427310285643220	35.2164929323613260	-21.76726911
rs Centered Fixed	127577563.32704885	-169644368.24313599	13138473.444519326	-12016.3787728729480	-9003.4840556769759	-21.76907222

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axis. Given a primary direction $\vec{P}$ and a secondary direction $\vec{S}$, the primary axis is oriented along a unit vector given by

$$\hat{P} = \frac{\vec{P}}{\left|\vec{P}\right|} \tag{13.2}$$

The unit vector defining the secondary axis is constructed by projecting the secondary direction $\vec{S}$ into the plane perpendicular to the primary direction, and unitizing the resulting vector. This is done by calculating

$$\hat{S} = \frac{\vec{S} - \left(\vec{S} \cdot \hat{P}\right) \hat{P}}{\left|\vec{S} - \left(\vec{S} \cdot \hat{P}\right) \hat{P}\right|} \tag{13.3}$$

In general, two points are needed to specify a direction.

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Chapter 14

SpaceObjects: Spacecraft and Formation Classes

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The Spacecraft and Formation classes used in GMAT are the core components studied when running the system. Instances of these classes serve to model spacecraft state information as the model evolves. They also serve as containers for hardware components used to extend the model to include finite burn analysis, contact calculations, spatial mass distributions, and full six degree of freedom modeling. The core elements of this modeling are presented in this chapter. The hardware extensions are documented in Chapter 15.

14.1 Component Overview

The central nature of Spacecraft and Formation objects in GMAT's mission model makes the design of the supported features of these classes potentially quite complex. The state data and related object properties required for these objects must meet numerous requirements, including all of the following:

1. Supply State information to force model
   - Origin dependent data, MJ2000 Earth Equator orientation
   - Cartesian states
   - «Future» Equinoctial states
2. Support input representations
   - Convert between different representations
   - Preserve accuracy of input data
3. Support coordinate systems
   - Support internal MJ2000 Cartesian system for propagation
   - Allow state inputs in different systems
   - Show state in different systems on demand
4. Support time systems
   - TAI ModJulian based internal time system

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- Support ModJulian
- Support Gregorian
- Convert all time systems

5. Support mass and ballistic properties
   - Basic spacecraft mass
   - Cd, Cr, Areas
   - Mass in tanks
   - «Future» Mass depletion from maneuvers
   - «Future» Moments of Inertia
6. Support tanks and thrusters
   - Add and remove tanks and thrusters
   - «Future» Deplete mass during finite burn
   - «Future, partially implemented» Model burn direction based on thruster orientations (BCS based)
7. GUI
   - Provide epoch information
     - Epoch representation string
     - Epoch in that representation
     - Supply different representation on request
     - Preserve precision of input epoch data
   - Provide state information
     - State type string
     - State in that representation
     - Provide units and labels for state elements
     - Convert to different representations
     - Preserve precision of input state data
   - Provide support for finite maneuvers
8. Scripting
   - Support all GUI functionality from scripting
   - Provide element by element manipulations of state data
   - Allow element entry for data not in the current state type without forcing a state type change
9. Provide Range Checking and Validation for all Editable Data
10. «Future» Support attitude
    - Allow attitude input
    - Convert attitude states
11. «Future» Support sensors
    - Add and remove
    - Conical modeling

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- Masking
- Contact information based on sensor pointing (BCS based)

GMAT defines a base class, SpaceObject, for the common elements shared by spacecraft and formations. The primary feature of the SpaceObject class is that it provides the data structures and processes necessary for propagation using GMAT's numerical integrators and force models. Classes are derived from this base to capture the unique characteristics of spacecraft and formations. Additional components that interface with the propagation subsystem should be added to GMAT in this hierarchy; the propagation subsystem is designed to work at the SpaceObject level.

The SpaceObject subsystem uses three categories of helper classes: PropStates, Converters, and Hardware. In one sense, the SpaceObject classes can be viewed as containers supporting the features needed to model objects in the solar system that evolve over time through numerical integration in GMAT.

The core data needed for propagation is contained in the PropState helper class. Each SpaceObject has one PropState instance used to manage the data directly manipulated by the numerical integrators. The PropState manages the core epoch and state data used by the propagation subsystem to model the SpaceObjects as they evolve through time. Details of the PropState class are given in Section 14.2.3.

Each SpaceObject includes components used to take the data in the PropState and convert it into a format appropriate for viewing and user interaction. The conversion subsystem described in Section 14.5 provides the utilities needed to convert epoch data, coordinate systems, and state element representations. The conversion routines needed to meet the requirements are contained in a triad of conversion classes: TimeConverter, CoordinateConverter, and RepresentationConverter, that share a common base that enforces consistent interfaces into the conversion routines. These conversion routines interact with the state and epoch data at the SpaceObject level on GMAT; therefore, conversions on a Formation object are performed using identical calls to conversions for individual Spacecraft. In other words, the state or epoch data for a Formation is transformed for all members of the Formation with a single call, and that call looks identical to the same transformation when performed on a single spacecraft.

The spacecraft as modeled in GMAT is a fairly simple object, consisting of several key properties required to model ballistics and solar radiation forces. The state complexities are managed in the SpaceObject base class. Additional spacecraft hardware – fuel tanks, thrusters, and eventually sensors and other hardware elements – are modeled as configurable hardware elements that are added as needed to Spacecraft objects. Hardware elements that contribute to the spacecraft model are broken out into separate classes modeling the specific attributes of those elements. Users configure fuel tanks and thrusters as entities that the spacecraft uses for finite maneuvering. These elements include structures that allow location and orientation configuration in the Spacecraft's body coordinate system, so that detailed mass and moment data can be calculated during the mission. A future release of GMAT will add support for attitude calculations and, eventually, sensors, so that attitude based maneuvering, full six degree of freedom modeling, and detailed contact modeling can be incorporated into the system. These components are discussed in more detail in Chapter 15.

The remainder of this chapter details the design of the components that implement the core SpaceObject classes, Spacecraft and Formation. It includes the design specification for the converters GMAT uses to support these classes, along with a discussion of how these elements interact to provide the conversions needed to meet the system requirements.

14.2 Classes Used for Spacecraft and Formations

Figure 14.1 shows the details of the classes derived from SpacePoint that are used when modeling spacecraft and formations of spacecraft. The class hierarchy for the spacecraft subsystem consists of three core classes: the SpaceObject class, which contains the common elements of the subsystem, the Spacecraft class, which acts as the core component for all spacecraft modeling, and the Formation class, which collects spacecraft and subformations into a single unit for modeling purposes. This subsystem also contains a helper class, the

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PropState, which encapsulates the data that evolves as the model is run, simplifying the interface to the propagation subsystem. In addition, two of the hardware classes – Thruster and FuelTank – are shown in the figure.

14.2.1 Design Considerations

The central role of the Spacecraft and Formation SpaceObjects in GMAT's models drives several design considerations related to the consistent display and use of these objects in the model. Before presenting the design of the classes used for these objects, several of the considerations that went into this design will be discussed.

14.2.1.1 Data Consistency Philosophy

The SpaceObject subsystem follows a convention that requires that the state data in the PropState always stays correct with respect to the model. In other words, once some data in the state vector is set, changes to other properties of the SpaceObject do not change the state with respect to the model. That means that if the internal origin changes for a SpaceObject, the data in the state vector is translated to the new location, and the velocity data is updated to reflect the speed of the SpaceObject with respect to the new origin. In order to change the state of a SpaceObject in GMAT's model, the actual state data must be changed. Changing the coordinate system or origin does not change the position or velocity of the SpaceObject with respect to other objects in the space environment; instead, it changes the values viewed for the SpaceObject by updating the viewed data in the new coordinate system. The epoch also remains unchanged upon change of the coordinate system, the representation, or elements of the state vector.

Epoch data is simpler (because it is independent of location in the space environment), but follows the same philosophy. Internally the epoch data is stored in the TAI modified Julian time system. Users can view the epoch data in any of GMAT's defined time systems. Changing the time system does not change the internal epoch data, only the way that data is presented. Epoch data is changes by directly updating the epoch. Upon change of epoch, the state of the spacecraft remains unchanged with respect to the SpaceObject's origin. However, a side effect of changing the epoch on a SpaceObject is that the locations of the objects in the solar system may shift, so the location of the SpaceObject with respect to other solar system objects may be different.

14.2.1.2 Data Presented to the User

Each SpaceObject includes data members used to track the current default views of the data. The epochType member is used to store the current format for viewing the epoch data. State data requires two components to fully define the view of the state data: the coordinateType member tracks the coordinate system used to view the state data, and the stateType member the representation for that view of the state data. These three members – epochType, coordinateType, and stateType – define the views used when a SpaceObject is written to a file, displayed on a GUI panel, or accessed as strings for other purposes.

Access to the state and epoch data as Real values returns the internal data elements: the epoch is returned as a TAI modified Julian value, and the state data is returned as Cartesian Mean-of-J2000 Earth equatorial data, referenced to the origin specified for the SpaceObject. The SpaceObjects provide methods that retrieve the data in other formats as well; the values described here are those returned using the default GetRealParameter methods overridden from the GmatBase class.

State data can be read or written either element by element or as a vector of state data. The former approach is taken by the Script Interpreter when setting a spacecraft's state as expressed element-by-element in the script, like shown here:

```
Create Spacecraft sat;
sat.StateType = Keplerian;
sat.SMA = 42165.0;
```

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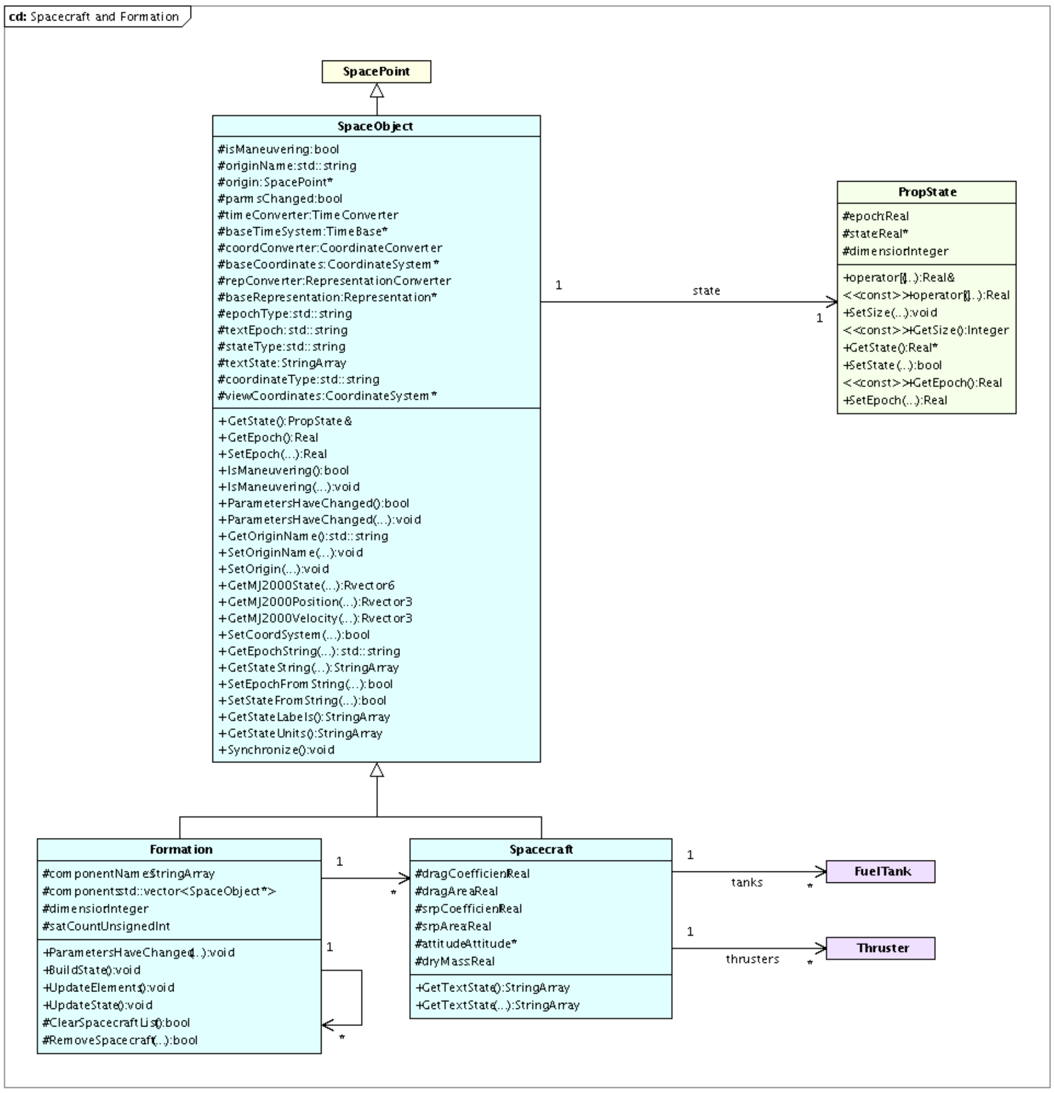
cd: Spacecraft and Formation
SpacePoint
SpaceObject
#isManeuvering:bool
#originName:std::string
#origin:SpacePoint*
#parm sChanged:bool
#tim eConverter:TimeConverter
#baseTimeSystem:TimeBase*
#coordConverter:CoordinateConverter
#baseCoordinates:CoordinateSystem*
#repConverter:RepresentationConverter
#baseRepresentation:Representation*
#epochType:std::string
#textEpoch:std::string
#stateType:std::string
#textState:StringArray
#coordinateType:std::string
#viewCoordinates:CoordinateSystem*
+GetState():PropState&
+GetEpoch():Real
+SetEpoch(...):Real
+IsManeuvering():bool
+IsManeuvering(...):void
+ParametersHaveChanged():bool
+ParametersHaveChanged(...):void
+GetOriginNam e():std::string
+SetOriginNam e(...):void
+SetOrigin(...):void
+GetMJ2000State(...):Rvector6
+GetMJ2000Position(...):Rvector3
+GetMJ2000Velocity(...):Rvector3
+SetCoordSystem(...):bool
+GetEpochString(...):std::string
+GetStateString(...):StringArray
+SetEpochFromString(...):bool
+SetStateFromString(...):bool
+GetStateLabels():StringArray
+GetStateUnits():StringArray
+Synchronize():void
1
state
1
PropState
#epochReal
#stateReal*
#dimensionInteger
+operator[](...):Real&
<<const>>+operator[](...):Real
+SetSize(...):void
<<const>>+GetSize():Integer
+GetState():Real*
+SetState(...):bool
<<const>>+GetEpoch():Real
+SetEpoch(...):Real
Formation
#com ponentNam esStringArray
#com ponentsstd::vector<SpaceObject*>
#dimensionInteger
#satCountUnsignedInt
+ParametersHaveChanged(...):void
+BuildState():void
+UpdateElements():void
+UpdateState():void
#ClearSpacecraftList():bool
#RemoveSpacecraft(...):bool
1
*
1
*
Spacecraft
#dragCoefficientReal
#dragAreaReal
#srpCoefficientReal
#srpAreaReal
#attitudeAttitude*
#dryMassReal
+GetTextState():StringArray
+GetTextState(...):StringArray
1
tanks
*
FuelTank
1
thrusters
*
Thruster

Figure 14.1: Class Structure for Spacecraft and Formations

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```
sat.ECC = 0.0011;
sat.INC = 0.25;
sat.RAAN = 312.0;
sat.AOP = 90.0;
sat.TA = 270.0;
```

The GUI works with the state data as a single entity, rather than element-by-element. Accordingly, the panel that displays spacecraft state data accesses this data with a single call that returns the full state data[1].

Spacecraft states can be displayed in many different representations. Rather than code text descriptions for the different components of each representation into the representation converter, each representation includes structures to provide the labels and units used for the components. The SpaceObjects provide methods to retrieve these values.

Some state representations have optional settings for specific elements. For example, the Keplerian representation can specify the anomaly in one of several forms: elliptical states can specify a true anomaly, eccentric anomaly, or mean anomaly, while hyperbolic orbits use either the hyperbolic anomaly or a mean anomaly defined off of the hyperbolic anomaly. Representations that support this type of option also provide a method, SetOption(), to set the option. SpaceObjects provide methods to access these methods as well, so that the representation options can be set through calls to the SpaceObject.

14.2.2 The SpaceObject Class

GMAT's force model constructs a state vector that is manipulated by the system's numerical integrators to advance the state vector through time, as described in Chapter 22. The core building block for the construction of this state vector is the SpaceObject, a class used in GMAT as the base class for Spacecraft and Formations[2], as shown in the class diagram, Figure 14.1.

The SpaceObject class supports all operations and data elements that Spacecraft and Formations share in common. In particular, the vector used by the propagators to model evolution over time is encapsulated in the SpaceObject class. Conversions that involve the data in this vector are performed at the SpaceObject level. The SpaceObject class maintains pointers to the elements that are necessary for these conversions.

SpaceObject instances also act as containers for several helper classes, responsible for performing coordinate system conversions, state transformations between different state representations, and time system conversions that allow the object's epoch information to be presented to users in common time systems, described in Section 14.5. The SpaceObject class implements several methods that call those components to supply requested data. The returned data from these calls is always an std::string or StringArray. The SpaceObject class manages the underlying Real data internally, and uses these as checkpoints to manage the precision of the output, to validate that the data is consistent, and to ensure that all data presented to the users is consistent with the internal data structures in the SpaceObject.

Class Attributes

- **PropState state**: The container for the raw state and epoch data that gets propagated. Details of the PropState class are provided in Section 14.2.3.
- **bool isManeuvering**: A flag used to indicate if there is a finite burn active for any of the members of the SpaceObject.

[1]A future release of GMAT will provide a scripting option to set the full state in a single script line, using the format

```
Create Spacecraft sat;
sat.StateType = Keplerian;
sat.State = [42165.0, 0.0011, 0.25, 312.0, 90.0, 270.0];
```

[2]A future release will include the State Transition Matrix (STM) in the SpaceObject class hierarchy.

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- **std::string originName**: The name of the SpacePoint that is the origin of the data contained in the SpaceObject's PropState.
- **SpacePoint *origin**: A pointer to the SpacePoint that is the origin of the data in the state.
- **bool parmsChanged**: A flag used to indicate if the size or data contained in the PropState has changed, so that consumers of those data can perform updates.
- **SpacePoint *origin**: The origin used for the state data.
- **CoordinateSystem *baseCoordinates**: The coordinate system used for the state data. This coordinate system is a Mean-of-J2000 Earth-Equator system, with the origin set to the SpaceObject's origin.
- **std::string epochType**: Text descriptor for the current epoch type used for display.
- **TimeConverter timeConverter**: The time converter used by this SpaceObject.
- **«Future» TimeBase* baseTimeSystem**: The time system matching the epochType.
- **std::string coordinateType**: Text descriptor for the current coordinate system used for display.
- **CoordinateConverter coordConverter**: The coordinate system converter used by this SpaceObject.
- **CoordinateSystem* baseCoordinates**: The coordinate system associated with the SpaceObject's PropState.
- **CoordinateSystem* viewCoordinates**: The coordinate system associated with the SpaceObject's coordinateType, used for display.
- **std::string stateType**: Text descriptor for the current state representation used for display.
- **RepresentationConverter repConverter**: The representation converter used by this SpaceObject.
- **«Future» Representation* baseRepresentation**: The representation used for display.
- **std::string textEpoch**: The most recently accessed string version of the epoch. This string is only updated if the epoch field is accessed as a string using GetEpochString(), and the epoch or epoch type has changed since the last access.
- **StringArray textState**: The most recently accessed string version of the state. This string array is only updated if the state is accessed as a string array using GetStateString(), and the coordinate type or representation has changed since the last access.

Methods

- **PropState &GetState()**: Returns the internal PropState.
- **Real GetEpoch()**: Returns the TAI modified Julian epoch of the SpaceObject, obtained from the PropState.
- **Real SetEpoch(Real ep)**: Sets the SpaceObject's epoch to a new value. The input parameter is the new TAI epoch. This mathod passes the new epoch into the PropState for storage.
- **bool IsManeuvering()**: Returns a flag indicating if a finite burn is currently active for the SpaceObject.

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- **void IsManeuvering(bool mnvrFlag)**: Sets the flag indicating the presence of a finite burn.
- **bool ParametersHaveChanged()**: Returns a flag indicating that the state data has been changed outside of the propagation subsystem, and therefore the states need to be refreshed.
- **void ParametersHaveChanged(bool flag)**: Method used to indicate that an external change was made, and therefore states should be refreshed before propagating.
- **std::string GetOriginName()**: Returns the name of the SpacePoint used as the origin of the state data.
- **void SetOriginName(const std::string &cbName)**: Sets the name of the origin used for the state data.
- **void SetOrigin(SpacePoint *cb)**: Sets the SpacePoint corresponding to the origin of the state vector. The SpacePoint passed in the parameter cb is the new origin, and gets set on the base coordinate system as its origin.
- **Rvector6 GetMJ2000State(A1Mjd &atTime)**: Returns the Cartesian state relative to the SpaceObject's J2000 body[3].
- **Rvector3 GetMJ2000Position(A1Mjd &atTime)**: Returns the Cartesian position relative to the SpaceObject's J2000 body.
- **Rvector3 GetMJ2000Velocity(A1Mjd &atTime)**: Returns the Cartesian velocity relative to the SpaceObject's J2000 body.
- **bool SetCoordSystem(CoordinateSystem* coordsys)**: Sets the viewCoordinates member to the input coordinate system.
- **std::string GetEpochString(std::string toTimeType)**: Returns the current epoch in string form, in the format in the toTimeType input. If toTimeType is an empty string, epochType is used as the format for the output.
- **StringArray GetStateString(std::string toType, std::string toCoords, CoordinateSystem* toCS)**: Returns the SpaceObject state in the representation specified by toType, in the coordinate system set by toCoords, using the internal coordinate converter and the input coordinate system, toCS. If toCS is NULL, the coordinate converter locates the required coordinate system. If, in addition, toCoords is an empty string, viewCoordinates is used for the output coordinate system. If the toType is also an empty string, the baseRepresentation is used.
- **bool SetEpochFromString(std::string epochString, std::string timeType)**: Sets the epoch in the PropState using the input epochString, which is formatted using the input timeType.
- **bool SetStateFromString(StringArray stateString, std::string fromType, std::string fromCoords, CoordinateSystem* fromCS)**: Sets the state in the PropState using the data in the stateString array, which has the representation specified in the fromType string in coordinate system fromCoords, which has an instance in the fromCS input.
- **StringArray GetStateLabels()**: Returns a string array containing the labels identifying the state elements.
- **StringArray GetStateUnits()**: Returns a string array containing the units for the state elements.
- **void Synchronize()**: Method used to fill the textEpoch and textState from the data in the PropState.

[3]The current GetMJ2000 methods take an a.1 epoch as the epoch for the calculation. A future release will change this call to use TAI epochs.

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14.2.3 The PropState Class

All SpaceObjects contain a member PropState element that is designed to encapsulate all data needed to propagate the SpaceObject. This member class is used to provide the single state vector propagated as the core component seen by GMAT's propagators. The PropState objects can contain data for a single spacecraft, multiple spacecraft (typically flown in a Formation), and related mass depletion and state transition matrix data. The propagator subsystem ensures that these data are treated appropriately during propagation.

Each PropState instance defined the following data members and methods:

Class Attributes

- **Real epoch**: The current epoch for the state. This value is a TAI modified Julian value, and is used in the force model to specify the epoch for force evaluations.
- **Real* state**: The state vector that gets propagated.
- **Integer dimension**: The total number of elements in the state vector.

Methods

- **Real &operator[](const Integer el)**: Provides element by element access to the state vector, so that the components can be set using the same syntax as is used to set C++ array elements.
- **Real operator[](const Integer el) const**: Provides element by element access to the state vector, so that the components can be read using the same syntax as is used to read C++ array elements.
- **void SetSize(const Integer size)**: Resizes the state vector. This method copies the current state data into the resized vector once the new vector has been allocated.
- **const Integer GetSize() const**: Returns the current size of the state vector.
- **Real *GetState()**: Returns the state vector. The returned vector is the internal Cartesian state used by the propagators. The state data is in Mean-of-J2000 Earth-Equatorial coordinates, referenced to the SpaceObject's origin.
- **bool SetState(Real *data, Integer size)**: Sets the state vector to match the input vector. If the size parameter is less than or equal to the dimension of the state vector, the data vector is copied into the state vector, filling from the start until the indicated number of elements is filled. If size is greater than the PropState dimension, the method returns false. The input state is in Mean-of-J2000 Earth-Equatorial coordinates, referenced to the SpaceObject's origin.
- **Real GetEpoch() const**: Returns the value of the epoch data member. The returned value is a TAI modified Julian value.
- **Real SetEpoch(const Real ep)**: Sets the value of the epoch data member. The input value is a TAI modified Julian value.

14.3 The Spacecraft Class

One key component that supplies PropState data to GMAT is the Spacecraft class, used to model satellites in the mission control sequence. Each satellite studied in the mission has a corresponding Spacecraft object, configured to simulate the behavior of that satellite. The Spacecraft contains core data elements necessary to model the physical characteristics of the satellite, along with the inherited SpaceObject properties that form the core state representations used for propagation.

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In GMAT, the Spacecraft model allows for the addition of new satellite components that model specific hardware elements. The current implementation supports fuel tanks and thrusters for use when modeling finite maneuvers. The base class for the hardware subsystem was designed to be flexible, incorporating data elements designed to model the location and orientation of the hardware relative to a satellite body coordinate system. The orientation data is used in GMAT to set the thruster direction during finite burns. Once the thrust direction has been determined, it it rotated based on the satellite's attitude to determine the thrust direction in the propagation frame, so that the maneuver acceleration can be incorporated into the force model. This modular hardware incorporation is also the first step towards incorporating moments of inertia into the model, so that full six degree of freedom modeling can be performed in GMAT. Additional details of the hardware model are provided in Chapter 15.

14.3.1 Internal Spacecraft Members

Spacecraft objects are SpaceObjects, so they contain all of the data structures associated with SpaceObjects described above. They manage a StringArray that contains the current state as expressed in the current state representation. This array typically contains the state as seen on the GUI or in the script file that configured the Spacecraft; the data in this array is only updated when needed for display purposes.

The Spacecraft class contains data members controlling the core ballistics of the object. Mass is handled as a core Spacecraft mass plus all masses associated with the hardware attached to the Spacecraft. The force model accumulates the mass into a total mass used in the acceleration calculations. Areas and force coefficients are included in the Spacecraft model for drag and solar radiation pressure calculations.

14.3.2 Spacecraft Members

The Spacecraft class provides data memebers used to manage the ballistic properties of the spacecraft. Properties are defined to manage the spacecraft mass, incident areas for drag and solar radiation pressure perturbations, associated coefficients of drag and reflectivity, and the structures needed to add hardware elements to the core spacecraft objects. The members that provide this support are:

Class Attributes

- **Real dragCoefficient**: The coefficient of drag, C_d (see equation 24.4), used when calculating atmospheric forces acting on the spacecraft.
- **Real dragArea**: The area of the spacecraft encountering the atmosphere.
- **Real srpCoefficient**: The reflectivity coefficient, C_R (see equation 24.3), used when calculating accelerations from solar radiation pressure.
- **Real srpArea**: The area exposed to solar radiation, for the purposes of calculating the solar radiation pressure force.
- **Real dryMass**: The total mass of the spacecraft, excluding fuel and other massive hardware elements.
- **StringArray tankNames**: Names of the fuel tanks that the spacecraft uses.
- **StringArray thrusterNames**: Names of the thrusters that the spacecraft uses.
- **ObjectArray tanks**: Array of fuel tanks on the spacecraft. Fuel tanks are added to spacecraft by making local copies of defined tanks. Each fuel tank contributes fuel mass to the total mass of a spacecraft. Fuel is depleted from the tanks during finite maneuvers[4].

[4]Mass depletion is scheduled for implementation during the summer of 2007.

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- **ObjectArray thrusters**: Array of thrusters attached to the spacecraft. Thrusters are added to spacecraft by making local copies of defined thrusters. Each thruster has a location and pointing direction defined in teh spacecraft's body coordinate system. The applied thrust dir ection is computed by rotating the thrust direction based on teh spacecraft's attitude[5]. The thruster mass should be included in the dry mass of the spacecraft.

- **Real totalMass**: The total mass of the spacecraft, including fuel and other massive hardware elements. This is a calculated parameter, available only as an output. Users cannot set the spacecraft's total mass.

Methods The support for Spacecraft state and epoch access and manipulation is provided by the SpaceObject base class. Access to the new data members described above is provided using the GmatBase access methods described in Section 9.3. Generally speaking, the ballistic properties are accessed using the GetRealParameter and SetRealParameter methods overrifdden from the base class. Hardware elements are set by name, and configured on the Spacecraft by passing in pointers to configured hardware elements which are then cloned inside the spacecraft tto make the local copy used when executing the mission control sequence. Since most of the infrastructure for these steps is described elsewhere, the list of new methods on the Spacecraft is rather sparse, consisting of notes describing Spacecraft specific details implemented for these core methods:

- **virtual Real GetRealParameter(const Integer id) const**: Returns the real parameters listed in the data member section. Of particular interest here is the treatment of the mass parameter. Requests can be made for either the dry mass of the spacecraft or the total mass of the spacecraft. When the total mass is requested, the returned value is the output of the UpdateTotalMass() method described below.

- **virtual bool TakeAction(const std::string &action, const std::string &actionData = "")**: TakeAction in the Spacecraft class adds the following new actions to the object:

  - *SetupHardware*: Examines the hardware on the spacecraft, and sets up internal linkages required for this hardware. For example, each thruster reqires a pointer to a fuel tank; that connection is configured by this action.
  - *RemoveHardware*: Removes one or all hardware elements from the Spacecraft. If a name is specified for the hardware element, only that element is removed. If the actionData string is empty, all hardware elements are removed.
  - *RemoveTank*: Removes one or all fuel tanks from the Spacecraft. If a name is specified for the fuel tank, only that tank is removed. If the actionData string is empty, all fuel tanks are removed.
  - *RemoveThruster*: Removes one or all thrusters from the Spacecraft. If a name is specified for the thruster, only that thruster is removed. If the actionData string is empty, all thrusters are removed.

The Spacecraft Class includes the following protected methods used to maintain some of the internal data structures, and to generate data needed for the public methods:

- **Real UpdateTotalMass()**: Updates the total mass by adding all hardware masses to the dry mass.

- **Real UpdateTotalMass() const**: Updates the total mass by adding all hardware masses to the dry mass. The const version does not update the internal member, and therefore can be called by other const methods.

[5]The current implementation uses either an inertial attitude or a velocity-normal-binormal attitude for this calculation.

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14.4 Formations

In GMAT, SpaceObjects can be grouped together and treated as a single entity, the Formation, which evolves over time as a single state vector. Each Formation can contain Spacecraft, other Formations, or any other SpaceObject defined in the system. Formations are modeled using instances of the Formation class, described in this section.

Class Attributes

- **StringArray componentNames**: Names of the SpaceObjects in the formation.
- **std::vector <SpaceObject *> components**: Pointers to the formation members.
- **Integer dimension**: Size of the state vector used in propagation.
- **UnsignedInt satCount**: Number of SpaceObjects in the components vector.

Methods The Formation class defines the following methods, used to manage the objects in the Formation:

- **virtual void BuildState()**: Constructs the PropState for the Formation.
- **virtual void UpdateElements()**: Updates the member SpaceObjects using the data in the Formation PropState.
- **virtual void UpdateState()**: Updates the internal PropState data from the member SpaceObjects.
- **virtual bool TakeAction(const std::string &action, const std::string &actionData = "")**:TakeAction in the Formation class adds two actions to the object:
  - *Clear*: Calls ClearSpacecraftList() to remove all SpaceObjects from the Formation.
  - *Remove*: Calls RemoveSpacecraft() with a specific SpaceObject name to remove that SpaceObject from the Formation.

Formation also contains two protected methods that are used to pupport the public interfaces:

- **bool ClearSpacecraftList()**: Clears the list of SpaceObjects in the Formation. This method clears both the list of SpaceObject names and the list of instance pointers.
- **bool RemoveSpacecraft(const std::string &name)**: Removes a SpaceObject from the list of Formation members. This method removes both the SpaceObject name from the componentNames member and the instance pointer from the components list.

14.5 Conversion Classes

GMAT's Spacecraft and Formation models act as a data provider for state information that is fed into the propagation system. Users interact with this aspect of the model by selecting the view of the data, spacecraft by spacecraft, in one of many different coordinate systems and state representations at a user specified epoch. On a coarse level, the views into the state data can be broken into three separate components: the time system used to track the epoch for the spacecraft, the coordinate system that specifies the origin and orientation of coordinate axes defining the position and velocity of the spacecraft, and the representation used to express this state data – a set of Cartesian or Keplerian elements, or some other representation based on the needs of the user.

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Internally, these data are managed as Mean-of-J2000 Earth-Equatorial states, translated to the origin specified for the SpaceObject, in either the Cartesian or equinoctial representation[6]. Epoch data is stored internally in international atomic time (TAI, Temps Atomique International), in a modified Julian time format measured in days from January 5, 1941 at 12:00:00.000.

The Conversion classes and the related base classes defining the interfaces for the conversion types are designed to satisfy GMAT's extensibility requirements. Users can define new coordinate systems as needed, from either GMAT's graphical user interface or from a script file. Representations and time systems are more difficult to add to the system because the underlying math and is more specialized to meet the needs of the system. Users that need to add state representations or time systems not currently in GMAT should refer to Chapter 32.

The basic philosophy for conversions performed by GMAT is that all conversions proceed from the internal data type, and go through that type when converting from one system to another. Conversions for epoch data are referenced to the base TAI epoch. Coordinate system conversions are referenced to the Mean of J2000 Earth Equatorial system. Element conversions are referenced to the Cartesian or equinoctial state representation.

All of the conversion components that support the Spacecraft and Formation classes have a similar structure. Each acts as a pipeline from the data in the SpaceObject to the code that transforms that data into the requested format. In that sense, the converters play the role of the controller in a simplified model-view-controller pattern, as described in Section B.6. The SpaceObject plays the role of the model, and the presentation to the user – the GMAT GUI or the Script file – presents a view of these data to the user.

There are three converters used by the SpaceObjects for this purpose. Each SpaceObject has a Time-Converter, a CoordinateConverter, and a RepresentationConverter. The Converter classes contain instances or references to the support classes used in the conversions. Each support class represents a single view of the data. The support classes implement a conversion method that transform the internal data into the requested view.

The class hierarchy for the converters and the support classes is shown in Figure 14.2[7]. Each converter is derived from the Converter base class. All converters support the ability to take a PropState and transform the data in that state into the requested format for display and manipulation by the user. They also support the inverse operation, converting a set of user data specified into a PropState. The interfaces for these conversions are contained in the Converter base class.

Each Converter subclass holds a reference to the data type used in the PropState as the base representation for the corresponding data. The object that owns the PropState is responsible for setting this reference.

14.5.1 The Converter Base Class

All conversions performed for spacecraft and formations are managed through the Converter classes. GMAT provides three types of converters: time system converters, coordinate system converters, and state representation converters. Each of these converters manages the corresponding conversion code. The SpaceObjects wrap these calls in methods that simplify interface to the data. Specific conversions are made through the calls to the Convert method on the appropriate converters.

The Converter base class has the following internal data members and methods:

Class Attributes

- **static StringArray supportedConversions**: String array of all of the defined conversions supported by this converter.

[6]The current implementation in GMAT uses Cartesian elements exclusively; equinoctial representations will be added as an option for the PropState data when the Variation of Parameters integrators are incorporated into the system.

[7]Figure 14.2 shows the long term design for the conversion classes. The code base developed for the first release of GMAT supports the interfaces needed for conversion, but only partially implements the illustrated design.

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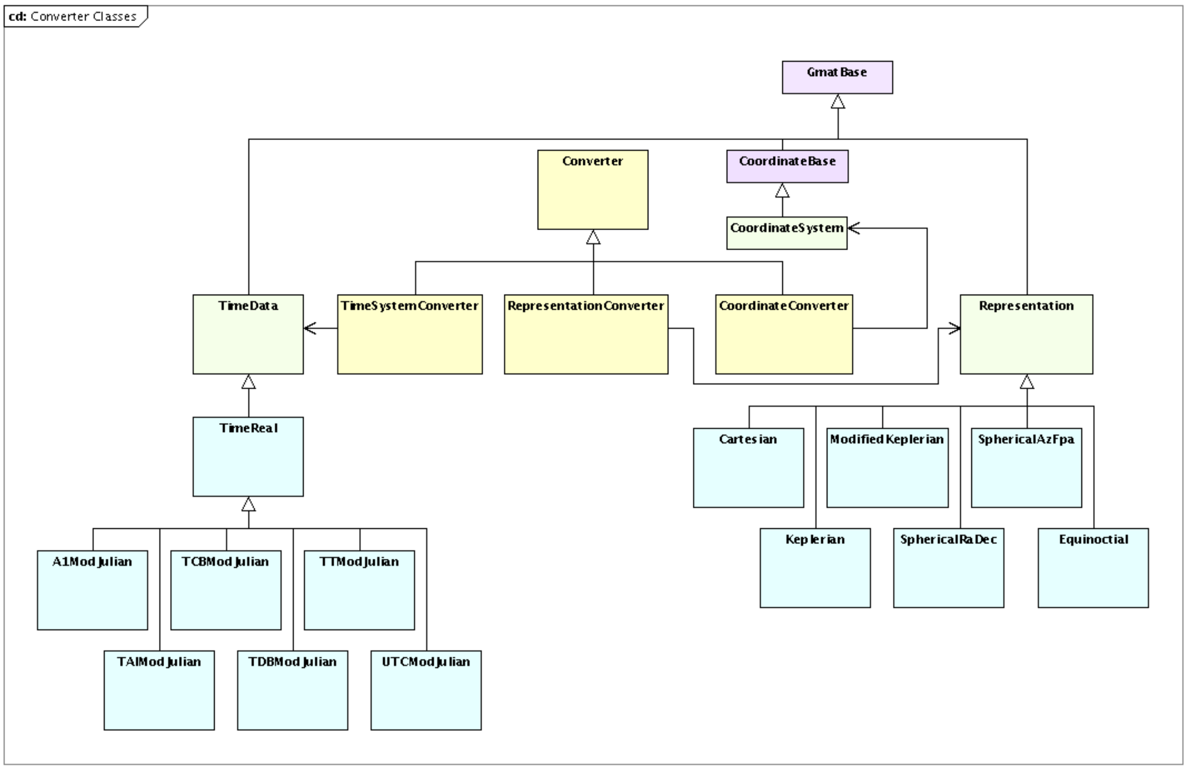

Figure 14.2: Classes Used to Provide Views of the SpaceObject State Data. The converter classes are shown in yellow. Base classes for the View support classes are green, and specific support classes are shown in blue.

- **Integer precision**: Precision used for numeric data when converting to a string format.

Methods

- **void Initialize()**: Method called to prepare and validate the converter for use in a SpaceObject.
- **static bool AddConversion(const std::string &conversionType, GmatBase *toBase)**: Method used to add support for a new conversion to the Converter. This method is used to add configured CoordinateSystems to the CoordinateConverter. The TimeConverter and RepresentationConverter classes do not support addition of new systems in the current builds of GMAT.
- **static StringArray GetSupportedConversions()**: Method used to return the list of all of the conversions supported by the Converter.
- **std::vector<Real> Convert(const PropState &fromState, std::string toType, GmatBase*=NULL toObject) = 0**: Abstract method that converts data from a PropState into the requested type.
- **PropState Convert(std::vector<Real> fromState, std::string fromType, GmatBase*=NULL fromObject) = 0**: Abstract method that fills a PropState in the internal representation from input data of the specified type.
- **virtual StringArray ToString(std::string toFormat, std::vector<Real> value, std::string fromFormat) = 0**: Abstract conversion routine that takes a state in Real vector (`value`) in a specified format (`fromFormat`) and converts it to a string array in a target format (`toFormat`).

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- **virtual std::vector<Real> ToReal(std::string fromFormat, StringArray value, std::string toFormat) = 0**: Abstract conversion routine that takes a the text form of a state in StringArray (`value`) in a specified format (`fromFormat`) and converts it to a Real vector in a target format (`toFormat`).

14.5.2 Time Conversions

The TimeConverter class provides implementations for the abstract methods inherited from the Converter base class. The current code base supports time conversions using C-style functions enclosed in a namespace, TimeConverterUtil. The TimeConverter class wraps these conversions so that there is a time conversion interface in GMAT that looks identical to the other conversion interfaces in the system. A future release of the system will rework the time conversions do that the class structure matches the class hierarchy shown in Figure 14.2. The following descriptions provide initial steps toward this goal, marked as with the prefix "«Future»" for elements that are not planned for the system until these elements are incorporated during these time system revisions[8].

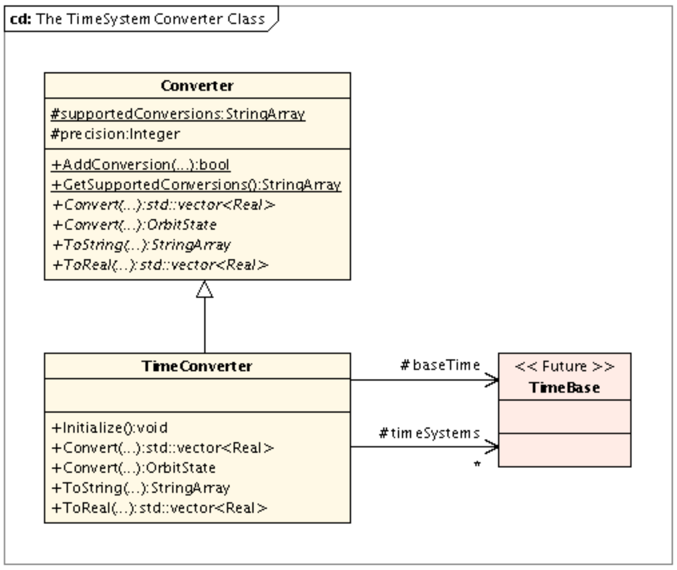
cd: The TimeSystem Converter Class
Converter
#supportedConversions:StringArray
#precision:Integer
+AddConversion(...):bool
+GetSupportedConversions():StringArray
+Convert(...):std::vector<Real>
+Convert(...):OrbitState
+ToString(...):StringArray
+ToReal(...):std::vector<Real>
TimeConverter
+Initialize():void
+Convert(...):std::vector<Real>
+Convert(...):OrbitState
+ToString(...):StringArray
+ToReal(...):std::vector<Real>
#baseTime
#timeSystems
*
<< Future >>
TimeBase

Figure 14.3: Classes Used to Convert Epoch Data

The TimeConverter class is shown in Figure 14.3. The properties of this class, including the arguments for the methods that are hidden in the figure, are tabulated below.

Class Attributes

- **«Future» TimeBase *baseTime**: An instance of the base time system used internally in GMAT. This member contains a pointer to a TAIModJulian instance so that the conversion code has the time system for methods that use PropStates at one end of the conversion.

[8]GMAT is, by design, extensible to incorporate new components as they are identified and constructed by the GMAT community, without violating the integrity of the official code base. The time system code as currently implemented would require rework in the GMAT's base code to support any new time system, violating this requirement; the design shown here provides the framework needed to correct this discrepancy.

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- **«Future» std::vector<TimeBase*> timeSystems**: A vector containing pointers to each of the defined time systems in GMAT, so that the conversion code can perform conversions without requiring time system pointers on the function calls.

Methods

- **void Initialize()**: Method called to prepare and validate the converter for use in a SpaceObject.
- **std::vector<Real> Convert(const PropState &fromState, std::string toType, GmatBase*=NULL toObject)**: Method that converts the TAI epoch data from a PropState into the requested type. The resulting modified Julian data is stored in the first element of the returned array.
- **PropState Convert(std::vector<Real> fromState, std::string fromType, GmatBase*=NULL fromObject)**: Method that sets the epoch on a PropState to the epoch contained as the first element in the input data (`fromState`), which is expressed in the time system given by the name in the `fromType` string.
- **virtual StringArray ToString(std::string toFormat, std::vector<Real> value, std::string fromFormat) = 0**: Conversion routine that takes epoch data in a vector of Reals in a specified format (`fromFormat`) and produces the string equivalent of each element in the requested format, given by `toFormat`, in the returned StringArray.
- **virtual std::vector<Real> ToReal(std::string fromFormat, StringArray value, std::string toFormat) = 0**: Conversion routine that takes one or more epochs in a StringArray (`value`) in a specified format (`fromFormat`) and converts them into a vector of Real data in a target format (`toFormat`). The resulting data is a vector of modified Julian data in the target time system. If a request is made from Gregorian data in the Real vector, an exception is thrown.

14.5.2.1 The TimeSystem Classes

As mentioned above, the current time system conversion code does not use a class bases system to handle the time systems. This section will be completed when the time system code is brought into conformance with the conversion system design.

14.5.3 Coordinate System Conversions

Figure 14.4 shows the CoordinateConverter class, used to transform state data between different coordinate systems. The CoordinateConverter class works with state data expressed in Cartesian coordinates exclusively. Consumers that have state data in other representations first convert the data into Cartesian coordinates, and then use the facilities provided by instances of this class to transform between coordinate systems.

The CoordinateConverter objects work with any coordinate system defined by the user. The other two converters provided by GMAT – the TimeConverter class and the RepresentationConverter class – require code compiled into GMAT in order to function[9]. Coordinate systems in GMAT can be defined at run time, as described in [UsersGuide]. The dynamic nature of these objects requires greater versatility in the conversion methods. Consumers of these methods must provide pointers to instances of the coordinate systems used in the conversions.

14.5.3.1 CoordinateConverter Attributes and Methods

Class Attributes

[9]A future release of GMAT may allow dynamic definition of representations and time systems. That facility is not planned for near term GMAT functionality.

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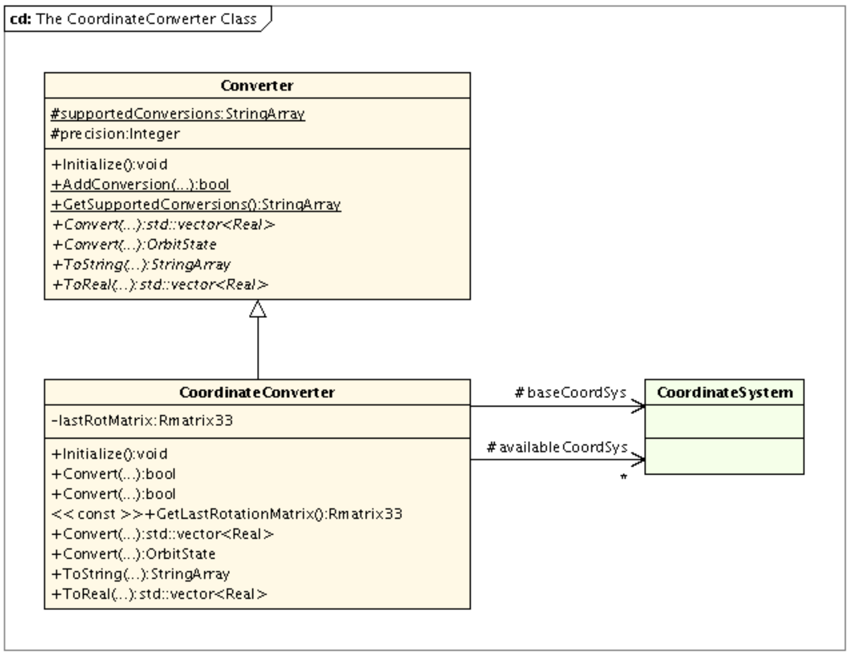
cd: The CoordinateConverter Class
Converter
#supportedConversions:StringArray
#precision:Integer
+Initialize():void
+AddConversion(...):bool
+GetSupportedConversions():StringArray
+Convert(...):std::vector<Real>
+Convert(...):OrbitState
+ToString(...):StringArray
+ToReal(...):std::vector<Real>
CoordinateConverter
-lastRotMatrix:Rmatrix33
+Initialize():void
+Convert(...):bool
+Convert(...):bool
<< const >>+GetLastRotationMatrix():Rmatrix33
+Convert(...):std::vector<Real>
+Convert(...):OrbitState
+ToString(...):StringArray
+ToReal(...):std::vector<Real>
#baseCoordSys
#availableCoordSys
*
CoordinateSystem

Figure 14.4: Classes Used to Convert Between Coordinate Systems

- **CoordinateSystem *baseCoordSys**: An instance of the CoordinateSystem class used as the base class for conversions involving a PropState. This member is initialized to NULL, and set by SpaceObjects that need it prior to use.
- **Rmatrix33 lastRotMatrix**: The most recent rotation matrix used in coordinate conversions, stored so that it can be accessed externally.
- **std::map <std::string, CoordinateSystem*> availableCoordSys**: A map of coordinate systems available for use in methods that do not pass on CoordinateSystem pointers. These pointers are stored in a map so that they can be accessed by name.

Methods

- **void Initialize()**: Method called to prepare and validate the converter for use in a SpaceObject.
- **bool Convert(A1Mjd epoch, Rvector inState, CoordinateSystem* inCoord, Rvector outState, CoordinateSystem* outCoord, bool forceNutationComputation = false, bool omitTranslation = false)**: General purpose conversion routine that converts a Cartesian Rvector in a given input coordinate system into a Cartesian Rvector in the output coordinate system.
- **bool Convert(A1Mjd epoch, Real* inState, CoordinateSystem* inCoord, Real* outState, CoordinateSystem* outCoord, bool forceNutationComputation=false, bool omitTranslation=false)**: General purpose conversion routine that converts a Cartesian Real array in a given input coordinate system into a Cartesian Real array in the output coordinate system. This method requires that the input and output Real arrays both contain the Cartesian state in the first six elements.
- **Rmatrix33 GetLastRotationMatrix() const**: Method used to access the most recent rotation matrix used in conversions.

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- **std::vector<Real> Convert(const PropState &fromState, std::string toType, GmatBase* toCS)**: Method that converts the state in the input PropState into the specified CoordinateSystem. The toCS parameter is a pointer to an instance of the target coordinate system. This method uses the base coordinate system, baseCoordSys, as the coordinate system of the input PropState. The calling code must ensure that the base coordinate system is set correctly.
- **PropState Convert(std::vector<Real> fromState, std::string fromType, GmatBase* fromCS)**: Method that sets the state in the data in a PropState in the base coordinate system, given an input state in a specified CoordinateSystem. The `fromCS` parameter is a pointer to an instance of the coordinate system used for the input state, `fromState`. This method uses the base coordinate system, baseCoordSys, as the coordinate system of the target PropState. The calling code must ensure that the base coordinate system is set correctly.
- **StringArray ToString(std::string toFormat, std::vector<Real> value, std::string fromFormat)**: Method that takes a Cartesian state contained in a vector of Reals is a specified coordinate system, and converts it into a target coordinate system, then stores the data in a StringArray at the precision set for the converter.
- **std::vector<Real> ToReal(std::string fromFormat, StringArray value, std::string toFormat)**: Method that takes a Cartesian state contained in a StringArray in a specified coordinate system, and converts it into a target coordinate system, then stores the data in a vector of Reals.
- **void AddCoordinateSystem(CoordinateSystem *cs)**: Method used to add a CoordinateSystem pointer to the map of available coordinate systems.

14.5.3.2 The CoordinateSystem Classes

Coordinate Systems in GMAT are described in detail in Chapter 13.

14.5.4 State Representation Conversions

Once the coordinate system has been selected for a state, the actual format for the data must also be selected. The state can be displayed in many different ways: as Cartesian data, as the corresponding Keplerian elements, or in any other representation defined in GMAT. The conversion from the Cartesian state into a selected representation is managed by the RepresentationConverter class, shown in Figure 14.5.

14.5.4.1 RepresentationConverter Attributes and Methods

Class Attributes

- **SpacePoint* origin**: The SpacePoint defining the coordinate system origin. Some representations need this object to determine the representation data; for instance, the Keplerian representation needs the gravitational constant for the body at the origin.
- **StringArray elements**: A vector of text string labels for the elements. This vector contains the labels for the most recent target conversion.
- **StringArray units**: A vector of text string labels for the element units. This vector contains the units for the most recent target conversion.
- **«Future» Representation baseRep**: The representation used for the PropState data.
- **«Future» std::vector<Representation*> supportedReps**: A vector of instances of all supported representations, provided so that conversions can be made without passing in a pointer to a target representation.

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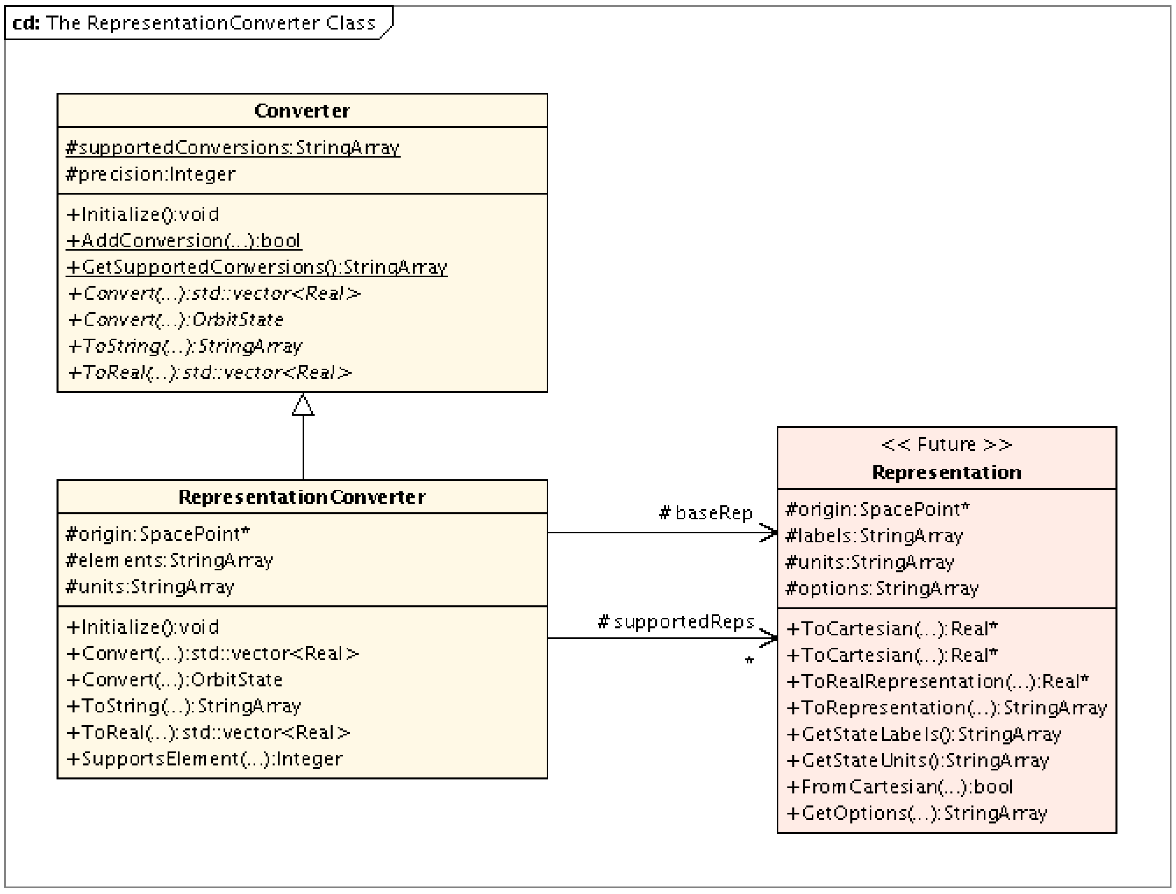
cd: The RepresentationConverter Class
Converter
#supportedConversions:StringArray
#precision:Integer
+Initialize():void
+AddConversion(...):bool
+GetSupportedConversions():StringArray
+Convert(...):std::vector<Real>
+Convert(...):OrbitState
+ToString(...):StringArray
+ToReal(...):std::vector<Real>
RepresentationConverter
#origin:SpacePoint*
#elements:StringArray
#units:StringArray
+Initialize():void
+Convert(...):std::vector<Real>
+Convert(...):OrbitState
+ToString(...):StringArray
+ToReal(...):std::vector<Real>
+SupportsElement(...):Integer
#baseRep
#supportedReps
*
<< Future >>
Representation
#origin:SpacePoint*
#labels:StringArray
#units:StringArray
#options:StringArray
+ToCartesian(...):Real*
+ToCartesian(...):Real*
+ToRealRepresentation(...):Real*
+ToRepresentation(...):StringArray
+GetStateLabels():StringArray
+GetStateUnits():StringArray
+FromCartesian(...):bool
+GetOptions(...):StringArray

Figure 14.5: Classes Used to Convert State Representations

Methods

- **«Future» bool AddRepresentation(Representation* rep)**: Method used to register a new representation with the converter. This method is used to register new representations that are built into shared libraries loaded at run time.

- **std::vector<Real> Convert(const PropState &fromState, std::string toType, GmatBase* toRep=NULL)**: Method that converts the state in the input PropState into the specified Representation. The optional toRep parameter is a pointer to an instance of the target Representation; if it is not provided, the converter finds an instance in its internal array of Representations. This method uses the base representation, baseRep, as the representation of the input PropState. The calling code must ensure that the base representation is set correctly.

- **PropState Convert(std::vector<Real> fromState, std::string fromType, GmatBase* fromRep)**: Method that sets the state in the data in an PropState in the base representation, given an input state in a specified Representation. The `fromRep` parameter is a pointer to an instance of the Representation used for the input state, `fromState`. This method uses the base Representation, baseRep, as the representation of the target PropState. The calling code must ensure that the base representation is set correctly.

- **std::string SupportsElement(std::string label)**: Method used to query all supported representations to determine which representation supports a specified element. The return value is the name of the supporting representation.

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- **StringArray ToString(std::string toFormat, std::vector<Real> value, std::string fromFormat="Cartesian"):** Conversion routine that generates a text view of the state contained in the input Real vector in a target representation. The resulting StringArray contains data at the Converter's precision.
- **std::vector<Real> ToReal(std::string fromFormat, StringArray value, std::string toFormat="Cartesian"):** Conversion routine that takes a text version of a state in a StringArray, expressed in a specified representation, and converts it into a Real vector of data in a target representation.

14.5.4.2 The Representation Classes

«Future»[10] All state representations share a common interface, enforced by the Representation base class. Representations like the Keplerian representation that provide options for certain elements provide the list of options for the elements on an element by element basis..

14.6 Conversions in SpaceObjects

The SpaceObject classes – SpaceObject, Spacecraft, and Formation, and other classes as they are added to GMAT – all share a common representation of locations in the GMAT SolarSystem, the PropState. As its name implies, the PropState class is the core component that interacts with the propagation subsystem; it contains the epoch, position and velocity data that is advanced to model the motion of user defined objects in the solar system. The data stored in the PropState is a TAI epoch and the Mean-of-J2000 Cartesian positions and velocities of the objects that are propagated. The origin for these data is a SpacePoint object defined in the solar system. Each SpaceObject includes a pointer to the SPacePoint defining the origin and a CoordinateSystem object configured as a Mean-of-J2000 Earth-Equatorial origin-centered coordinate system to facilitate conversions between the data in the encapsulated PropState and external consumers of the data.

The PropState data is encapsulated inside of SpaceObject instances. Users interact with the PropState indirectly, by making calls to these SpaceObjects. This feature provides a buffering mechanism to GMAT's SpaceObjects, so that the data in the PropState can be formatted for presentation purposes for the user. The SpaceObject class provides interfaces that convert the internal PropState data into other formats for display, and that take data from those formats and convert them into the internal PropState structures needed for computation.

SpaceObjects include four data structures used this buffering of the state data. The epochType and stateType data members are strings containing the current settings for the displayed format of the epoch and state representation. String versions of the epoch and state in these formats are stored in the textEpoch and textState data members. These string versions of the data are the versions that users interact with when configuring a mission, either from the GUI or using the scripting interface. The following paragraphs describe the procedure followed when performing these interactions.

14.6.1 SpaceObject Conversion Flow for Epoch Data

Figure 14.6 shows the procedure employed to send and receive epoch data for a SpaceObject using the string format needed for display and output purposes. Epochs can be displayed in either Gregorian or Modified Julian format, using one of several different supported time systems. The time system used and the format for the output are separate entities, and treated as such in GMAT. The internal epoch data is stored in the TAI system as a Modified Julian Real number. This data is retrieved for external manipulation as a string, using the GetEpochString() method on the SpaceObject that owns the epoch. Updated epoch data is passed into the SpaceObject using the SetEpochFromString method.

[10] Like the time conversion classes, the representation conversion classes do not currently conform to the design presented here. Accordingly, in the following descriptions, the elements that are not planned for immediate implementation are marked as future enhancements.

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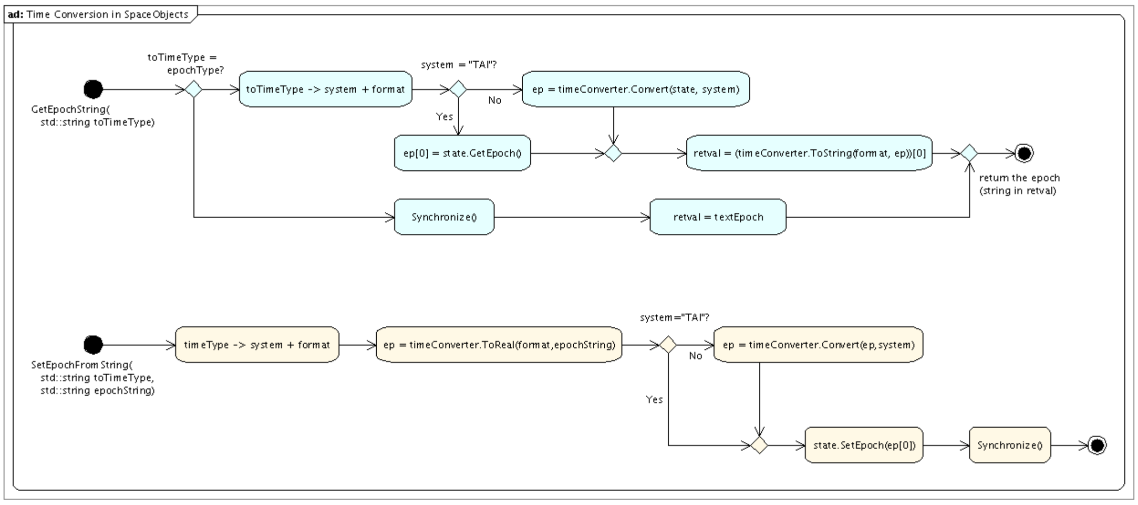
ad: Time Conversion in SpaceObjects
toTimeType = epochType?
GetEpochString(std::string toTimeType)
toTimeType -> system + format
system = "TAI"?
No
Yes
ep = timeConverter.Convert(state, system)
ep[0] = state.GetEpoch()
retval = (timeConverter.ToString(format, ep))[0]
return the epoch (string in retval)
Synchronize()
retval = textEpoch
SetEpochFromString(std::string toTimeType, std::string epochString)
timeType -> system + format
ep = timeConverter.ToReal(format,epochString)
system="TAI"?
No
Yes
ep = timeConverter.Convert(ep,system)
state.SetEpoch(ep[0])
Synchronize()

Figure 14.6: Procedure for Retrieving or Setting a Formatted Epoch

The top activity diagram in the figure shows the procedure followed to retrieve the current epoch data from the SpaceObject using the GetEpochString method. The first action taken is a test to determine if the target time format matches the epoch format used in the SpaceObject. If so, then the string that is returned is the textEpoch data member for the SpaceObject, as set immediately after synchronizing the textEpoch with the PropState. If the time systems do not match, the target time system is broken into two pieces: the time system used and the format for the string. The format portion is the suffix on the toTimeType parameter, and is either “ModJulian” or “Gregorian”. The GetEpochString method retrieves the epoch from the PropState and, if the target system is not TAI, converts it into the target time system. Then it takes that ModJulian real number, and converts it into a formatted string using the timeConverter’s ToString method.

The lower activity diagram in Figure 14.6 shows the procedure followed when setting the epoch from the GUI or script, using the SetEpochString method on the SpaceObject. The first parameter in this call specifies the format of the input time. It is broken into the input time system and the format of the string. The time converter then constructs a modified Julian real value for the input string using its ToReal method. If the input time is not a TAI time, it is then converted into TAI. The resulting modified Julian epoch is then set on the PropState using the SetEpoch method. Finally, the Synchronize method is called on the SpaceObject to update the string representation of the epoch with the data in the PropState.

14.6.2 SpaceObject Conversion Flow for State Data

The state data in the PropState can be manipulated either element by element or as a complete vector. The following paragraphs describe the conversion procedures for both approaches.

14.6.2.1 Converting State Vectors

Figure 14.7 shows the procedures employed to convert the state in vector form. State conversions are always a two step procedure. The state data in the PropState is always defined with respect to the Mean-of-J2000 Earth Equatorial coordinate axes orientation, wit h the coordinate origin located at a user specified origin. The internal data is stored in the Cartesian representation[11]. Users can view the state in any defined

[11]A future update will allow internal storage in either Cartesian or Equinoctial elements, so that Variation of Parameters propagation methods can be implemented.

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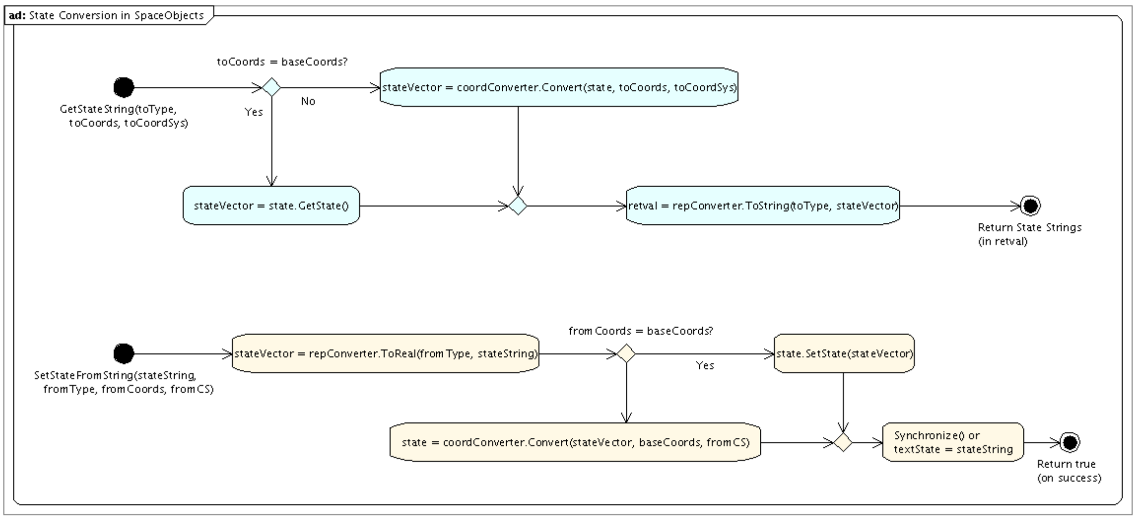
ad: State Conversion in SpaceObjects
toCoords = baseCoords?
GetStateString(toType, toCoords, toCoordSys)
Yes
No
stateVector = coordConverter.Convert(state, toCoords, toCoordSys)
stateVector = state.GetState()
retval = repConverter.ToString(toType, stateVector)
Return State Strings (in retval)
SetStateFromString(stateString, fromType, fromCoords, fromCS)
stateVector = repConverter.ToReal(fromType, stateString)
from Coords = baseCoords?
Yes
state.SetState(stateVector)
state = coordConverter.Convert(stateVector, baseCoords, fromCS)
Synchronize() or textState = stateString
Return true (on success)

Figure 14.7: Procedure for Retrieving or Setting a Formatted State

coordinate system using any representation defined in GMAT. Hence the procedure for building the state for display to the user potentially involves both a coordinate transformation and an element conversion, as shown in the figure.

Conversion of the PropState data for display is shown in the top diagram in the figure. The state vector is requested using the GetStateString method, which contains three parameters: the target representation in the toType parameter, the name of the target coordinate system in the toCoords parameter, and a pointer to an instance of the target coordinate system. The SpaceObject has a pointer to a base coordinate system, along with the name of the base system. If these match the target coordinate system, then the coordinate conversion step can be skipped; otherwise, the internal state vector in the PropState is converted into the target coordinate system. The resulting intermediate state vector is then converted into a StringArray in the target representation using the ToString() method on the SpaceObject's representation converter.

The lower diagram in Figure 14.7 shows the inverse process, used to set the state vector on a SpaceObject through the SetStateFromString method. This method has four parameters: the input state in the StringArray parameter stateString, the representation that that StringArray uses (fromType), the name of the coordinate system (fromCoords) used for the input state, and a pointer to an instance of that coordinate system (fromCS). First the input state is converted into a Cartesian vector using the SpaceObject's RepresentationConverter. Once the Cartesian state has been constructed, it is transformed into the internal coordinate system and stored in the SpaceObject's PropState. Finally, the SpaceObject's text representation of the state is updated suing the Synchronize method[12]

14.6.2.2 Converting Single Elements

The procedure for setting single state elements is shown in Figure 14.8. This procedure is slightly more involved than the procedure employed to set a complete state because the procedure includes provisions for setting elements from one representation while maintaining a different text representation of the state in the textState buffer. This allows a user to script, for example, a semimajor axis for a spacecraft that stores its state in a Cartesian representation. Element setting is performed using the standard SetStringParameter method defined for all GmatBase subclasses.

[12]If both the representation and internal coordinate system for the PropState match the input values, the input state vector strings are copied into the testState member, and Synchronize() is not called.

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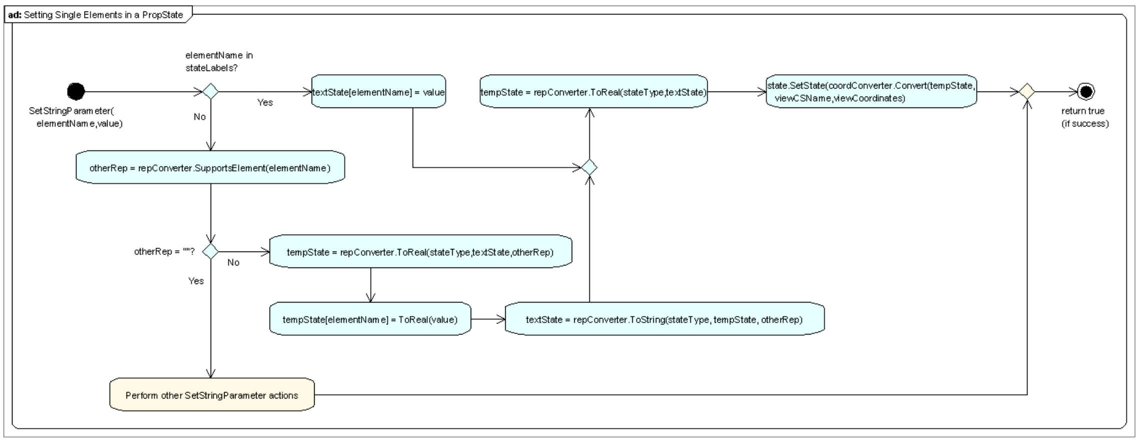
ad: Setting Single Elements in a PropState
elementName in stateLabels?
SetStringParameter(elementName,value)
Yes
No
textState[elementName] = value
tempState = repConverter.ToReal(stateType,textState)
state.SetState(coordConverter.Convert(tempState, viewCSName,viewCoordinates)
return true (if success)
otherRep = repConverter.SupportsElement(elementName)
otherRep = ""?
No
Yes
tempState = repConverter.ToReal(stateType,textState,otherRep)
tempState[elementName] = ToReal(value)
textState = repConverter.ToString(stateType, tempState, otherRep)
Perform other SetStringParameter actions

Figure 14.8: Procedure for Setting a Single Element in the State

The procedure employed for setting a single element when the element's name is a member of the current state representation is straightforward. The string containing the new element data in inserted into the textState string array, converted into a real vector in Cartesian coordinates by the representation converter, and then into the internal coordinate system by the coordinate system converter. This state is set on the PropState.

If the element is not a member of the current representation, the procedure is slightly more complicated. The textState is converted from the current state type into a vector of real numbers in the representation containing the element that is being set. The element is set to the input value, and the resulting vector is converted back into the textState StringArray. Then the textState is converted into the internal representation and coordinate system as described in the previous paragraph.

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Chapter 15

Spacecraft Hardware

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Chapter 14 described the structure of the core spacecraft model used in GMAT. This chapter examines the components that can be used to extend the spacecraft model to include models of hardware elements needed to model finite maneuvers and sensor measurements.

15.1 The Hardware Class Structure

15.2 Finite Maneuver Elements

15.2.1 Fuel tanks

15.2.2 Thrusters

15.3 Sensor Modeling in GMAT

GMAT does not contain sensor modeling capabilities at this time. The Hardware class infrastructure was designed to support sensor modeling at a later date.

15.4 Six Degree of Freedom Model Considerations

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Chapter 16

Attitude

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16.1 Introduction

GMAT provides the capability to model the attitude of a spacecraft. The attitude can be computed in any of three different ways: kinematically, by performing six-degree-of-freedom calculations, or by reading an attitude file (format(s) TBD). The current version of GMAT has only two types of kinematic modeling available; other methods are to be implemented at a later date.

16.2 Design Overview

When the user creates a Spacecraft object, via the GUI or a script, and s/he needs to compute or report the attitude of that spacecraft at one or more times during the run, s/he must specify a type of attitude for the spacecraft. The user must also set initial data on the spacecraft attitude.

A Spacecraft object therefore contains a pointer to one Attitude object, of the type specified by the user. This object will need to be created and set for the spacecraft using its SetRefObject method. The spacecraft object contains a method to return its attitude as a direction cosine matrix, and a method to return its angular velocity.

GMAT can model several different types of attitude, as mentioned above, each computing the attitude differently. However, since the types of attitude representations are common to all models, many of the data and methods for handling attitude are contained in a base class, from which all other classes derive.

The base class for all attitude components is the Attitude class. It contains data and methods required to retrieve spacecraft attitude and attitude rate data. The method that computes the attitude is included as a pure virtual method, and must be implemented in all leaf classes.

The base Attitude class contains methods that allow the user, the spacecraft, or other GMAT subsystems, to request attitude and attitude rate data in any of several different parameterizations. Attitude may be returned as a quaternion, a direction cosine matrix, or a set of Euler angles and a sequence. An attitude rate is retrievable as an angular velocity or as an Euler axis and angle (computed using the Euler sequence).

Also included in the base Attitude class are many static conversion methods, allowing other parts of GMAT to convert one attitude (or attitude rate) parameterization to another, depending on its needs, without having to reference a specific spacecraft or attitude object.

As mentioned above, GMAT includes several different attitude models. Kinematic attitude propagation options are 1) a Coordinate System Fixed (CSFixed) attitude; 2) a Spinner attitude; and 3) Three-Axis Stabilized attitude (TBD).

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To implement these, GMAT currently has a Kinematic class that is derived from the Attitude class. The CSFixed (Coordinate System Fixed) and Spinner attitude classes derive from the Kinematic class and, as leaf classes, contain implementations of the method, inherited from the base class Attitude, that computes the attitude at the requested time.

16.3 Class Hierarchy Summary

This section describes the current attitude classes in GMAT, summarizing key features and providing additional information about the class members. Figure 16.1 presents the class diagram for this subsystem.

16.3.0.1 Attitude

The Attitude class is the base class for all attitude classes. Any type of attitude that is created by user specification, via a script or the GUI, will therefore include all public or protected data members and methods contained in the Attitude class. Key data and methods are:

Data members

- **eulerSequenceList**: a list of strings representing all of the possible Euler sequences that may be selected by the user
- **refCSName**: the name of the reference coordinate system - the user must supply this
- **refCS**: a pointer to the reference coordinate system - this must be set using the attitude object's SetRefObject method
- **initialEulerSeq**: an UnsignedIntArray containing the three values of the initial Euler sequence
- **initialEulerAng**: an Rvector3 containing the three initial Euler angles (degrees)
- **initialDcm**: an Rmatrix33 containing the initial direction cosine matrix
- **initialQuaternion**: Rvector representation of the initial quaternion
- **initialEulerAngRates**: Rvector3 containing the initial Euler angle rates (degrees/second)
- **initialAngVel**: Rvector3 containing the initial angular velocity (degrees/second)

Methods

- **GetEpoch()**: returns the epoch for the attitude
- **SetEpoch(Real toEpoch)**: sets the value for the attitude; this method is called by the GUI, script interpreter or spacecraft
- **SetReferenceCoordinateSystemName(const std::string &refName)**: sets the reference coordinate system name
- **GetEulerSequenceList()**: returns a list of strings representing all possible Euler sequence values
- **GetQuaternion(Real atTime)**: returns the quaternion representation of the attitude, computed at the A1Mjd time atTime
- **GetEulerAngles(Real atTime)**: returns the Euler angle representation of the attitude, computed at the A1Mjd time atTime

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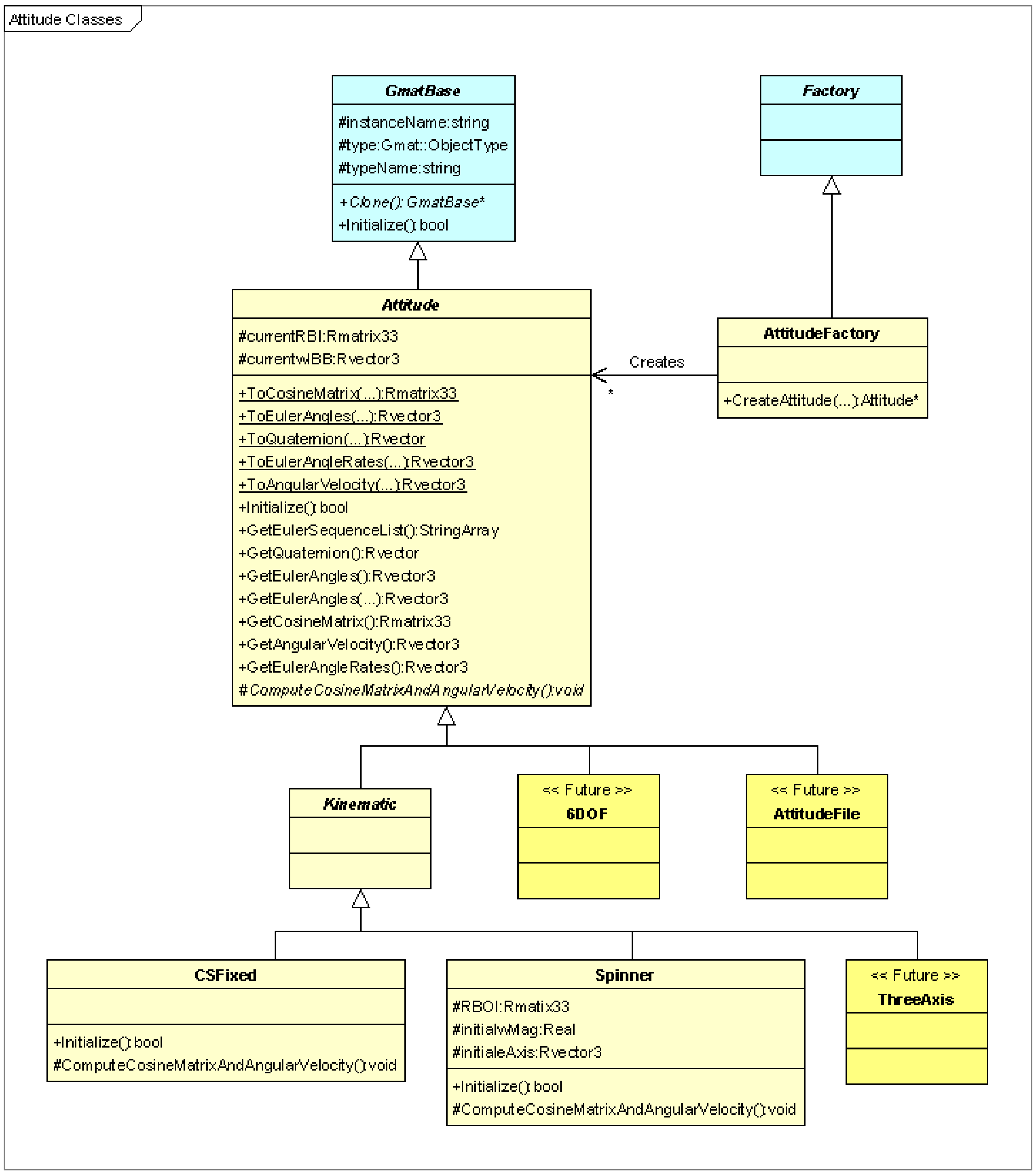
Attitude Classes
GmatBase
#instanceName:string
#type:Gmat::ObjectType
#typeName:string
+Clone(): GmatBase*
+Initialize(): bool
Factory
Attitude
#currentRBI:Rmatrix33
#currentwIBB:Rvector3
+ToCosineMatrix(...):Rmatrix33
+ToEulerAngles(...):Rvector3
+ToQuaternion(...):Rvector
+ToEulerAngleRates(...):Rvector3
+ToAngularVelocity(...):Rvector3
+Initialize(): bool
+GetEulerSequenceList():StringArray
+GetQuaternion():Rvector
+GetEulerAngles():Rvector3
+GetEulerAngles(...):Rvector3
+GetCosineMatrix():Rmatrix33
+GetAngularVelocity():Rvector3
+GetEulerAngleRates():Rvector3
#ComputeCosineMatrixAndAngularVelocity():void
Creates
*
AttitudeFactory
+CreateAttitude(...):Attitude*
Kinematic
<< Future >>
6DOF
<< Future >>
AttitudeFile
CSFixed
+Initialize(): bool
#ComputeCosineMatrixAndAngularVelocity():void
Spinner
#RBOI:Rmatix33
#initialwMag:Real
#initialeAxis:Rvector3
+Initialize(): bool
#ComputeCosineMatrixAndAngularVelocity():void
<< Future >>
ThreeAxis

Figure 16.1: Attitude Classes

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- **GetCosineMatrix(Real atTime)**: returns the direction cosine matrix representation of the attitude, computed at the A1Mjd time atTime
- **GetAngularVelocity(Real atTime)**: returns the angular velocity representation of the attitude rate, computed at the A1Mjd time atTime
- **GetEulerAngleRates(Real atTime)**: returns the Euler angle rates representation of the attitude rate, computed at the A1Mjd time atTime

In addition to class methods, there are several static methods in the base Attitude class that may be used without instantiating an object of type Attitude. These are all methods to convert between attitude representations or between attitude rate representations (angles are assumed to be in radians). They are:

- **ToCosineMatrix(const Rvector &quat1)**: converts the input quaternion to a direction cosine matrix
- **ToCosineMatrix(const Rvector3 &eulerAngles, Integer seq1, Integer seq2, Integer seq3)**: converts the input Euler angles and sequence to a direction cosine matrix
- **ToEulerAngles(const Rvector &quat1, Integer seq1, Integer seq2, Integer seq3)**: converts the input quaternion to Euler angles, given the input Euler sequence
- **ToEulerAngles(const Rmatrix33 &cosMat, Integer seq1, Integer seq2, Integer seq3)**: converts the input direction cosine matrix to Euler angles, given the input Euler sequence
- **ToQuaternion(const Rvector3 &eulerAngles, Integer seq1, Integer seq2, Integer seq3)**: converts the input set of Euler angles and sequence to a quaternion
- **ToQuaternion(const Rmatrix33 &cosMat)**: converts the input direction cosine matrix to a quaternion
- **ToEulerAngleRates(const Rvector3 angularVel, Integer seq1, Integer seq2, Integer seq3)**: converts the input angular velocity to Euler angle rates, using the input Euler sequence
- **ToEulerAngleRates(const Rvector3 eulerRates, Integer seq1, Integer seq2, Integer seq3)**: converts the input Euler angle rates to angular velocity, using the input Euler sequence

16.3.0.2 Kinematic

The Kinematic class is the base class for the kinematic models: Coordinate System Fixed, Spinner, and Three-Axis Stablized (TBD). At this time, there are no additional data members or methods for this class.

16.3.0.3 CSFixed

The CSFixed class models a Coordinate System Fixed attitude. The user supplies the initial attitude and specifies the reference coordinate system, from the current set of default and user-defined coordinate systems, to which the attitude is fixed. Since the attitude is fixed to this coordinate system, no initial attitude rate need be provided. The code in this class then computes the attitude at a requested time using the initial input data and the rotation matrix between the reference coordinate system and the inertial coordinate system at the specified time, obtained from the Coordinate System subsystem. There are no significant data members.

Methods

- **ComputeCosineMatrixAndAngularVelocity(Real atTime)**: computes the direction cosine matrix and angular velocity at the requested time; these data can then be retrieved in other representations as well

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16.3.0.4 Spinner

This class models a Spinner attitude. The user must supply an initial attitude and reference coordinate system when initializing a Spinner attitude. In addition, s/he must provide an initial attitude rate. This rate does not change over time, for this model. The initial epoch is expected to be an A1Mjd time, input as a Real, and is assumed to be the same as the orbit epoch (i.e. when the orbit epoch is set, the spacecraft knows to use that epoch for the attitude as well). This class can then compute the attitude at a specified time, using the initial input data and the rotation matrix from the reference coordinate system to the inertial coordinate system at the epoch time. It contains some protected data members to store data computed on initialization.

Methods

- **ComputeCosineMatrixAndAngularVelocity(Real atTime)**: computes the direction cosine matrix and angular velocity at the requested time; these data can then be retrieved in other representations as well

16.4 Program Flow

After an Attitude object is created and passed to a Spacecraft object, the initial data must be set. Then, as it is for most objects, the Initialize method must be called on the attitude. After that, the Attitude object is ready to compute the spacecraft attitude at any time requested.

16.4.1 Initialization

As mentioned above, the user must specify attitude initial data for a spacecraft, via the GUI or the script. An example script appears here:

```
%-----------------------------------------------------------------------
%------------------ Spacecraft Attitude Mode ----------------------------
%-----------------------------------------------------------------------
Sat.AttitudeMode = {Kinematic, 6DOF, FromFile};
Sat.KinematicAttitudeType = { Spinner, CSFixed};  % 3-Axis TBD

%-----------------------------------------------------------------------
%------------------ Spacecraft Attitude Coordinate System ---------------
%-----------------------------------------------------------------------
Sat.AttitudeCoordinateSystem = MJ2000Ec;

%-----------------------------------------------------------------------
%------------- Spacecraft Attitude Initial Data ------------------------
%-----------------------------------------------------------------------
Sat.AttitudeStateType = {EulerAngles, Quaternion, DCM};
Sat.EulerAngleSequence = {123, 132, 213, 312, ... 321};
Sat.EulerAngle1 = 5.0;    % degrees
Sat.EulerAngle2 = 10.0;    % degrees
Sat.EulerAngle3 = 15.0;    % degrees
% Sat.q1 = 0.0;   % these are set if the type is Quaternion
% Sat.q2 = 0.0;
% Sat.q3 = 0.0;
% Sat.q4 = 1.0;
% Sat.DCM11 = 1.0;     % set if attitude type is DCM
```

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```
% Sat.DCM12 = 0.0;
...
% Sat.DCM33 = 1.0;

Sat.AttitudeRateStateType = {EulerAngleRates, AngularVelocity};
Sat.EulerAngleRate1 = 5.0;
Sat.EulerAngleRate2 = 5.0;
Sat.EulerAngleRate3 = 5.0;
% Sat.AngularVelocityX = 5.0;  % set if attitude rate type is angular velocity
% Sat.AngularVelocityY = 5.0;
% Sat.AngularVelocityZ = 5.0;
```

In all models, the initial attitude may be input as a direction cosine matrix, a quaternion, or a set of Euler angles and sequence. The initial rate may be input as an angular velocity or as an Euler axis and angle (to be used along with an Euler sequence from the input attitude specification).

16.4.2 Computation

GMAT uses the initial data to compute the attitude at any time requested. For better performance, GMAT keeps track of the last attitude computed, and the time for which it was computed, and only recomputes when necessary.

For the two models implemented thus far, it is necessary for GMAT to compute a rotation matrix (and for the CSFixed attitude, its derivative as well) between the inertial (MJ2000 Equatorial) coordinate system and the specified reference coordinate system. GMAT has this capability, implemented in its Coordinate System subsystem.

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Chapter 17

Script Reading and Writing

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GMAT stores mission modeling data in a text file referred to as a GMAT script file. The scripting language used in GMAT is documented in [UsersGuide]. This chapter describes the architecture of the ScriptInterpreter subsystem, which is used to read and write these files.

GMAT scripts, like MATLAB scripts, are case sensitive. In the sections that follow, script elements, when they appear, will be written with the proper case. That said, this chapter is not meant to be a comprehensive text on GMAT scripting. Script lines and portions of lines are presented here for the purpose of describing the workings of the ScriptInterpreter and related classes.

17.1 Loading a Script into GMAT

Figure 17.1 shows the sequence followed when GMAT opens a script file and reads it, constructing internal objects that model the behavior dictated by the script. Some of the detailed work performed in this process is dictated by the properties of the objects; the figure provides the general flow through the process. The figure is color coded to reflect three basic groupings of actions taken while reading a script file. The large scale flow through the ScriptInterpreter system is colored blue; actions that affect configured objects are colored green, and actions related to the time ordered Mission Sequence are colored yellow. This figure shows a fair amount of complexity; the section describing the subsystem classes breaks this complexity into more manageable pieces.

When a user instructs GMAT to read a script, either from the command line or from the graphical user interface, the Moderator receives an InterpretScript() command containing the name of the file that needs to be read. This command calls the Interpret() command on the ScriptInterpreter, which uses the classes and methods provided in the Interpreter subsystem and described in this chapter, to read the script and configure the objects described in it.

There are four types of physical lines in a script file: (1) comment lines, which start with a percent sign (%), (2) object definition lines, which start with the word "Create", (3) command lines, which start with the text assigned to a GmatCommand class, and (4) assignment lines, which optionally start with the word "GMAT"[1]. Comments can be appended on the end of script lines; when that happens, all of the text following the percent sign comment delimiter is associated with the line and referred to as an inline comment in this document.

[1]The GMAT keyword is automatically inserted on assignment lines when a script is written. The ScriptReadWriter class has an internal flag that toggles this feature on and off when writing, so that future versions of GMAT can provide the ability to turn this feature on or off.

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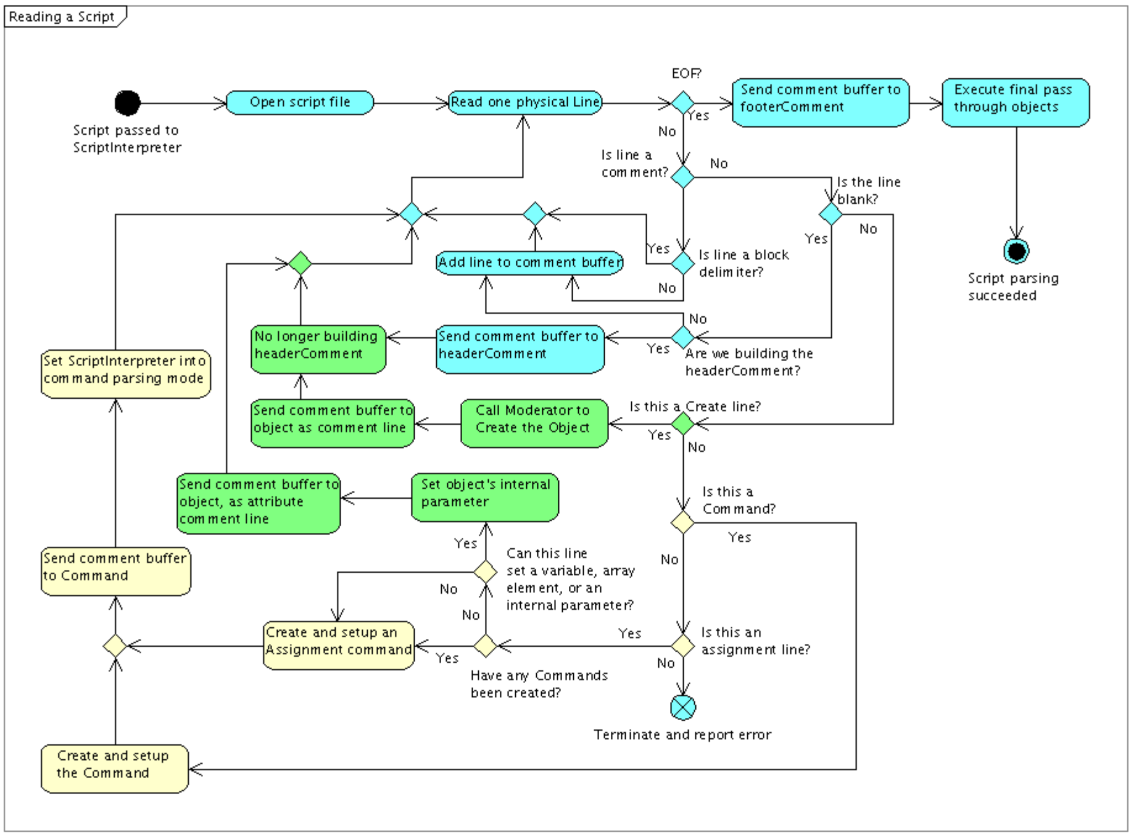
Reading a Script
Script passed to ScriptInterpreter
Open script file
Read one physical Line
EOF?
Yes
No
Send comment buffer to footerComment
Execute final pass through objects
Script parsing succeeded
Is line a comment?
No
Is the line blank?
Yes
No
Yes
Is line a block delimiter?
No
Add line to comment buffer
No
Are we building the headerComment?
Yes
Send comment buffer to headerComment
No longer building headerComment
Send comment buffer to object as comment line
Call Moderator to Create the Object
Is this a Create line?
Yes
No
Set ScriptInterpreter into command parsing mode
Send comment buffer to object, as attribute comment line
Set object's internal parameter
Is this a Command?
Yes
No
Can this line set a variable, array element, or an internal parameter?
Yes
No
No
Send comment buffer to Command
Create and setup an Assignment command
Yes
Have any Commands been created?
Yes
Is this an assignment line?
No
Terminate and report error
Create and setup the Command

Figure 17.1: Sequence Followed when Loading a Script into GMAT

The script file is read one "logical block" at a time, using the ScriptReadWriter helper class. A logical block consists of one or more physical lines in the script file. Each logical block can have three elements: one or more lines of opening comments (identified with leading % characters), an instruction that tells GMAT to do something, and an inline comment appended to the end of the instruction. Each logical block has at least one of these elements, but need not have all three. Inline comments cannot exist on their own – they require the instruction component.

The instruction element can be split up over multiple physical lines in the script file, as long as each physical line is terminated by ellipsis (...). Inline comments for a multiline instruction must be placed at the end of the last physical line of the block. White space at the beginning of each line of an instruction is discarded. Lines that are continued using ellipsis markers pick up an extra space in place of the ellipsis characters. Instructions in a logical blocks can be terminated with a semicolon; this character has no effect in GMAT[2]. Once a logical block has been read from the file using these rules, it is analyzed to determine the type of information contained in the block.

The ScriptInterpreter treats comment lines that start with the sequence " `%-------`" as a special type of comment, called a block delimiter. These lines are ignored by the ScriptInterpreter when reading a script. Details concerning comment handling are presented later in this chapter, as are the detailed control flow procedures GMAT follows when working with scripts.

[2]Semicolons are used in MATLAB to suppress display of the result of the line of text. Since GMAT scripts can be read in the MATLAB environment, the GMAT scripting language allows, but does not require, a semicolon at the end of an instruction.

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17.1.1 Comment Lines

Comments in GMAT scripts are started with the percent sign (%). Comments can exist in one of two different forms: either on individual lines, or inline with other GMAT scripting, as shown here:

```
1     %---------------------------------------------------------------------
2     %-----------             Spacecraft Components            ------------
3     %---------------------------------------------------------------------
4
5     % This is the main spacecraft in the mission.
6     Create Spacecraft mainSat     % Not to be confused with MaineSat
7     GMAT mainSat.X  = 42165.0     % Start at GEO distance
8     GMAT mainSat.Y  = 0.0
9     GMAT mainSat.Z  = 0.0
10         % This is the velocity part.  I've intentionally made the
11         % indentation ugly to make a point: leading white space is
12         % preserved in comment lines.
13    GMAT mainSat.VX = 0.0         % But slower than a circular orbit
14    GMAT mainSat.VY = 1.40
15    GMAT mainSat.VZ = 0.95
```

Lines 1-3 and lines 5 and 10-12 are individual comment lines. Lines 6, 7 and 13 contain inline comments. The individual comment lines fall into two categories: lines 1-3 here are block delimiter lines, denoted by the delimiter identifier at the start of each line, while lines 5 and 10-12 are user supplied comments. The ScriptInterpreter inserts the block comments automatically when a script is written, and skips over those comment lines when reading the script. The user provided comments like lines 5 and 10-12 are stored with the data provided immediately after those lines. In this script snippet, for example, the comment "`% This is the main spacecraft in the mission`" is associated with the object creation line, and stored as an object level comment for the Spacecraft named mainSat. The comments on lines 10-12:

```
10         % This is the velocity part.  I've intentionally made the
11         % indentation ugly to make a point: leading white space is
12         % preserved in comment lines.
```

are associated with the assignment line "`GMAT mainSat.VX = 0.0`", and stored, including linebreaks, in the data member associated with the object parameter mainSat.VX. Each entire line is stored, including the leading whitespace, so that the ScriptInterpreter can reproduce the comment verbatim.

Inline comments are stored with the GMAT structure that most closely matches the comment line. Hence the inline comment on line 6 is stored in the data member associated with the Spacecraft mainSat, while the inline comments on lines 7 and 13 are stored incorresponding members of a StringArray in that object that maps the comment to the corresponding spacecraft parameters: mainSat.X and mainSat.VX for this example.

The ScriptInterpreter makes these associations when it finds comments in a script. Comment lines are buffered in the ScriptInterpreter, and written to the next resource encountered in the script file. The GmatBase class contains the data structures and interfaces needed to implement this functionality. These interfaces are shown in Figure 17.2.

There are two additional types of comment blocks that GMAT manages. Comments that occur at the beginning and at the end of a script are saved in the ScriptInterpreter in case they are needed for display on the GUI or when writing a script. The header comment consists of all comment lines found at the start of a script to the first blank line in the script. If an instruction is detected before a blank line, the header comment is set to the empty string. Similarly, the script's footer comment consists of all comments that are found after the final instruction in the script. If no comments are found after the final instruction, the footer comment is set to the empty string.

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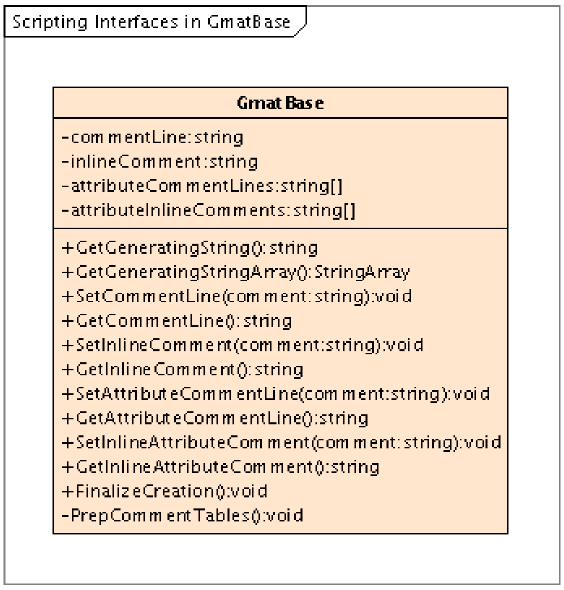
Scripting Interfaces in GmatBase
GmatBase
-commentLine:string
-inlineComment:string
-attributeCommentLines:string[]
-attributeInlineComments:string[]
+GetGeneratingString():string
+GetGeneratingStringArray():StringArray
+SetCommentLine(comment:string):void
+GetCommentLine():string
+SetInlineComment(comment:string):void
+GetInlineComment():string
+SetAttributeCommentLine(comment:string):void
+GetAttributeCommentLine():string
+SetInlineAttributeComment(comment:string):void
+GetInlineAttributeComment():string
+FinalizeCreation():void
-PrepCommentTables():void

Figure 17.2: Scripting Interfaces in the User Classes

17.1.2 Object Definition Lines

When the ScriptInterpreter detects an object definition instruction (starting with the word "Create"), it breaks the line into three pieces: the initial "Create" keyword, the type name for the object that needs to be created, and one or more names used for the created objects. When multiple objects are created on a single line, the object names are separated using commas[3]. Three examples of object definition are provided here:

```
    Create Spacecraft MMSRef;
    Create Spacecraft MMS1, MMS2, MMS3, MMS4;
    Create Array squareArray[3, 3] notSquare[4, 7] vector[6]
```

The first script line here ("`Create Spacecraft MMSRef;`") demonstrates basic object creation. When the ScriptInterpreter parses this line, it calls the Moderator and instructs it to create an instance of the Spacecraft class named MMSRef. The Moderator calls the appropriate factory (the spacecraft factory in this case) and obtains the object. It then adds this object to the configured objects, and returns the object pointer to the ScriptInterpreter. The ScriptInterpreter validates the returned pointer, ensuring that the pointer is not NULL, performs finalization on the object by calling the "`FinalizeCreation()`" method, and then moves to the next line. If no factory is available to create the object, the Moderator throws an exception which the ScriptInterpreter handles. The ScriptInterpreter throws an expection that is displayed to the user, indicating the line number of the offending line, the nature of the error encountered, and, in quotation marks, the text of the line that caused the error.

The second script line ("`Create Spacecraft MMS1, MMS2, MMS3, MMS4;`") works identically, calling the Moderator four consecutive times to create the four spacecraft named MMS1, MMS2, MMS3, and MMS4. Each object is created, validated by testing the returned pointer to see if it is NULL, and finalized using

[3]Note that commas are required. This restriction comes from the interoperability requirement between GMAT and MATLAB. If the commas are omitted, then when MATLAB parses the line, it creates a cell array for the elements following the Create keyword. A similar constraint applies to all script instructions when the blocks in the instruction exist outside of parentheses, brackets, or braces.

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`FinalizeCreation()`. The ScriptInterpreter loops through the list of requested objects, and performs this procedure one name at a time.

The array creation line ("`Create Array squareArray[3, 3] notSquare[4, 7] vector[6]`") requires a bit of additional parsing. Arrays require the count of the number of rows and columns[4] in the array before it can be constructed. These counts are contained in square braces in the array creation line. Each array on the line has a separate field indicating this size. If a user specifies a single dimension for the array, as in the case of the array named `vector` in this example, that dimension is the column count for the object: `vector` as specified here is a 1 by 6 array. Once the size parameters have been parsed, the ScriptInterpreter proceeds as before: the Moderator is called and instructed to create an array with the desired dimensions. This array is created in the factory subsystem, added to the object configuration, and returned to the ScriptInterpreter for pointer validation. Once the pointer has been validated, the ScriptInterpreter executed the `FinalizeCreation()` method on the new object, and then proceeds to the next line of script.

17.1.3 Command Lines

If the logical block is not an object definition line, the ScriptInterpreter next checks to see if the line is a GMAT command. GMAT commands all start with the keyword assigned to the specific command; examples include `Propagate`, `For`, `Maneuver`, `Target`, and `BeginFiniteBurn`. A typical (though simple) command sequence in a script is shown here:

```
For i = 1 : 5
   Propagate propagator(satellite, {satellite.ElapsedDays = 1.0})
EndFor;
```

The command sequence is usually found after all of the objects used in the script have been defined and configured in the script file. A complete list of the commands available in the configuration managed GMAT code[5] can be found in the User's Guide[UsersGuide]. The ScriptInterpreter builds a list of commands in the system upon initialization. It uses this list to determine if a script line contains a command. If the first word in the script line is in the list of commands, the ScriptInterpreter calls the Moderator, requesting a command of the indicated type. The Moderator uses the factory subsystem to create the command. It then adds the command to the Mission Sequence using the `Append` method on the first command in the sequence. One item to note here: the commands manage the time ordering of the sequence through the `Append` interface of the GmatCommand classes; the ScriptInterpreter does not directly set the command sequence ordering.

Once a command has been created in the Moderator, the Moderator returns the new command to the ScriptInterpreter. At this point, the command has not yet been configured with the details of the script line that was used to create it. GMAT commands can be configured in one of two different ways: they can parse and configure internal data using methods inside the command, or they can receive configuration settings from the ScriptInterpreter. Only one of these options exists for each command – either the command is self-configuring, or it relies on the ScriptInterpreter for configuration. Self-configuring commands override the InterpretAction method defined in the GmatCommand base class to parse the script line; this approach allows the creation of commands that do not follow a generic configuration strategy. The default implementation of the InterpretAction method returns false, indicating that the ScriptInterpreter needs to complete the command configuration. Further details of command configuration can be found in Chapter 26.

The ScriptInterpreter takes the newly created command and passes the script line into it. Then the ScriptInterpreter calls the InterpretAction method on the command. If the InterpretAction method succeeds, the ScriptInterpreter considers the command fully configured, completing parsing for this line of script. If the InterpretAction method returns false, the ScriptInterpreter parses the rest of the command line and configures the command accordingly.

[4]GMAT does not support matrices with more than 2 dimensions at this time.

[5]Note that since commands are user objects, the command list can be expanded using a user defined library, as discussed in Chapter 32.

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17.1.4 Assignment Lines

The final type of logical block that the ScriptInterpreter can encounter is an assignment line. GMAT assignment lines all take the form

```
<<Left Hand Side>> = <<Right Hand Side>>
```

Assignment lines perform multiple purposes in GMAT. Assignment lines can be used to initialize the internal data for an object, to reset the value of a piece of internal data, to set one object's data to match another object's, or to perform custom calculations as described in Chapter 30. This complexity adds an underlying wrinkle to GMAT's internal structure when parsing an assignment line: assignment lines in a script can set object data or represent Assignment commands in the Control Sequence. The ScriptInterpreter tracks the state of a script while parsing; it starts the parsing sequence in "object" mode, and toggles into "command" mode when the first command is encountered. This mode switching has direct implications on the way assignment commands are handled: when in object mode, assignment commands can set the values of parameters on configured objects. In command mode, this parameter setting is deferred until the script is executed. The following script segment illustrates this difference:

```
1    Create Spacecraft sat;                          % Start in object mode
2    Create Propagator prop;
3    GMAT sat.SMA = 10000.0;                         % Set some object parameters
4    GMAT sat.ECC = 0.25;
5    GMAT sat.TA = 0.0;
6
7    Propagate prop(sat, {sat.Apoapsis});              % Switches to command mode
8    GMAT sat.SMA = 12500.0;                           % Brute force circularization
9    GMAT sat.ECC = 0.0;
10   Propagate prop(sat, {sat.ElapsedDays = 1.0});
```

The assignment lines in this script all begin with the GMAT keyword. The first three assignments (lines 3 - 5) are used to set the internal data on the Spacecraft named sat. When the ScriptInterpreter builds the Propagate command on line 7, it switches into command mode. The next assignment lines, lines 8 and 9, do not set the internal data on sat during script parsing. Instead, they each construct an Assignment command which is inserted into the command sequence, configured to set the internal Spacecraft data when that Assignment command fires during the run of the mission. In effect, the assignments made here are postponed; the Spacecraft parameter is set to the scripted value when the Assignment command executes for the scripted line, rather than when the ScriptInterpreter parsed the line of script. This toggling from object mode into command mode makes it possible for a user to reset object properties partway through the execution of a script; other uses include the ability to alter the mass of the spacecraft, modeling the release of a stage during a mission, and adding new spacecraft to or removing spacecraft from a formation that has already propagated for a period of time.

When an assignment line is parsed by the ScriptInterpreter, the ScriptInterpreter first breaks the line into three pieces: the left hand side, the equals sign, and the right hand side. If the equals sign is missing, the ScriptInterpreter throws an exception and exits. The left hand side (LHS) may start with the keyword "GMAT". If it does, this word is ignored by the ScriptInterpreter[6]. After the optional keyword, the LHS of the line can consist of one and only one entity: either an object parameter, an object name, or an array element identity, as shown here:

```
GMAT sat.X = ...                        % An object parameter
forceModel.Gravity.Earth.Degree = ...   % A nested object parameter
```

[6]The GMAT keyword simplifies script interchangability between GMAT and MATLAB; the GMAT keywork can be used to tell MATLAB that the line is a special construct, built for GMAT, when a script file is read in the MATLAB environment.

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```
3      sat2 = ...                                 % Object assignment
4      GMAT squareArray(1,3) = ...                % Array element setting
5      vector(3) = ...                            % More array element setting
6      myFormation.Add = ...
7      GMAT SatReplacement1.Z = ...               % Another object parameter
```

Note that the GMAT preface on lines 1, 4, and 7 is optional. When a valid right hand side (RHS) is provided, all of these lines will be parsed correctly by the ScriptInterpreter. Line 2 deserves some special consideration here. This line sets a parameter on an object owned by a force model. The ScriptInterpreter includes parsing capabilities that it uses to drill into owned objects like this one; these capabilities are described in the class descriptions later in this chapter.

The right side of an assignment line provides the data that is set for the left side. This data can be a number, a string, an object name, a GMAT or MATLAB function, an array or array element, or an equation. Working from the partial lines presented earlier, some examples of complete assignment lines are:

```
1      GMAT sat.X = 7218.88861988453;         % A number
2      forceModel.Gravity.Earth.Degree = 12   % An integer for a nested object
3      sat2 = sat3                            % All object attributes (except the name)
4      GMAT squareArray(1,3) = sat1.VZ        % Array element set to an object property...
5      vector(3) = BuildZComponent(sat2)      % ...and to a function return value
6      myFormation.Add = SatReplacement1      % A string -- here an object name
7      GMAT SatReplacement1.Z = vector(3);    % An array element
```

The ScriptInterpreter provides the interfaces required to configure these RHS elements as well. It first analyzes the RHS string and determines the type of expression encoded in the string. The string is then decomposed into its constituent elements, which are configured based on the detected type information. If the ScriptInterpreter is operating in object mode, it remains in object mode as long as the LHS is an object parameter and the RHS provides data compatible with that parameter. If this condition is not met, then the ScriptInterpreter builds an Assignment command for the assignment line, and sets up the objects for this command.

Once all of the lines in a script file have been parsed and the corresponding actions taken, the ScriptInterpreter takes a final pass through the objects in memory. This final pass is used to set intermediate pointers where needed for the user interface – for instance, Spacecraft created in a script need to have pointers set to referenced coordinate systems so that conversions between element representations can be performed on the user interface.

17.2 Saving a GMAT Mission

The procedure followed when writing a script file from GMAT is markedly simpler than that followed when parsing a script file. Figure 17.3 shows the basic control flow exercised when the ScriptInterpreter writes a script file. First the ScriptInterpreter initializes itself if it has not been initialized previously, and opens the output stream that is the target of the script. Then the ScriptInterpreter retrieves the configured items by type, and writes these items to the output stream. Comment lines are inserted at appropriate places during this process, as indicated in the figure. After all of the configured objects have been written, the ScriptInterpreter walks through the command sequence, writing the commands out in order. This completes the script writing process.

Script writing is significantly simplified because each user configurable object in GMAT includes a method, `GetGeneratingString()`, which returns the full script string required to reproduce the object. This interface is included in the GmatBase class diagram, Figure 17.2. The `GetGeneratingString()` method essentially serializes any GMAT object derived from GmatBase (see Section 9.3). When the `GetGeneratingString` function is called, the object builds this string based on its internal data. Command strings consist of a

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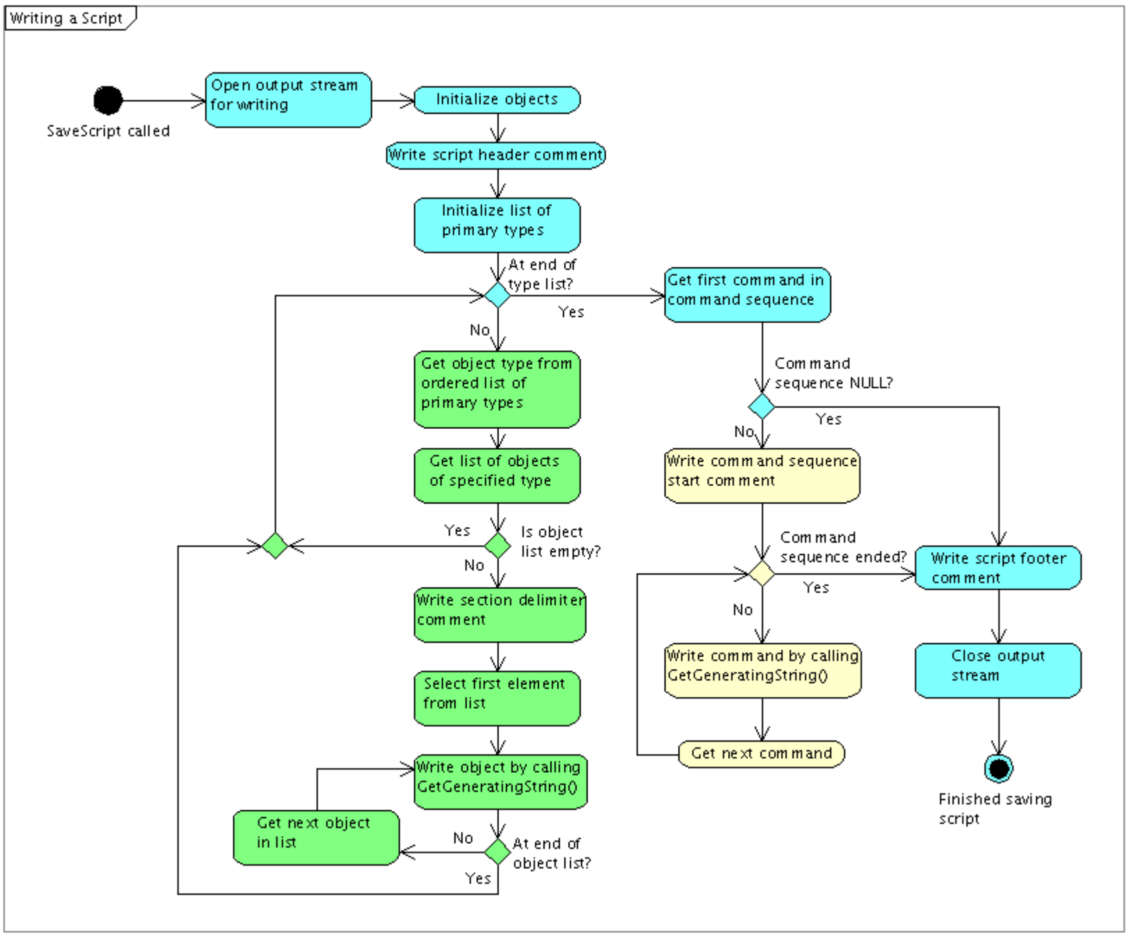
Writing a Script
SaveScript called
Open output stream for writing
Initialize objects
Write script header comment
Initialize list of primary types
At end of type list?
Yes
No
Get first command in command sequence
Command sequence NULL?
Yes
No
Get object type from ordered list of primary types
Get list of objects of specified type
Write command sequence start comment
Yes
Is object list empty?
No
Command sequence ended?
Yes
No
Write script footer comment
Write section delimiter comment
Write command by calling GetGeneratingString()
Close output stream
Select first element from list
Get next command
Write object by calling GetGeneratingString()
Finished saving script
Get next object in list
No
At end of object list?
Yes

Figure 17.3: Sequence Followed when Writing a Script

single instruction, optionally decorated with preceding comments or inline comments. Configured objects build multi-instruction strings, consisting of an opening "Create" line and the assignment lines required to set the internal object parameters. Details of this process are shown in Figure 17.4. The ScriptInterpreter just calls this method sequentially on the objects to write the requested script.

This same facility is used at several other places in GMAT. The MATLAB interface supports serialization and passing of GMAT objects into MATLAB classes. This support is also provided by the `GetGeneratingString()` method. Similarly, the GMAT graphical user interface includes a popup window that shows scripting for all GMAT objects and commands. The `GetGeneratingString()` method is called to populate this window.

17.3 Classes Used in Scripting

The preceding sections described the process followed when reading and writing scripts. This section outlines how those processes are implemented in GMAT.

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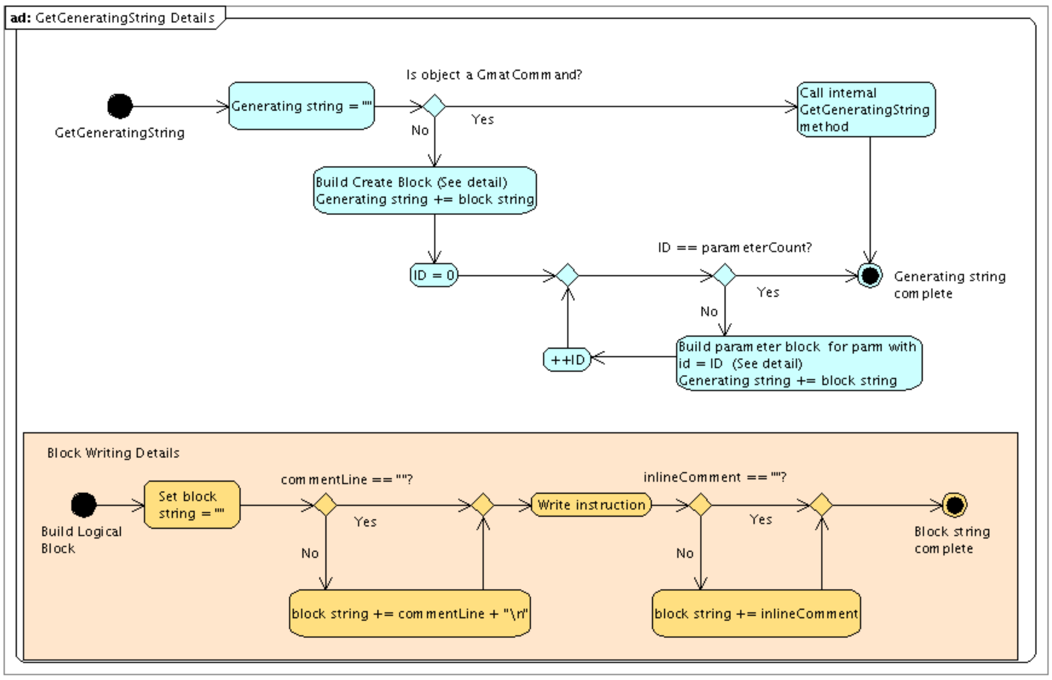
ad: GetGeneratingString Details
GetGeneratingString
Generating string = ""
Is object a GmatCommand?
Yes
No
Call internal GetGeneratingString method
Build Create Block (See detail) Generating string += block string
ID = 0
ID == parameterCount?
Yes
No
Generating string complete
Build parameter block for parm with id = ID (See detail) Generating string += block string
++ID
Block Writing Details
Build Logical Block
Set block string = ""
commentLine == ""?
Yes
No
block string += commentLine + "\n"
Write instruction
inlineComment == ""?
Yes
No
block string += inlineComment
Block string complete

Figure 17.4: Sequence Followed by `GmatBase::GetGeneratingString()` when Writing a Script

17.3.1 The Script Interpreter

The ScriptInterpreter is the class that manages the reading and writing of script files for GMAT. It makes use of several helper classes when actually reading and writing scripts, along with core Interpreter functions from the Interpreter base class. Actions taken by the ScriptInterpreter can be broken into two categories: script reading and script writing. The complexity of these processes is shown in Figures 17.1 and 17.3. In this section, the Interpreter and ScriptInterpreter classes are described, along with their helper classes, the ScriptReadWriter and the TextParser. These classes are shown in Figure 17.5. Then the process followed to accomplish each of the reading and writing tasks is presented. Script reading is particularly complex, so the script reading procedure is broken into descriptions of the process followed for each of the four types of script blocks GMAT supports. The description of the class interactions performed when reading a script can be found in Section 17.4. The class interactions followed when writing a script are outlined in Section 17.4.

17.3.1.1 Global Considerations

The Interpreter subsystem used several components that exist at the program scope in GMAT. There are three enumerations used by the Interpreters that are defined in the Gmat namespace:

- **Gmat::ParameterType**: An enumeration used to identify the data type for internal parameters in GmatBase derived objects.
- **Gmat::WriteMode**: An enumeration that identifies the type of output requested from a call to an object's GetGeneratingString() method.
- **Gmat::BlockType**: An enumeration identifying the type of logical block parsed from a script.

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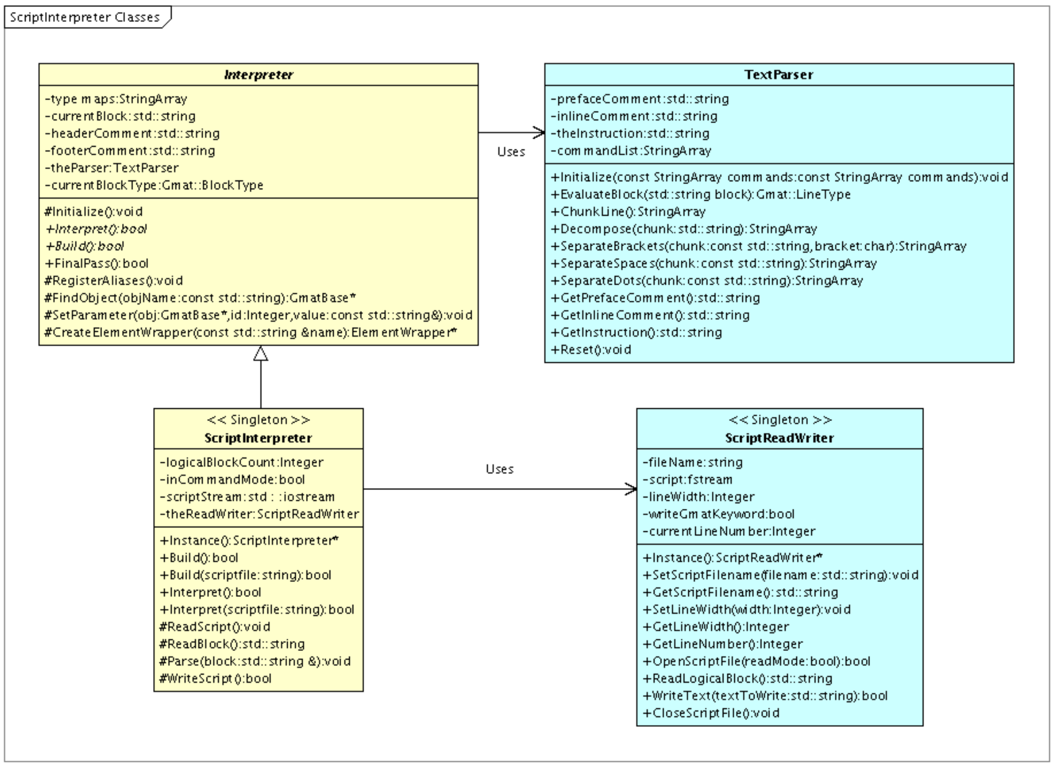
ScriptInterpreter Classes
Interpreter
-typemaps:StringArray
-currentBlock:std::string
-headerComment:std::string
-footerComment:std::string
-theParser:TextParser
-currentBlockType:Gmat::BlockType
#Initialize():void
+Interpret():bool
+Build():bool
+FinalPass():bool
#RegisterAliases():void
#FindObject(objName:const std::string):GmatBase*
#SetParameter(obj:GmatBase*,id:Integer,value:const std::string&):void
#CreateElementWrapper(const std::string &name):ElementWrapper*
Uses
TextParser
-prefaceComment:std::string
-inlineComment:std::string
-theInstruction:std::string
-commandList:StringArray
+Initialize(const StringArray commands:const StringArray commands):void
+EvaluateBlock(std::string block):Gmat::LineType
+ChunkLine():StringArray
+Decompose(chunk:std::string):StringArray
+SeparateBrackets(chunk:const std::string,bracket:char):StringArray
+SeparateSpaces(chunk:const std::string):StringArray
+SeparateDots(chunk:const std::string):StringArray
+GetPrefaceComment():std::string
+GetInlineComment():std::string
+GetInstruction():std::string
+Reset():void
<< Singleton >>
ScriptInterpreter
-logicalBlockCount:Integer
-inCommandMode:bool
-scriptStream:std::iostream
-theReadWriter:ScriptReadWriter
+Instance():ScriptInterpreter*
+Build():bool
+Build(scriptfile:string):bool
+Interpret():bool
+Interpret(scriptfile:string):bool
#ReadScript():void
#ReadBlock():std::string
#Parse(block:std::string &):void
#WriteScript():bool
Uses
<< Singleton >>
ScriptReadWriter
-fileName:string
-script:fstream
-lineWidth:Integer
-writeGmatKeyword:bool
-currentLineNumber:Integer
+Instance():ScriptReadWriter*
+SetScriptFilename(filename:std::string):void
+GetScriptFilename():std::string
+SetLineWidth(width:Integer):void
+GetLineWidth():Integer
+GetLineNumber():Integer
+OpenScriptFile(readMode:bool):bool
+ReadLogicalBlock():std::string
+WriteText(textToWrite:std::string):bool
+CloseScriptFile():void

Figure 17.5: Classes in the ScriptInterpreter Subsystem

The first two of these enumerations, ParameterType amd WriteMode, are used in a fairly rigid manner in the Interpreter subsystem. ParameterTypes are used to determine how to access the internal data on objects for reading and writing; the object is queried for the type of the internal parameter, and that parameter is accessed accordingly. For example, when a parameter value on an object needs to be set, the Interpreter use the results of this query to call the correct set method on the object – SetRealParameter for floating point data, SetIntegerParameter for integers, SetStringParameter for strings, and other calls for their corresponding types.

When calling the GetGeneratingString methods on objects, the Interpreters need to identify the style of text that is required. This style is identified using the identifiers in the WriteMode enumeration. The ScriptInterpreter uses the Gmat::SCRIPTING entry from this list. Objects that are passed to MATLAB use the Gmat::MATLAB_STRUCT entry, and so forth.

The BlockType enumeration has four members: COMMENT_BLOCK, DEFINITION_BLOCK, COMMAND_BLOCK, and ASSIGNMENT_BLOCK. These members are used to identify the type of logical block parsed from a script, as described in Section 17.4.

17.3.1.2 The ScriptInterpreter Class

The ScriptInterpreter class manages the script reading and writing process. Derived from the Interpreter class, this singleton[7] has methods that use a ScriptReadWriter to open and close file streams and to use those streams to perform the actions required to load and save GMAT scripts. The entry point methods that take input from the stream include the word "Interpret" in their names; the methods that launch the

[7]See Section B.1

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serialization of GMAT objects and that subsequently write them out to streams use the work "Build" as part of the method name.

The key ScriptInterpreter data members and methods are described below.

Class Attributes

- **Integer logicalBlockCount**: A counter that counts the logical blocks of script as they are read.
- **bool inCommandMode**: A flag that is used to detect when a script switches from object parameter mode into command mode, so that assignment blocks can be configured correctly.
- **std::iostream scriptStream**: The stream used for script reading or writing.
- **ScriptReadWriter* theReadWriter**: A pointer to the ScriptReadWriter used when reading or writing the script.

Methods

- **ScriptInterpreter* Instance()**: The method used to obtain the pointer to the singleton.
- **bool Build()**: Method used to write a script to the stream. This method calls WriteScript() to perform the actual work required when writing a script.
- **bool Build(const std::string &scriptfile)**: Method used to initialize the stream to an output file. This method calls Build() (above) after setting up the stream.
- **bool Interpret()**: Method used to read a script from the stream. This method calls the protected ReadScript() method to perform the actual script reading tasks.
- **bool Interpret(const std::string &scriptfile)**: Method used to initialize the stream to an input file. This method calls Interpret() (above) after setting up the stream.
- **void ReadScript()**: The method that controls script reading. This method is called by Interpret(). The process followed in the ScriptInterpreter::ReadScript() method and the methods it calls is shown in Figure 17.6 and the diagrams derived from it, and described in Section 17.4.
- **std::string ReadLogicalBlock()**: Method that obtains a logical block from teh ScriptReadWriter for the ReadScript() method.
- **void Parse(std::string &block)**: Method that interprets a logical block for the ReadScript() method.
- **bool WriteScript()**: Control method used to write a script. This protected method is called by the Build() method when a script needs to be written. The process followed in the WriteScript() method is shown in Figure 17.11 and described in Section 17.4.2.

17.3.1.3 The Interpreter Base Class

The Interpreter base class defines the interfaces into the Interpreter system, and provides functionality shared by all GMAT Interpreters. This class contains the data structures necessary to manage data that exists at the mission scope rather than at object scope, like header and footer comments.

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Class Attributes

- **StringArray type maps**: Lists of the names of classes of corresponding types of configurable objects. There are separate maps for commands (**commandMap**), hardware components (**hardwareMap**), forces (**physicalmodelMap**), solvers (**solverMap**), parameters (**parameterMap**), stopping conditions (**stopcondMap**), and functions (**functionMap**). These arrays are populated when the Interpreter is initialized.
- **std::string currentBlock**: the current logical block of script, used while parsing.
- **std::string headerComment**: The optional commentary, provided by the user, that precedes all instructions in a GMAT mission.
- **std::string footerComment**: The optional commentary, provided by the user, that completes all instructions in a GMAT mission.
- **TextParser theParser**: A TextParser used to pieces of text.
- **enum currentBlockType**: An identifier for the type of the current logical block of text, used when reading a script.

Methods

- **void Initialize()**: Fills or refreshes the type maps by retrieving the lists of type names from the Moderator.
- **bool Interpret()**: Retrieves input from a stream and translates it into GMAT actions. This abstract method is implemented by all derived Interpreters.
- **bool Build()**: Accesses GMAT objects and writes them to a stream. This abstract method is implemented by all derived Interpreters.
- **void FinalPass()**: Invoked after objects have been interpreted from a stream, this method sets pointers for object references that are required outside of the Sandbox, so that required functionality can be provided prior to initialization for a mission run. Derived Interperters should call this method as the last call in their Interpret() methods if internal pointers are not set during execution of the method.
- **void RegisterAliases()**: Some GMAT script identifiers can be accessed using multiple text strings. The RegisterAliases() method creates a mapping for these strings so that scripts are parsed correctly. The current GMAT system has five aliased parameter strings: "PrimaryBodies" and "Gravity" are both aliases for "GravityField" forces, "PointMasses" is an alias for 'a PointMassForce, "Drag" is an alias for a DragForce, and "SRP" is an alias for SolarRadiationPressure.
- **GmatBase* FindObject(const std::string objName)**: Method used to find a configured object.
- **void SetParameter(GmatBase *obj, const Integer id, const std::string &value)**: Method used to set parameters on configured objects. Note that while the input value is a string, it is converted to the correct type before being set on the object.
- **ElementWrapper* CreateElementWrapper(const std::string &name)**: Method used to create wrapper instances needed to use object properties, Parameters, array elements, and other types of object data inside of the commands that implement the Mission Control Sequence. The wrapper infrastructure is described in Section 26.4.3.

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17.3.2 The ScriptReadWriter

File management tasks necessary to scripting are provided by the ScriptReadWriter class. This class, a singleton, is used by the ScriptInterpreter to retrieve script data a logical block at a time and to write script files out on user request. It does not directly interact with GMAT objects; rather, it provides the interfaces into the file system that are used to store and retrieve GMAT configurations in the file system.

Class Attributes

- **std::string fileName**: The current script name.
- **std::fstream script**: an std::fstream object used to read or write the script.
- **Integer lineWidth**: The maximum line width to use when writing a script; the default width is 0 characters, which is treated as an unlimited line width.
- **bool writeGmatKeyword**: A flag used to determine if the keywork GMAT is written when a script file is written. This flag defaults to true, and all assignment lines are prefaed with the GMAT keyword. Future builds of GMAT may toggle this feature off.
- **Integer currentLineNumber**: The current physical line number in the script file.

Methods

- **TextReadWriter* Instance()**: Accessor used to obtain the pointer to the TextReadWriter singleton.
- **void SetScriptFilename(const std::string &filename)**: Sets the name of the script file.
- **std::string GetScriptFilename()**: Gets the current name of the script file.
- **void SetLineWidth(Integer width)**: Sets the desired line width. If the input parameter is less than 20 but not 0, GMAT throws an exception stating that line widths must either be unlimited (denoted by a value of 0) or greater than 19 characters.
- **Integer GetLineWidth()**: Gets the desired line width.
- **Integer GetLineNumber()**: Gets the line number for the last line read.
- **bool OpenScriptFile(bool readMode)**: Opens the file for reading or writing, based on the read mode (true to read, false to write). This method sets the fileStream object to the correct file, and opens the stream.
- **std::string ReadLogicalBlock()**: Reads a logical block from the file, as described below.
- **bool WriteText(const std::string &textToWrite)**: Writes a block of text to the stream. The text is formatted prior to this call.
- **bool CloseScriptFile()**: Closes the file if it is open.

17.3.2.1 Overview of the ReadLogicalBlock() Method

The ReadLogicalBlock() method is designed to handle ASCII files written from any supported platform – Windows, Macintosh, or Linux – without needing to update the line ending characters. This method works by scanning each line for CR and LF characters, and treating any such character or combination of characters found as a physical line ending character. This process lets GMAT handle text files on all of the supported platforms[8].

[8]Here's what the Computer Dictionary (http://computing-dictionary.thefreedictionary.com/CR/LF) says about the line ending issue:

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For the purposes of the ReadLogicalBlock() method, a logical block is one or more physical lines of text in the script file, joined together into a single block of text. A script file indicates that physical lines should be connected by appending ellipsis ("...") to indicate that a line is continued. For example, if this scripting is found in the file:

```
Propagate Synchronized prop1(MMS), ...
   prop2(TDRS);
```

the encoded instruction that is returned is

```
Propagate Synchronized prop1(MMS),       prop2(TDRS);
```

Note that the white space is preserved in this process. The ellipsis characters are replaced by a single space.

17.3.2.2 ReadLogicalBlock(): Reading Comment Lines

Comments related to specific GMAT objects need to be preserved when reading and writing script files. The comments associated with specific objects are considered as part of the object's logical block. Thus, expanding on the example above, if the scripting reads

```
% Single step both formations
Propagate Synchronized prop1(MMS), ...
   prop2(TDRS);
```

the logical block that is returned is two physical lines:

```
% Single step both formations
Propagate Synchronized prop1(MMS),       prop2(TDRS);
```

where the line break delimits the separation between the comment prefacing the command from the text configuring the command object. Similarly, inline comments are preserved as part of the logical block; for example, the following scripting

```
% Build the spacecraft
Create Spacecraft Indostar1   % An Indonesian GEO
% Set up a Geostationary orbit
GMAT Indostar1.SMA = 42165.0    % Geosynchronous
GMAT Indostar1.ECC = 0.0005     % Circular
GMAT Indostar1.INC = 0.05       % Nearly equatorial
```

produces 4 logical blocks:

1. The object creation block:

   ```
   % Build the spacecraft
   Create Spacecraft Indostar1   % An Indonesian GEO
   ```

2. The first parameter setting block, with 2 comments:

   ```
   % Set up a Geostationary orbit
   GMAT Indostar1.SMA = 42165.0    % Geosynchronous
   ```

(Carriage Return/Line Feed) The end of line characters used in standard PC text files (ASCII decimal 13 10, hex 0D 0A). In the Mac, only the CR is used; in Unix, only the LF. When one considers that the computer world could not standardize the code to use to end a simple text line, it is truly a miracle that sufficient standards were agreed upon to support the Internet, which flourishes only because it is a standard.

Linux follows the Unix convention. Macintosh can be switched to Unix format or native Macintosh format.

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3. a second parameter block:

```
GMAT Indostar1.ECC = 0.0005     % Circular
```

4. and the final parameter block:

```
GMAT Indostar1.INC = 0.05       % Nearly equatorial
```

There are three additional types of comment blocks that the ReadLogicalBlock() method manages. These blocks, (1) the script header, (2) the script footer, and (3) section delimiter blocks, are not associated with specific GMAT objects, but rather with the script file as a whole.

GMAT script header comments are comment lines that begin on the first line of the script file, and that are terminated by a blank line. An example, taken, with minor edits, from one of the GMAT test scripts, is shown here:

```
% GMAT Script File
% GMAT Release Build 6.0, February 2006
%
% This test script uses the GMAT script language to convert from
% the Cartesian to the Keplerian state.  I only implemented the
% conversion for elliptic inclined orbits, as described in the
% math spec.  I didn't implement other special cases, because it
% would not test anything different in the inline math.


%  Create a s/c
Create Spacecraft Sat;
...
```

This script snippet contains a header comment, read into the logical block

```
% GMAT Script File
% GMAT Release Build 6.0, February 2006
%
% This test script uses the GMAT script language to convert from
% the Cartesian to the Keplerian state.  I only implemented the
% conversion for elliptic inclined orbits, as described in the
% math spec.  I didn't implement other special cases, because it
% would not test anything different in the inline math.
```

and an object creation logical block:

```
%  Create a s/c
Create Spacecraft Sat;
```

The script header comment is stored in the headerComment data member of the ScriptInterpreter. The comment associated with the object creation logical block is stored with the associated object, as described in the next section.

Some script files include comments after the last executable line of the script file. When such comments are found, they are collected into a single logical block and stored in the ScriptInterpreter's footerComment data member. The stored data in the header and footer comment blocks are written in the appropriate locations when a script file is saved using the Build() method of the ScriptInterpreter.

The final category of script comments, the section delimiters, are automatically generated when writing a script file, and ignored when reading a script. An example of a section delimiter is shown here:

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```
Create ImpulsiveBurn LunarPhasedV;
GMAT LunarPhasedV.Origin = Earth;
GMAT LunarPhasedV.Axes = VNB;
GMAT LunarPhasedV.VectorFormat = Cartesian;
GMAT LunarPhasedV.V = 0.027;

%--------------------------------------------------------------------------
%------------------------------ Propagators -------------------------------
%--------------------------------------------------------------------------

Create ForceModel LunarSB_ForceModel;
GMAT LunarSB_ForceModel.CentralBody = Earth;
GMAT LunarSB_ForceModel.PointMasses = { Earth, Sun, Luna};
```

Section delimiter comments exist on single lines, and always start with the string

```
%--------
```

with no preceding white space. When the ReadLogicalBlock() method encounters this string of characters at the start of a physical line, the physical line is ignored.

The ScriptInterpreter takes these logical blocks from the ScriptReadWriter, and uses the TextParser class to process each logical block. The facilities implemented in the TextParser and used for this processing are described next.

17.3.3 The TextParser Class

The ScriptReadWriter provides the interface to script files, and includes a method, ReadLogicalBlock(), that accesses a script file and reads it one logical block at a time. The ScriptInterpreter uses this method to obtain each logical block of text from a script. When ReadLogicalBlock() returns a script block, the ScriptInterpreter begins a process of breaking the block into pieces until the entire block has been consumed and interpreted into internal GMAT data structures. The ScriptInterpreter uses the TextParser to perform this decomposition.

The TextParser class is used to process logical blocks of script, breaking them into their constituent parts so that the Interpreters and Commands can setup the underlying class relationships and parameter values needed to model the mission described in the script file.

The TextParser class provides methods used by the ScriptIntererpter to iteratively decompose a logical block of text. This class supplies all of the low level parsing functionality necessary to manage script lines, and is used both by the ScriptInterpreter and by other classes – notably commands that are too complex to be treated generically. The TextParser does not parse inline mathematics; when inline math is detected by the ScriptInterpreter, it hands the parsing task off to the MathParser, described in Chapter 30.

Class Attributes

- **std::string prefaceComment**: All comment lines that precede the instruction in the current block of text. This member is the empty string if there are no comment lines preceding the instruction.
- **std::string inlineComment**: Any comment text that is appended to the instruction. This member is the empty string if there is no comment lines following the instruction.
- **std::string theInstruction**: The text that is decomposed to tell GMAT what to do.
- **StringArray commandList**: The list of available commands, excluding the GMAT keyword, which is used for assignments.

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Methods

- **void Initialize(const StringArray &commandList)**: Method that sets up the internal data for the TextParser. The parser's owner calls this method during construction, identifying all of the commands available to the parser in the current scope.

- **Gmat::LineType EvaluateBlock(const std::string &block)**: The method that takes a logical block and breaks it into three pieces: preface comments, the instruction in the block, and inline comments. These pieces are stored in internal TextParser data members until needed by the ScriptInterpreter. The method returns the type of block found, using these rules:

  1. If theInstruction is empty, the block is a COMMENT_BLOCK, otherwise
  2. If theInstruction has the word "Create" as the opening word, it is a DEFINITION_BLOCK, otherwise
  3. If theInstruction has a member of the commandList as the opening word, it is a COMMAND_BLOCK, otherwise
  4. The line is an ASSIGNMENT_BLOCK[9].

- **StringArray ChunkLine()**: Breaks the instruction string into logical groups, called "chunks" in this document. The instruction line is broken at white space and comma characters. Blocks marked with the grouping delimiters (), {}, and [] are kept together as independent chunks.

- **StringArray Decompose(std::string chunk)**: Breaks a text chunk into its constituent pieces, and returns them in a StringArray. This method is used to take a chunk from the ChunkLine() method, and break it into substrings. Decompose calls into the Separate methods described below, looking first for brackets to break apart, then commas and spaces, and finally periods.

- **StringArray SeparateBrackets(const std::string &text, const char bracket)**: Finds the text in a bracket grouping, and separates it into its constituent pieces. These pieces are returned in a StringArray. The first element of the array is the opening bracket, and the last element is the closing bracket.

  text: The string that contains the bracketed text.

  bracket: The opening bracket type; this is one of the following characters: '(', '{', '[', or '<'.

- **StringArray SeparateSpaces(const std::string chunk)**: Separates the chunk into pieces at whitespace and comma characters.

- **StringArray SeparateDots(const std::string chunk)**: Separates the chunk into pieces at period (aka "dot") characters.

- **std::string GetPrefaceComment()**: Accessor method used to get the preface comment from the logical block. If no preface was available, the method returns the empty string.

- **std::string GetInlineComment()**: Accessor method used to get the inline comment from the logical block. If no inline comment was available, the method returns the empty string.

- **std::string GetInstruction()**: Accessor method used to get the instruction from the logical block. If no instruction was available, the method returns the empty string.

- **void Reset())**: Clears the internal data in the TextParser.

[9]Note that identifying a line as an assignment line means that it will be used either to set an internal object parameter or to build an Assignment command in the mission sequence.

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17.4 Call Sequencing for Script Reading and Writing

The class descriptions described above provide a static picture of the components used to configure GMAT to run a script and to save a script for later use. In this section, the sequence followed for script reading and writing is presented to show how the structures and methods described for the classes interact with GMAT.

17.4.1 Script Reading Call Sequence

Script reading is the process through which the instructions in a script are translated into internal object configuration in GMAT. This process is, of necessity, rather complicated. However, the division of the types of lines that a script can contain into four sets: comment blocks, object definition blocks, command blocks, and assignment blocks, makes it possible to break the process into more manageable pieces. Accordingly, this section provides a top level look at the process followed when reading a script, followed by a description of the sequence executed for each type of logical block.

17.4.1.1 Process Followed for All Logical Blocks.

When the ScriptInterpreter is instructed to read a script, it performs some basic initialization in preparation for a new script file. The headerComment and footerComment bata members are set to empty strings, the logicalBlockCount data member is set to zero, the the TextParser owned by the ScriptInterpreter is reset to prevent inadvertent use of data from a previous script. Once these preliminary actions are completed, the script can be read.

Figure 17.6 shows the sequence followed when the ScriptInterpreter reads a script. The ScriptInterpreter sends the ScriptReadWriter the name of the script that needs to be read, and then requests that the script be opened for reading. If these commands succeed, the ScriptInterpreter uses the ScriptReadWriter to read the file, one logical block at a time.

The ScriptInterpreter calls the TextParser::EvaluateBlock method with each block of script that it receives from the ScriptReadWriter. That method breaks the logical block into three pieces: the comment lines that precede the instruction in the block, the instruction that needs to be interpreted to configure GMAT, and any inline comments that appear in the block. The TextParser examines the instruction portion of the block to determine what type of instruction is encoded in the block, and returns the type information using the LineType enumeration from the Gmat namespace.

The ScriptInterpeter then initiates actions that translate the block into components used to setup the script instructions, based on the type of block that was detected. The process foloowed for the four possible types of script line are detailed in the sections that follow this one, and illustrated in Figures 17.7 – 17.10.

Once the ScriptInterpreter has processed all of the blocks from a script, it instructs the ScriptReadWriter to close the script. The ScriptInterpreter then executes a final pass through the objects in the current configuration, setting a minimal set of object cross references that are required to make GMAT's GUI functional. When this final pass has been performed, control is returned to the Moderator with all of the instructions encoded in the script translated into GMAT objects.

The following paragraphs describe the details executed when translating each of the types of logical blocks that GMAT scripts use.

17.4.1.2 Comment Blocks

The only time the ScriptReadWriter returns a comment block – that is, a block of script that has no instructions, and consists only of comments – is when the block is either the header comment for the script or the footer comment for the script. Script files do not necessarily have either of these blocks. The ScriptInterpreter maintains an internal counter tht it uses to count the logical blocks as they are read from the file. If that counter is zero and a comment block is found, then the block is the header comment; otherwise it is the footer comment. Figure 17.7 shows this sequence.

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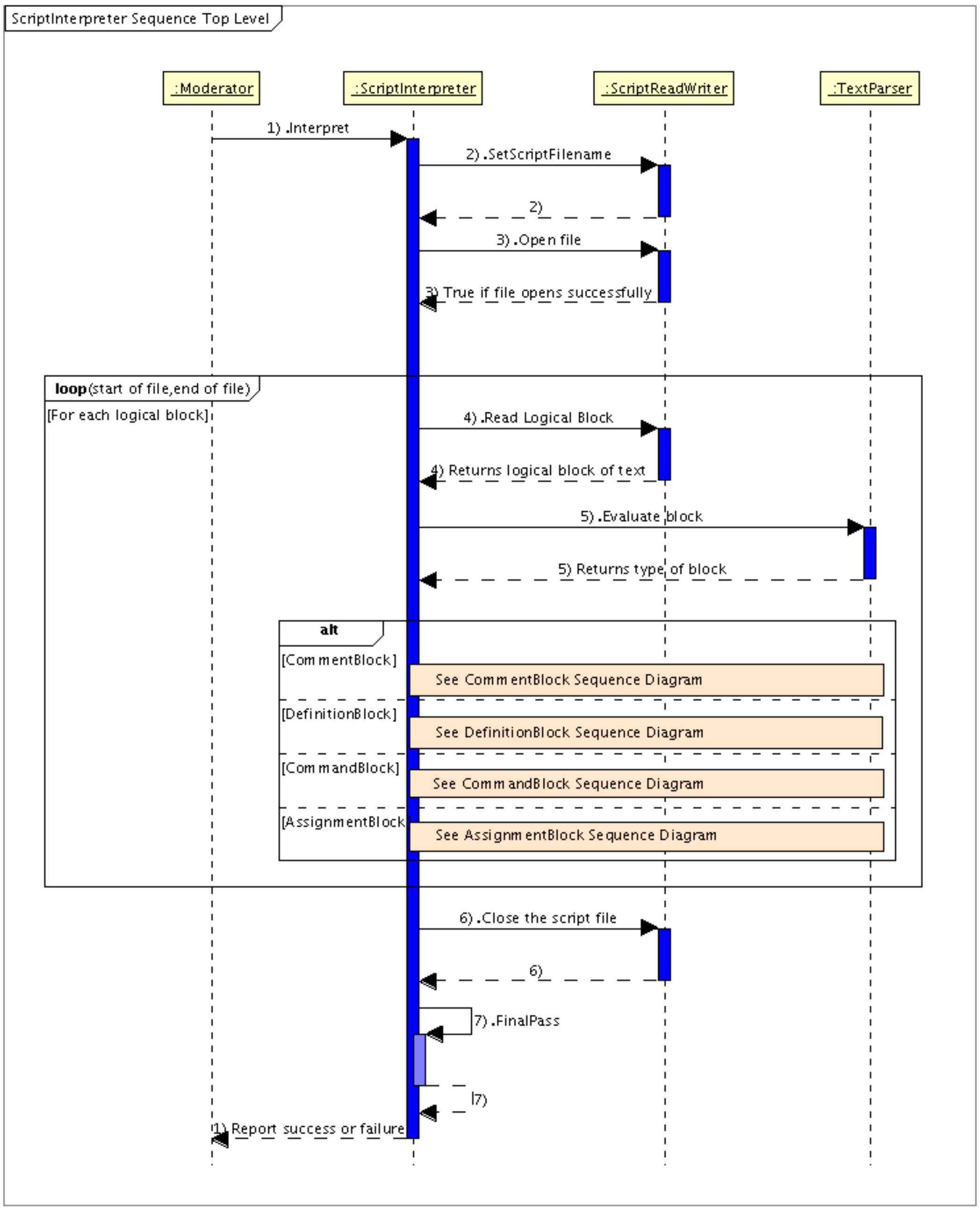
ScriptInterpreter Sequence Top Level
:Moderator
:ScriptInterpreter
:ScriptReadWriter
:TextParser
1) .Interpret
2) .SetScriptFilename
2)
3) .Open file
3) True if file opens successfully
loop(start of file,end of file)
[For each logical block]
4) .Read Logical Block
4) Returns logical block of text
5) .Evaluate block
5) Returns type of block
alt
[CommentBlock]
See CommentBlock Sequence Diagram
[DefinitionBlock]
See DefinitionBlock Sequence Diagram
[CommandBlock]
See CommandBlock Sequence Diagram
[AssignmentBlock]
See AssignmentBlock Sequence Diagram
6) .Close the script file
6)
7) .FinalPass
7)
1) Report success or failure

Figure 17.6: Overview of Interpreter Class Interactions when Reading a Script

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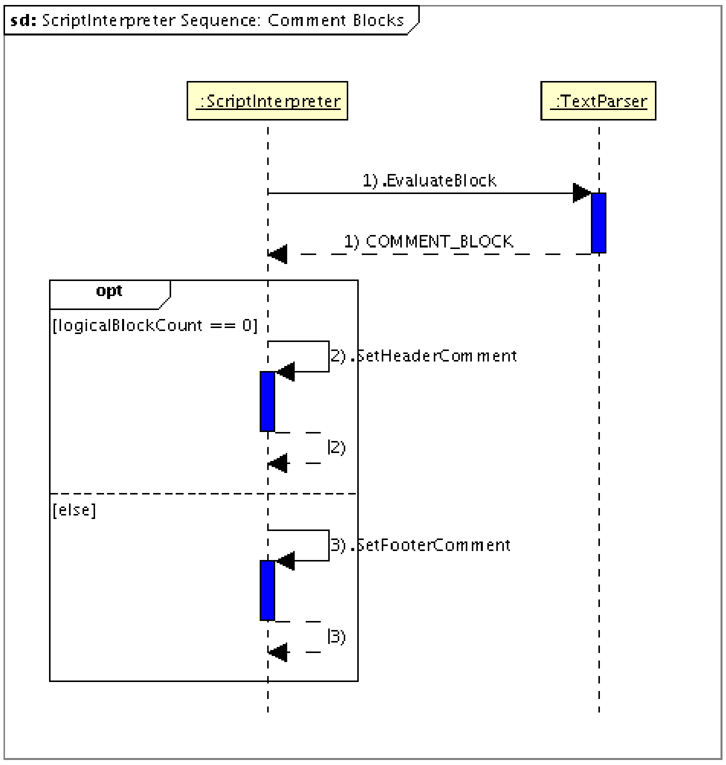

Figure 17.7: Interpreter Class Interactions when Reading a Comment Block

17.4.1.3 Object Definition Blocks

"Create" lines an a script file invoke object definition instructions, which are processed following the sequence shown in Figure 17.8. These instructions instantiate the user configurable objects that are used to model a mission.

When the TextParser tells the ScriptInterpreter that an object definition block has been detected, the ScriptInterpreter asks the TextParser to break the instruction in the block into smaller pieces, referred to as chunks. The text parser breaks the instruction at each white space or comma character in the instruction, and places these pieces, in order, into a StringArray, referred to here as the "chunkArray." Once the instruction has been broken into chunks, the chunkArray is returned to the ScriptInterpreter for processing.

Object definition instructions all have the format

```
Create <ObjectType> <Name1>[, <Name 2>, ...]
```

where ObjectType is a string identifying what type of object is desired – examples are a Spacecraft, a ForceModel, a Propagator, an Array, and so on. The instruction has one or more object names; one object will be created for each name found in the instruction. Object names start at the third element in the chunkArray, chunkArray[2]. If the size of the chunkArray is less than 3, the ScriptInterpreter throws an exception stating that no object name was found in the object definition line.

The object names in the instruction text are separated by commas, white space, or both. The Array object type has, in addition, a block specifying the array's dimensions, contained in square brackets. The array dimensions are written to a separate chunk in the chunkArray, starting from the opening square bracket ("[") and ending with the closing bracket ("]"), when the instruction is broken into pieces.

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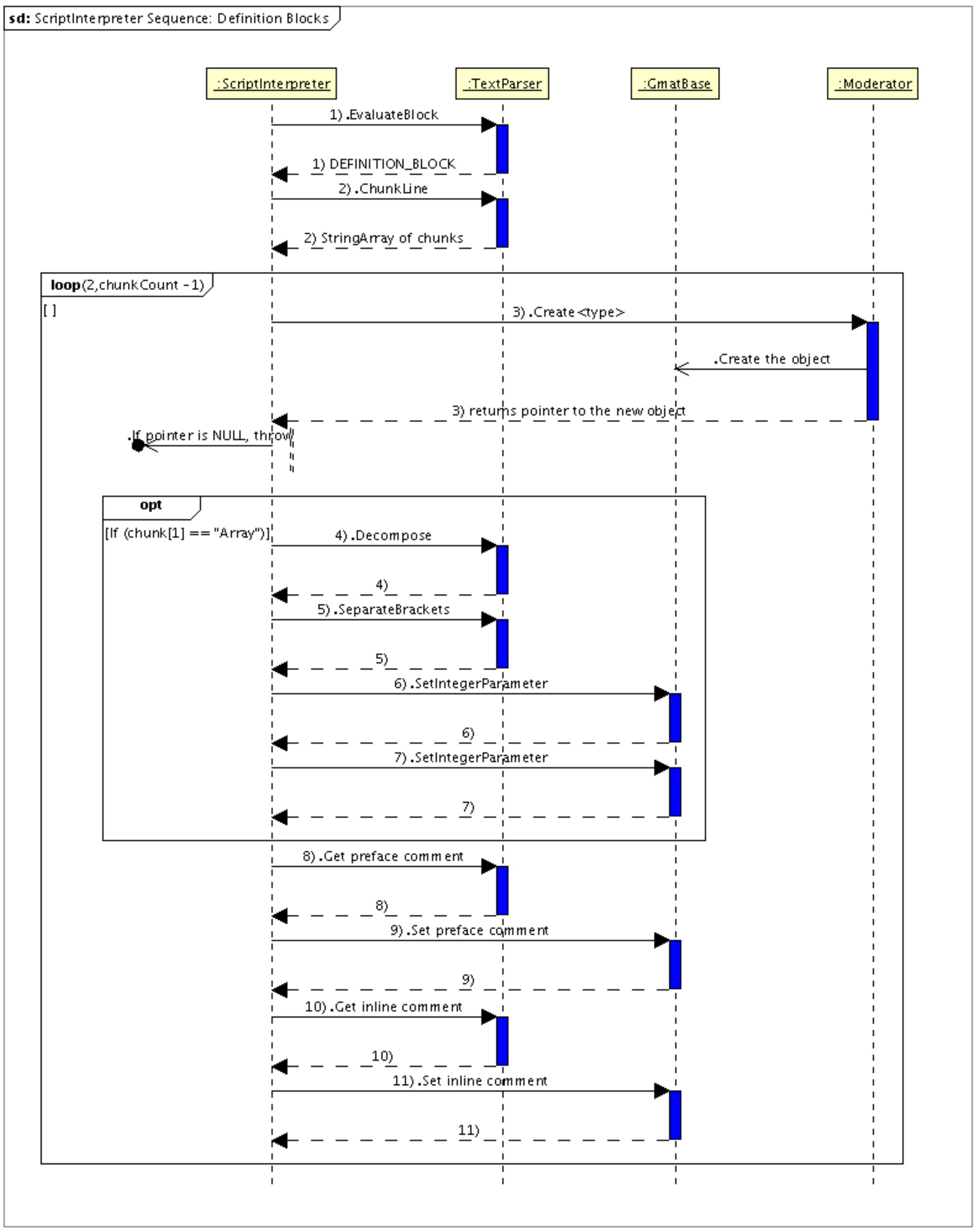

Figure 17.8: Interpreter Class Interactions when Reading an Object Definition Block

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Once the instruction has been broken into chunks, the ScriptInterpreter starts to loop through the list of object names found in the chunkArray. For each object name, it calls the Moderator to create an instance of the object. The Moderator returns a pointer to the new object, which the ScriptInterpreter checks. If the pointer is NULL, the ScriptInterpreter throws an exception stating that a requested object could not be created. This exception includes the name of the object, the object type, and the text of the instruction that attempted to create the object. If the returned pointer was not NULL, the ScriptInterpreter continues processing.

If the object created was an Array, the ScriptInterpreter takes the next chunk from the chunkArray, and asks the TextParser to break the bracketed dimensions apart. These dimensions are then passed into the new Array object to set the number of rows and columns for the array.

Finally, the ScriptInterpreter sets the comment strings for the new object by accessing the preface and inline pieces in the TextParser, and passing those pieces into the object. This completes the configuration of the object, so the ScriptInterpreter requests the next name from the chunkArray. It then repeats the process until all of the named objects have been created.

17.4.1.4 Command Blocks

The time ordered sequence of events executed when GMAT runs a mission sequence are encoded in commands – objects that instantiate the classes derived from the GmatCommand class, as described in Chapter 26. Figure 17.9 shows the sequence of events that is followed by the Script Interpreter when a command is configured. The first command detected by the script interpreter toggles the ScriptInterpreter's inCommandMode flag on, and sets the flag in the ScriptReadWriter so that all subsequent assignment blocks are treated as Assignment commands.

When a command is detected and set for configuration, the ScriptInterpreter calls the Moderator and asks for an instance of the command. It then sets the generating string on the command. Some commands parse the generating string internally, using the bool InterpretAction() method. Commands that use this method create an instance of the TextParser, and use its public methods to decompose the string into its constituent pieces. An example of this type of command is the Propagate command, which has a generating string that can consist of many different options. The complexity of the command makes it difficult to handle in a generic fashion in the ScriptInterpreter; hence it provides the parsing service internally. Commands that perform internal parsing return a value of "true" from the call to InterpretAction; those that expect to be configured by the ScriptInterpreter return "false."

If the command is not parsed internally, the instruction line is broken into chunks, using the cams call as performed for object definition. The resulting chunks are the command components needed to configure the command. The instruction components embedded in a GMAT command line typically exist in one of several different forms:

1. Stand alone commands. Some commands take no parameters at all, and are simply added to the command list unadorned. An example of this type of command is the EndTarget command, which identifies the end of a targeting loop.

2. Lists of referenced objects, separated by white space or commas. An example of this type of command is the Save command, which has the format

   ```
   Save <objectName>
   ```

   When a Save command is encountered, the name of the object is passed to the command using the SetReferenceObjectName()) method.

3. Lists of parameters, separated by white space or commas. An example of this type of command is the Report command, which has the format

   ```
   Report reportObject parameter1 parameter2 ...
   ```

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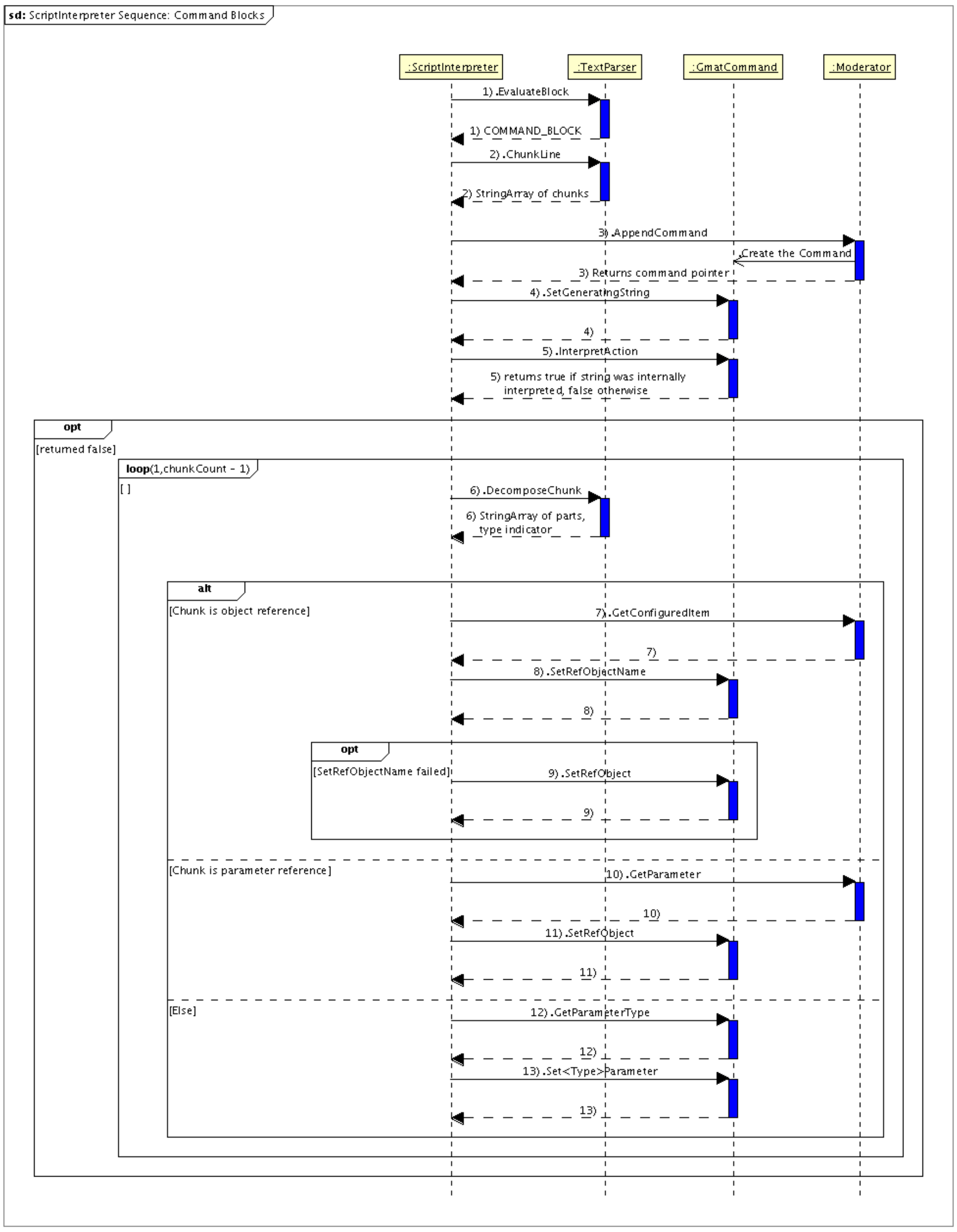

Figure 17.9: Interpreter Class Interactions when Reading a Command Block

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When a Report command is encountered, the name of the items in the list are passed to the command using the SetRefObject() method. The command validate teh first object as a ReportFile instance, and the subsequent objects as parameters.

4. Objects with references. Some commands identify objects that have associated objects. An example of this type of command is the BeginFiniteBurn command, which has the format

   ```
   BeginFiniteBurn <burnName>(<spacecraftName>)
   ```

   The objects identified on this line are accessed from the Moderator, and passed into the command as reference objects.

Once these components have been set on the command, the ScriptInterpreter sets the comment strings for the new object by accessing the preface and inline pieces in the TextParser, and passing those pieces into the object. This completes the configuration of the command, so the ScriptInterpreter requests the next name from the chunkArray. It then repeats the process until all of the named objects have been created.

17.4.1.5 Assignment Blocks

All logical blocks that are not comment blocks, object definitions, or commands are assignment blocks[10]. Processing for these blocks is shown in Figure 17.10. The result of parsing an assignment block can be either a changed value in a configured object or a new command inserted into the mission sequence, depending on the setting of the inCommandMode flag. If the assignment line includes a function call or inline mathematics, the ScriptInterpreter automatically switches into command mode and an appropriate command is created.

All assignment lines consist of an object identifier, and an optional equals sign followed by a right side expression (typically referred to as the "right hand side", or RHS). The only assignment lines that are missing the equals sign are function calls, which execute a CallFunction command. Assignment lines fall into the following categories:

1. Object properties. Object property assignments are used to set the internal data on configured objects. Object properties can be set to constant values, the current values of variables, or the value of an array element.

2. Objects. Objects can be set equal to other objects of the same type. When this form of assignment is used, the Copy() method of the object on the left side of the assignment is called with the object on the right as the input parameter.

3. Function calls. Function call lines are used to execute GmatFunctions and MatlabFunctions.

4. Mathematics. Scripted mathematics, as described in Chapter 30, are also managed on assignment lines.

Figure 17.10 shows the sequence of function calls required to interpret assignment lines. The command configurations segments, shown in green on the figure, execute the sequence described in the preceding section and shown on Figure 17.9.

17.4.2 Script Writing Call Sequence

The script writing process is considerably simpler than the reading process because all of the objects that need to be written to script already exist and are configured to meet the user's needs. Figure 17.11 shows the interactions performed between the GMAT classes when a script is written.

[10]Assignment lines in the current scripting for GMAT all start with the text string "GMAT". Since the ScriptInterpreter treats assignment lines last in the parsing sequence, this string is now optional, though recommended for any scripts that will be read in MATLAB to avoid confusing that system.

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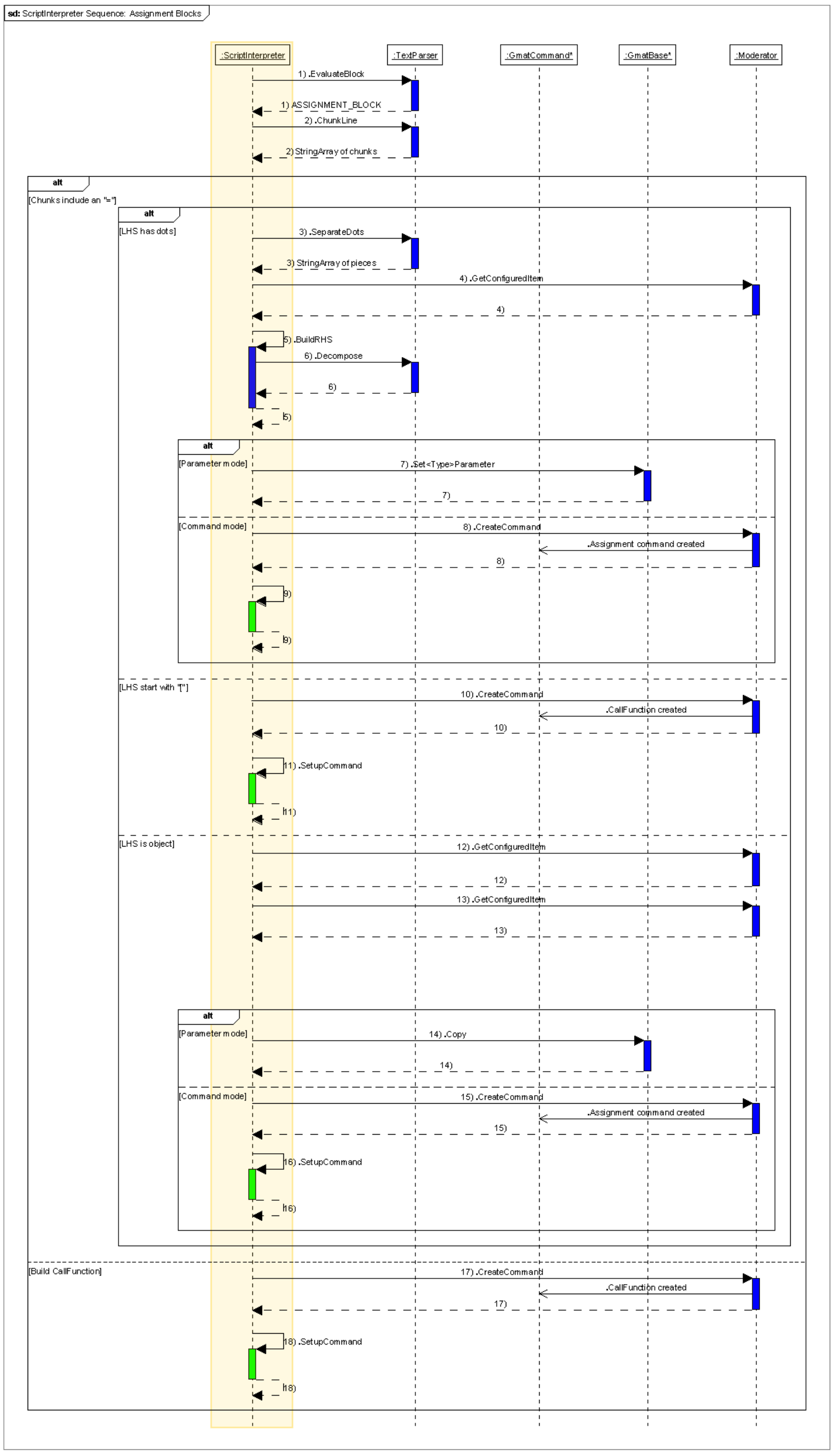

Figure 17.10: Interpreter Class Interactions when Reading an Assignment Block

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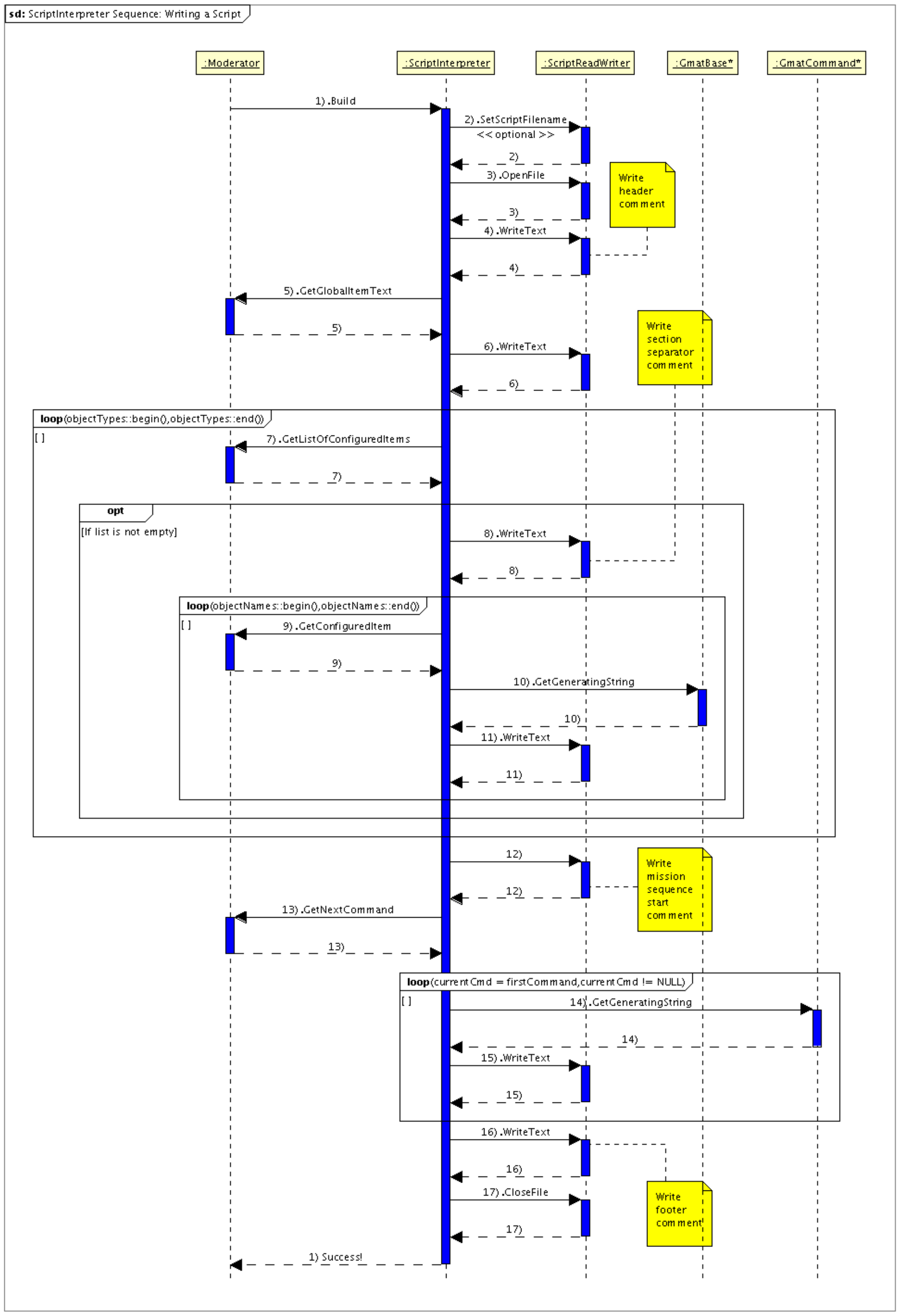

Figure 17.11: Calls Made when Writing a Script

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A script writing sequence is initiated then the Moderator calls the Build(std::string nameOfFile) method on the ScriptInterrpeter. If the nameOfFile parameter in the Build() call is not the empty string, then the ScriptInterpreter sets the script file name on the ScriptReadWriter to the name passed in with the call. Next the script is opened as an output stream. The header comment is written to the stream, followed by any global model information contained in the current GMAT run[11].

After all of these preliminary data have been written, the ScriptInterpreter writes the configured objects stored in the ConfigurationManager to the script stream. These configured objects are accessed by type, so that the resulting script presents the objects in sections based on the object type. The ScriptInterpreter calls the Moderator to get the list of objects by type. If the list is empty for a given type, the ScriptInterpreter skips to the next type. Each block of objects is prefaced by a section delimiter comment (as shown above). The section delimiters are generated internally in the ScriptInterpreter when it determines that there is an object of a specified type that needs to be written.

Configured objects are written in the following order: spacecraft, hardware, formations, force models, propagators, Burns, variables and arrays, coordinate systems, solvers, subscribers (plots, views and reports), and functions. Each configured object supplies its own serialized description, encoded in an std::string. This string is accessed using the object's GetGeneratingString() method; the ScriptInterpreter calls GetGeneratingString, and sends the resulting string to the ScriptReadWriter, which writes it to the script stream.

Once all of the configured objects have been written to the output stream, the ScriptInterpreter sends the block delimiter for the mission sequence to the ScriptReadWriter. The ScriptInterpreter then accesses the starting command in the mission sequence by calling the GetNextCommand() method on the Moderator. Since the command sequence is a linked list of GmatCommand objects, the ScriptInterpreter no longer needs to access the Moderator for command information. It sets an internal pointer to the first command in the list. This pointer, the current command pointer, is used to call GetGeneratingString() on that command. The returned string is passed to the ScriptReadWriter, which writes it to the script stream. The ScriptInterpreter then accesses the next command in the sequence by calling the Next() method. This process repeats as long as the pointer returned from the call to Next() is not NULL.

BranchCommands automatically include the string data for their branches when their GetGeneratingString() method is called. The ScriptInterpreter does not have any special code that needs to be run when a BranchCommand appears in the command sequence.

Once all of the commands in the command sequence have been written to the script stream, the ScriptInterpreter sends the footer comment to the TextReadWriter, which writes out the footer com ment. The ScriptInterpreter then tell the ScriptReadWriter to close the script stream, completing the script write function.

17.5 Interpreting GMAT Functions

GMAT scripting includes the ability to load and run smaller blocks of script using the GmatFunction class described in Section 31.2. This functionality is managed and driven by the CallFunction command and the GmatFunction class. The Interpreter subsystem provides a public base class method,

Interpreter::InterpretSubsequence(GmatFunction *function),

that builds the control sequence for the GmatFunction. This section describes how that method works. Figure 17.12 shows the basic flow followed in this process.

<Text to be completed.>

[11]The global information currently consists of the flags used by the SolarSystem to control the update intervals for planetary positions and the Earth nutation matrix. The Moderator call, GetGlobalItemText(), listed here returns the result of calling GetGeneratingString on the current SolarSystem. This method needs to be added to the Moderator.

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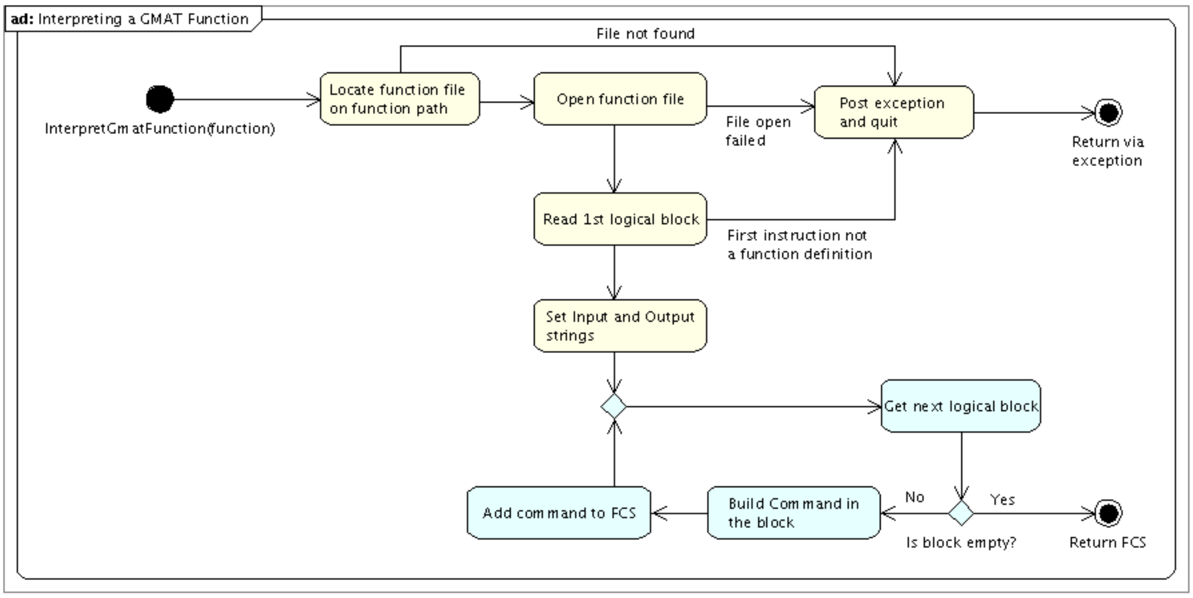
ad: Interpreting a GMAT Function
File not found
InterpretGmatFunction(function)
Locate function file on function path
Open function file
File open failed
Post exception and quit
Return via exception
Read 1st logical block
First instruction not a function definition
Set Input and Output strings
Get next logical block
No
Yes
Is block empty?
Return FCS
Build Command in the block
Add command to FCS

Figure 17.12: Interpreting a Function Control Sequence

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Chapter 18

The Graphical User Interface

???
???

I'm not sure yet how to structure this piece...

18.1 wxWidgets

18.2 GmatDialogs

18.3 The Interpreter Classes

This section may need to be in a separate (short) chapter.

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Chapter 19

External Interfaces

???
???

GMAT can be driven from the MATLAB environment, using the design presented in this chapter. More to be written later.

19.1 The MATLAB Interface

19.2 GMAT Ephemeris Files

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Chapter 20

Calculated Parameters and Stopping Conditions

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GMAT contains classes designed to perform numerous data calculations applicable to the analysis of spacecraft trajectories, orientations, and mission goals. These calculations are performed by the Parameter class hierarchy. This chapter describes, in some detail, the design of these Parameter classes.

The Parameter classes can be used in conjunction with the propagators to perform precision propagation, enabling the ability to stop on calculated values provided by the Parameter objects. Section 20.2 provides a description of the stopping condition classes. Stopping conditions are used by the Propagate command, described in Section 27.2.2.

20.1 Parameters

«To be completed.»

20.2 Stopping Conditions and Interpolators

Propagation in GMAT is described in Section 27.2.2. The propagation algorthme described there include descriptions about stopping at specific locations on a SpaceObject's trajectory, and include a discussion of the use of interpolators for these stopping points. The parameters and interpolators used for stopping are encapsulated in the stopping condition classes and interpolator classes shown in Figure 20.1. These classes are described in the following sections.

20.2.1 Stopping Conditions

Stopping conditions are implemented in two classes, as shown in the figure. These classes are described below.

Note: These sections need to be filled in. There will be some updates as implementation of the Propagate updates proceed.

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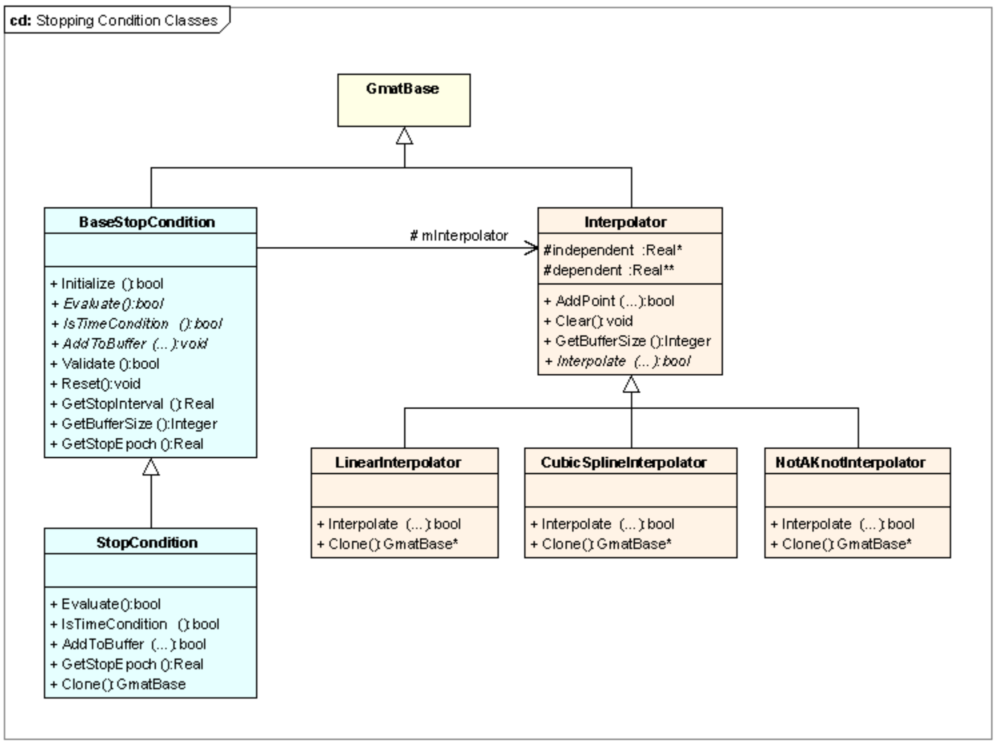

Figure 20.1: Stopping Condition Classes

20.2.1.1 The BaseStopCondition Class

Methods

- **bool Initialize()**
- **virtual bool Evaluate() = 0**
- **virtual bool IsTimeCondition() = 0**
- **virtual void AddToBuffer(bool isInitialPoint) = 0**
- **bool Validate()**
- **void Reset()**
- **Real GetStopInterval()**
- **Integer GetBufferSize()**
- **Real GetStopEpoch()**

20.2.1.2 The StopCondition Class

Methods

- **virtual bool Evaluate()**

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- **virtual bool IsTimeCondition()**
- **virtual void AddToBuffer(bool isInitialPoint)**
- **Real GetStopEpoch()**
- **GmatBase Clone()**

20.2.2 Interpolators

GMAT implements interpolators using a framework implemented in the Interpolator base class. Each derived class uses the Interpolator data structures and methods that implement the data buffers, add points to them, clear the buffers, and provide buffer size information. The base class provides the interface to the call to obtain interpolated data as an abstract method, Interpolate().

20.2.2.1 The Interpolator Class

Interpolator is the base class for all GMAT interpolators. It implements the data storage and access functions needed by interpolation routines, and provide the facilities needed to store and access the data in a ring buffer sized to match the interpolation algorithm.

Class Attributes

- **Real* independent**: The array of independent data used for interpolation.
- **Real** dependent**: The dependent data arrays used for interpolation.

Methods

- **bool AddPoint(Real ind, Real* date)**: Adds independent and dependent data to the arrays of data elements. The data is stores in these arrays using a ring buffer allocation, so that data does not need to be copied when the number of points in the buffer exceeds the allocated array sizes. Instead the new data overwrites the oldest values in the arrays.
- **void Clear()**: Resets teh rind buffer pointers, so that the buffers appear to be empty on their next use.
- **Integer GetBufferSize()**: Returns the number of data points that can be stored in the ring buffer.
- **virtual bool Interpolate(Real ind, Real* results) = 0**: The abstract method that gets overridden to implement specific interpolation algorithms.

20.2.2.2 The Linear, Cubic Spline, and Not-a-Knot Interpolators

GMAT implements three interpolators: a linear interpolator, a standard cubic spline interpolator using the algorithm described in [NRecipes], and the not-a-knot algorithm described in [MathSpec]. These classes implement two class specific methods:

Methods

- **GmatBase* Clone()**: Calls the class's copy constructor to make an exact copy of the interpolator.
- **virtual bool Interpolate(Real ind, Real* results)**: Implements the specific interpolation algorithm used by the interpolator.

The Clone method behaves as in all other GmatBase subclasses. The Interpolate() methods implement the interpolator specific algorithms, as described in the references.

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Chapter 21

Propagation in GMAT

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21.1 Propagator Overview

GMAT's model contains a subsystem that is used to move a user defined mission through time, following the sequence of events defined in the Mission Control Sequence. That subsystem is referred to as the propagation subsystem. In its most generic form, GMAT's propagation subsystem can be thought of as taking a mission state $\mathbf{X}_i$ at some time t_i and moving that state by some amount δt to some new time t_f, resulting in a new state $\mathbf{X}_f$. The components that are used to perform this change of state are the elements of the propagation subsystem. In other words, GMAT's propagation subsystem performs the actions needed to calculate the new state by performing the operation

$$\mathbf{X}_f(t_f) = F(\mathbf{X}_i(t_i), \delta t) \tag{21.1}$$

This chapter provides an overview of the definition of the quantities in this equation: the definition of the mission state vector and all of its components, the evolution operator F that moves the state vector, and an overview of the construction and decomposition of these quantities in GMAT.

GMAT's propagation subsystem is used to perform all analytic propagation and numerical integration needed by the system. That includes modeling the time lines for spacecraft and formations, mass depletion modeling during finite duration maneuvers, evolution of the state transition matrix, attitude propagation, evolution of physical properties and their variances as needed for orbit and attitude determination problems, and evolution of costate variables needed for optimal control problems. The diversity of propagation issues encountered in the coverage provided by the propagation subsystem makes it a potentially quite complicated collection of components. For that reason, the subsystem is broken into a collection of different elements each tailored to specific aspects of the propagation problem regime. The propagation problem requires a consistent, complete description of the evolution operators and the propagation vector, which are discussed briefly below and in detail in Chapters 22 and 23, respectively. This chapter concludes with a description of the scripting elements used to drive propagation in GMAT, using the Propagate command as an example of this scripting.

21.2 Propagator Overview

The function F in equation 21.1 defines the process that takes a vector of numbers defining system properties at one time and finds the values of those same properties at a different time. This process of moving the properties through time is performed using one or more evolution operators. The objects in GMAT that

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perform this evolution are the propagators. GMAT's propagators are designed to support evolution either forwards or backwards in time. The propagators can be set to run in a synchronized manner or independently of one another. The selection of the category and type of propagator that is used is selected by the user based on the types of parameters that need to be propagated.

GMAT Supports three different categories of propagators, defined by the type of data available for the propagation. The categories are

Analytic GMAT's analytic propagators take a known, closed form solution to the evolution problem and apply that solution to the propagation vector specified at some initial time to find its values at some other time. GMAT's analytic propagators use embedded evolution equations to calculate the values of parameters at the desired times.

Numerical The numerical propagators find a solution of the differential equations of motion for the parameters using a precision numerical integrator and derivative models. Propagators in this category consist of a pair of objects: a numerical integrator derived from the Integrator class and a derivative model derived from the PhysicalModel class.

Precalculated Precalculated parameter values are retrieved – and, if needed, interpolated – from files containing the time history of the parameter values.

Each category of propagator supplies implementations of core methods designed to standardize the propagation interface. The core propagation interfaces are defined in the Propagator base class. Every GMAT propagator uses these interfaces to perform the following actions:

- Map the propagation vector to known evolution operators
- Initialize all data structures and object references needed to propagate
- Load the initialized data structure immediately before propagating
- Propagate the propagation vector
- Reset the propagator to use its initial settings

The Propagator class defines these interfaces to perform the actions listed above:

GetPropagatorOrder GMAT includes both first and second order numerical integrators. This interface is used to determine which is needed for a particular integrator. The non-numerical integrators all report order 0.

SetPhysicalModel The SetPhysicalModel method sets the derivative model used for numerical integration, and – for all propagators – performs pre-initialization tasks required before initialization can proceed. This method ensures that all of the elements needed for evolution have been set for the propagator.

Initialize All of the reference object pointers and other interconnections necessary for propagation are set in the Initialize method. Propagators that do not allow for dynamic resizing of the propagation vector also use this method to initialize the propagation vector mapping needed for the evolution. Those that may require dynamic resizing perform a preliminary mapping during initialization.

Update The Update method is used to reset the propagator when the underlying physical model changes. This method is used to refresh the propagation vector mapping if the propagation vector has changed – for instance, when a transient derivative is applied or removed to model mass flow during a finite maneuver. It also resets some of the propagator's properties if needed, like the initial step size for variable step propagators.

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ResetInitialData The ResetInitialData method sets a flag telling the propagator that at the next call to propagate the propagation vector, the propagator's initial data needs to be updated prior to propagation.

Step State evolution is driven through calls to the Step method. Different categories and subcategories of propagators implement different versions of this method based on the needs and capabilities of the propagators.

These methods define the minimum level of interface required for every GMAT propagator. The Propagator subclasses extend this set based on the needs of the category of the propagator defined in the subclass.

The design details for the propagators are provided in Chapter 22.

21.3 Propagation Vector Overview

The propagators evolve a vector of data from one epoch to another. The data that evolves is contained in a column vector sized to match the evolving data. This vector is assembled and populated prior to propagation based on specifications scripted by the user. The propagation vector provides methods that support the following actions:

- Supply epoch information
- Supply propagation vector information, including all of the following:
  - Size of the vector
  - Element by element types for mapping the vector onto the propagator
- Supply the propagation vector

GMAT uses a class, PropVector, to model the propagation vector. The PropVector objects supply the information used to assemble the derivative vector needed for numerical integration, the epoch and state data needed for analytic propagation, or the epoch and time step information used for precalculated propagation.

The PropVector class defines these interfaces to perform the actions listed above:

GetEpoch and SetEpoch A PropVector contains data calculated at a single epoch. These GetEpoch and SetEpoch methods provide access to the epoch data in the PropVector.

GetDimension Retrieves the current size of the PropVector – that is, the number of elements that evolve over time. The dimension is used to initialize the propagator, and, in conjuction with the vector map, to ensure that the correct operator is used to evolve each element of the vector.

GetVectorMap Retrieves the mapping of the PropVector, element by element, so that the evolution components can be set correctly.

GetVector Retireves a pointer to the Real array of data for the vector. The retrieved vector has the size given by the dimension of the PropVector, mapped as specified in the vector map. Components that use the PropVector for propagation can both read and write to this retrieved vector. This violation of encapsulation is intentional, in order to make the propagation process as fast as possible in GMAT.

These interfaces define the minimal interfaces necessary for PropVector objects. They are defined as overridable interfaces so that classes can be derived form PropVector in the future as needed.

The PropVector class is managed through a mapping class, the MissionState. The MissionState class is a container class – it contains references to the objects providing state data that evolves using GMAT's evolution operators, as defined in its Propagator classes. The MissionState class provides methods accessed by the propagators to construct, retrieve, and update the PropVector. It manages the data flow between

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these objects and the propagation vectors manipulated by the Propagators. The MissionState builds the PropVectors used by the propagators, setting up the data vector and associated component mappings used by the propagator to assemble the elements needed for propagation.

The MissionState class defines a set of interfaces used to manage the data soureces used to assemble the PropVector. The interfaces supplied by the MissionState for these tasks are:

AddObject Adds an object that supplied data to one or more PropVectors.

Initialize Constructs the PropVector or PropVectors used by a propagator.

PrepareToPropagate Completes PropVector initialization needed prior to propagation.

GetPropVector Retrieves an assembled PropVector designed for propagation.

Each one of GMAT's propagators uses a MissionState object to manage the data that is propagated.

The PropVector and MissionState classes are described in detail in Chapter 23.

21.4 Scripting Propagation

As is described above, GMAT provides three approaches to propagation. The system can model the evolution of the state data by numerically integrating the equations of motion, providing a high precision model of the evolution, by reading the data from a pre-calculated file of data points (e.g. a SPICE file), or by using an analytical propagator that provides a fast, lower fidelity vector of propagated data. The propagation subsystem can perform these tasks for all of the parameters represented in the propagation vector: for the spacecraft orbit and attitude data, mass properties, for the state transition matrix and covariance matrices, and for any other parameters placed in the propagation vector, as long as the underlying propagation model supporting the parameter exists. For the numerical integrators, that means that the set of ordinary differential equations describing the evolution have been coded into the system. Similarly, analytic propagators require encoding of the analytic equations of motion. The precalculated data propagators require an ephemeris or similar time based file of the evolution of the paramteres that they propagate. GMAT is designed to support mixed mode propagation as well; elements propagated in a Mission Control Sequence command need not all be propagated using the same approach. Some can be propagated analytically or using a file while others are numerically integrated. The design implementing this mode is described in Chapter 22 and in the descriptions of the commands that support propagation.

Commands that drive propagation follow the process shown in Figure 21.1. The command is initialized in the Sandbox along with the rest of the Mission Control Sequence. During this initialization, specific pieces required to initialize each propagator driven by that command are performed. There are portions of the propagation process that cannot be initialized at this point in the mission run because they depend on data that may be changed when commands that precede the one invoking propagation fire. This final piece of initialization is performed in a method named PrepareToPropagate(), which is called when the command's Execute() method is called, immediately before the actual propagation. Finally, the propagation is performed in the body of the Execute() method associated with the command.

21.4.1 Example: The Propagate Command

Propagation is scripted in GMAT through the creation of propagator objects and the incorporation of these objects into the Mission Control Sequence through propagator enabled commands. The prototypical propagator enabled command is the Propagate command (described more fully in Section 27.2.2), scripted in its simplest form like this:

```
Propagate prop(sat)
```

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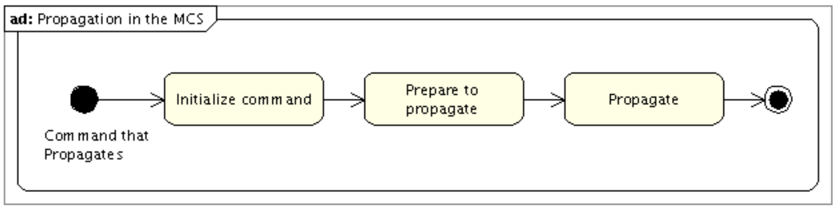

Figure 21.1: Command and Propagation Processes

The command shown here consists of three elements: the Propagate keyword, the name of the propagator that is used ("prop" in this case), and the object that is propagated, "sat" in this example. In order for this command to run, the objects used in teh propagation must exist, so there must be matching creation commands. Assuming that the command exists in the main script rather than a function, that means these lines must occur before the Propagate command line:

```
Create Spacecraft sat;
Create Propagator prop;
```

The propagated object can, of course, be any object that supplies a propagation vector for propagation.
The type of propagator is specified by setting the "Type" property on the propagator object, like this:

```
prop.Type = PrinceDormand78;  % Use a Prince-Dormand RK integrator
```

The Type setting for the propagator must be made before setting any other propagator properties because the properties for the propagator depend on the type of Propagator object that is being used. Every GMAT propagator has default values for each of its properties. Users override these settings to tailor the behavior of the propagator.
The following sections describe the scripting for each category of Propagator.

21.4.1.1 Scripting Numerical Integrators

The numerical integrators require an additional object defining the forces and other differential equations that are used to model the propagation. These pieces are gathered in a container class, the ODEModel class derived from PhysicalModel. The ODEModel class plays several roles in the propagation subsystem:

- It works with a MissionState object to create the propagation vector
- It coordinates the data mapping between the objects that are propagated and the propagation vector
- It handles the superposition tasks when the differential equations defining propagation consist of multiple components

The ODEModel class is described more fully in Section 22.3.1. Scripting for ODEModel objects depends on context. For orbit propagation, the ODEModel is scripted as a ForceModel component, using this syntax:

```
Create ForceModel forces;
forces.CentralBody = Earth;
forces.PrimaryBodies = {Earth};
forces.Drag = MSISE90;
forces.SRP = On;
forces.ErrorControl = RSSStep;
```

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```
forces.GravityField.Earth.Degree = 4;
forces.GravityField.Earth.Order = 4;
forces.GravityField.Earth.PotentialFile = 'JGM2.cof';
forces.PointMasses = {Sun, Luna, Mercury, Venus, Mars};

Create Propagator prop;
prop.Type = PrinceDormand78;
prop.FM = forces;
```

The forces that are included in the differential equations of motion are defined by specifying the desired elements and, when needed, properties of those elements. The resulting ODEModel is assigned to the integrator by assigning its name to the FM property of the Propagator.

21.4.1.2 Scripting Analytic Propagators

This section is TBD, based on requirements and design for analytic propagators when they are added to GMAT.

21.4.1.3 Scripting Precalculated Propagators

Detailed information for this section is TBD, based on requirements and design for the SPICE file component and discussions of other ephemeris based propagators planned for GMAT. However, the scripting discussion is underway, and included here, subject to extensive revision.

Propagation based on precalculated data is used in GMAT to propagate data for spacecraft, celestial bodies not modeled elsewhere, and other elements that are described using file-based time-indexed data.

Scripting for the precalculated propagators is similar to that for the numerical integrators. The precalculated propagators identify the propagator type as one of the supported file based propagator types, and identify a file – the file containing the ephemeris data – rather than a force model. An example of the setup for a SPICE file based precalculated propagator for the Clementine mission is given here:

```
Create Spacecraft Clementine
Clementine.EphemID = -40      % Clementine's NAIF ID

Create Asteroid Geographos    % Asteroid support is a future enhancement;
                              % use a Spacecraft with the current code base
Geographos.EphemID = 2006513  % No clue about the real NAIF ID for Geographos...

Create Propagator prop
prop.type = SPICE
prop.StepSize = 300    % seconds
prop.Ephemeris = DSPSE.SPK        % Ephem containing Clementine and Geographos
prop.Ephemeris = SolarBodies.SPK  % Second ephem used to add vectors together
```

Propagation with a SPICE file propagator is handled identically to that performed using other propagators. For the asteroid encounter phase of the mission above, a user could script the propagaton like this:

```
Create Variable i
For i = 0 : 2000
   Propagate prop(Clementine, Geographos)
EndFor
```

One constraint imposed in GMAT is that for a single ephemeris based propagator, each object that is propagated must be contained in the same ephemeris file. That means that in the example above, the

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ephemeris for both the Clementine spacecraft and the asteroid Geographos must exist in the SPICE file DSPSE.SPK. For this case, the same result could be achieved with separate ephemerides for the spacecraft and asteroid with this scripting:

```
Create Spacecraft Clementine
Clementine.EphemID = -40   % Clementine's NAIF ID

Create Asteroid Geographos    % Asteroid support is a future enhancement;
                              % use a Spacecraft with the current code base
Geographos.EphemID = 2006513  % No clue about the real NAIF ID for Geographos...

Create Propagator prop
prop.type = SPICE
prop.StepSize = 300    % seconds
prop.Ephemeris = Clementine.SPK   % Ephem containing Clementine
prop.Ephemeris = SolarBodies.SPK  % Second ephem used to add vectors together

Create Propagator geogProp
geogProp.type = SPICE
geogProp.StepSize = 300    % seconds
geogProp.Ephemeris = Asteroids.SPK    % Ephem containing Geographos
geogProp.Ephemeris = SolarBodies.SPK  % Second ephem used to add vectors together

Create Variable i
For i = 0 : 2000
   Propagate Synchronized prop(Clementine) geogProp(Geographos)
EndFor
```

Finally, you may have noted that a second ephemeris source is identified for the SPICE propagator. This option is scripted in these examples to allow conversion of the epheris data for propagated objects to other bodies in the model. For example, the ephemeris for Geographos is likely to be calculated with respect to the Sun. GMAT may need Earth-centered states, so the SPICE propagator needs to load the SPICE kernel that describes the Earth's location with respect to the Sun in order to add the position vectors together to build the state vector.

The following chapters provide details of the propagation subsystem components. Chapter 23 describes the PropVector and MissionState classes, and includes descriptions of the data mapping for vector elements and diagrams describing hte layout of the PropVector data for single and multiple objects. Chapter 22 describes the design of the propagator classes. The commands that control the propagation subsystem are described in Chapters 26 and 27.

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Chapter 22

GMAT's Propagators

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Chapter 23 describes the classes used to represent the state of the objects in a Mission Control Sequence, but does not define the pieces that perform the time evolution for that state. Those components – the propagators – are described in this chapter.

22.1 The Propagator Classes

The components that are instrumental in time evolution are shown in Figure 22.1.

The numerical integration portion of the propagation system, shown in green in the figure, consists of a differential equation model and numerical integrator paired to perform the precision integration. The ODEModel class is a container class that accumulates all of the differential equation data modeled in the mission, and reports the resulting changes in the elements of the state vector. Details of the force model components of the differential equation model are described in Chapter 24. Other differential equation models are described separately.

22.2 The Propagator Base Class

22.2.1 Class Attributes

- **PropVector *thePropVector**

22.2.2 Class Methods

- **bool Initialize()**

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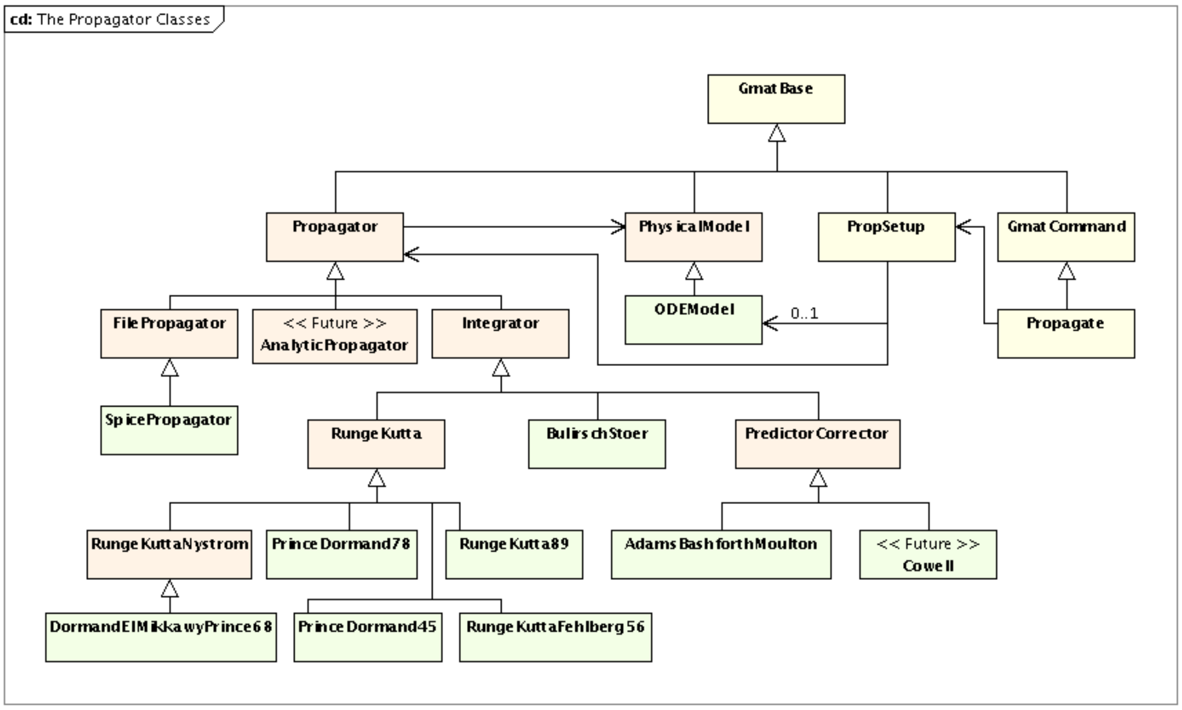

Figure 22.1: Classes Used to Propagate State Data. Base classes are shown in orange. Classes that instantiate the objects used in numerical integration are in green. Analytic propagation elements are in blue. Classes that are used to drive the propagation process, and other base level classes, are shown in yellow.

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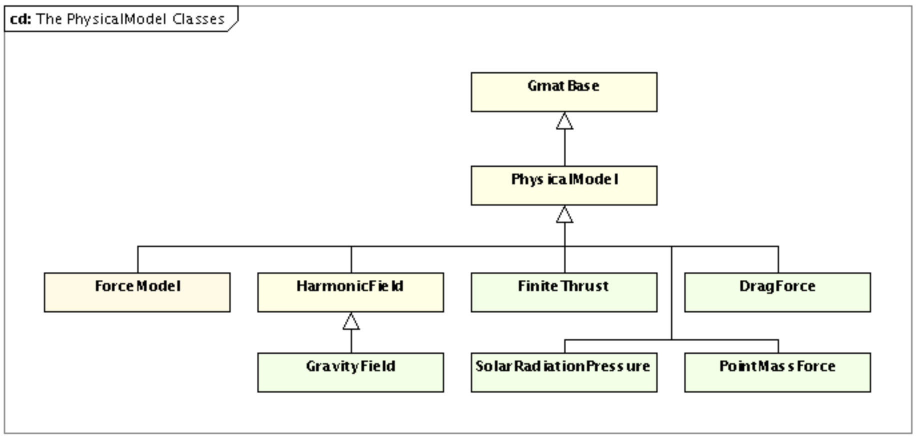

Figure 22.2: The Derivative Model Classes. This figure shows the classes used to provide derivative information to GMAT's integrators.

22.3 Numerical Integration

22.3.1 The Derivative Models

22.3.2 Initialization of the Derivative Model

22.3.3 Finalizing Initialization: The PrepareToPropagate() Method

22.3.4 Propagation

22.3.5 Completing Propagation

22.4 Analytic Propagation

22.5 File Based Propagation

22.6 Propagation Examples

22.6.1 A Numerical Integration Example

22.6.2 A SPICE File Propagation Example

22.6.3 A Mixed Mode Example

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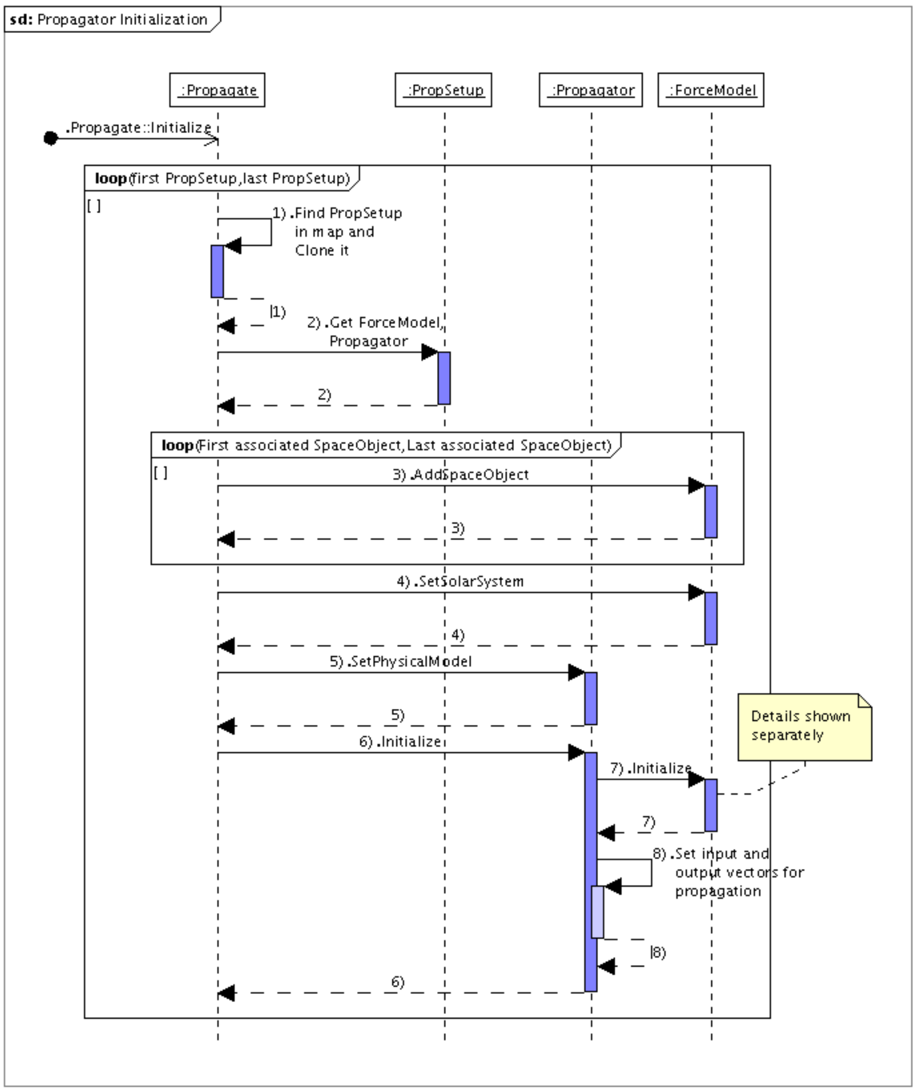
sd: Propagator Initialization
:Propagate
:PropSetup
:Propagator
:ForceModel
.Propagate::Initialize
loop(first PropSetup,last PropSetup)
[ ]
1) .Find PropSetup in map and Clone it
1)
2) .Get ForceModel, Propagator
2)
loop(First associated SpaceObject,Last associated SpaceObject)
[ ]
3) .AddSpaceObject
3)
4) .SetSolarSystem
4)
5) .SetPhysicalModel
5)
6) .Initialize
Details shown separately
7) .Initialize
7)
8) .Set input and output vectors for propagation
8)
6)

Figure 22.3: Propagator Initialization. This sequence diagram shows the process used to prepare a propagator for use in the Mission Control Sequence.

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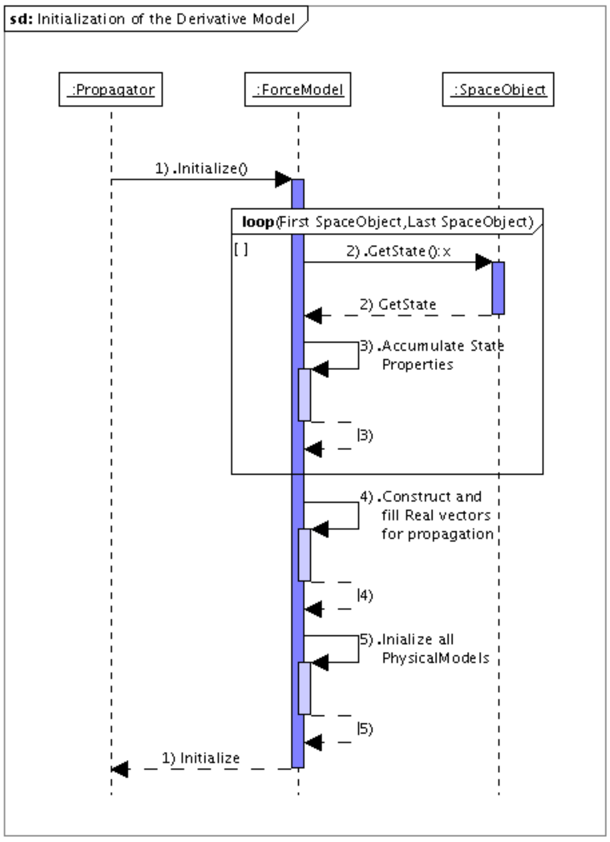
sd: Initialization of the Derivative Model
:Propagator
:ForceModel
:SpaceObject
1) .Initialize()
loop(First SpaceObject,Last SpaceObject)
[ ]
2) .GetState():x
2) GetState
3) .Accumulate State Properties
|3)
4) .Construct and fill Real vectors for propagation
|4)
5) .Inialize all PhysicalModels
|5)
1) Initialize

Figure 22.4: Derivative Model Initialization. This sequence diagram shows the process used to build the data that is numerically integrated during propagation.

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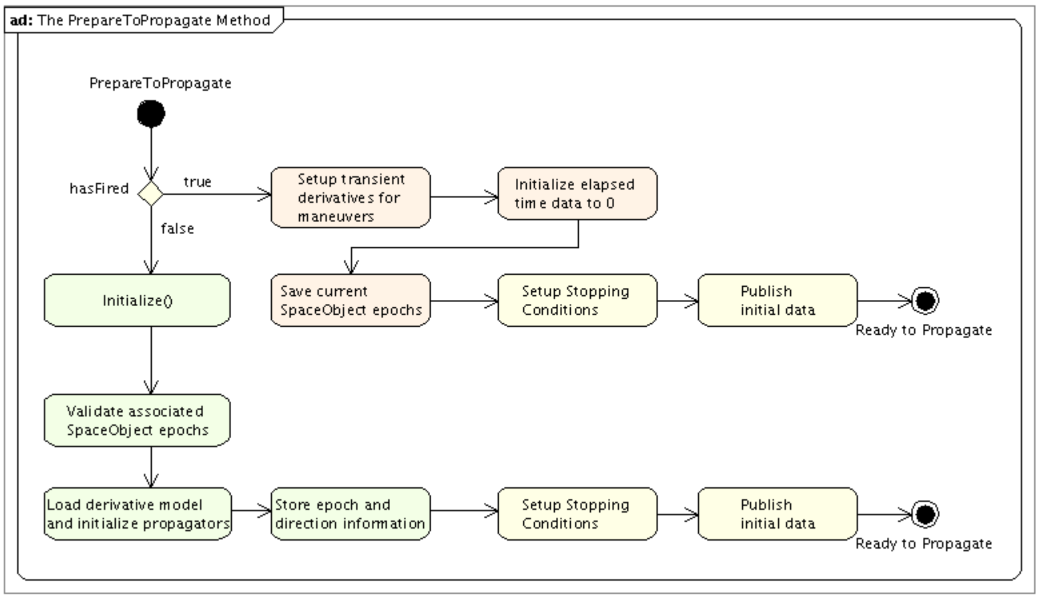
ad: The PrepareToPropagate Method
PrepareToPropagate
hasFired
true
false
Setup transient derivatives for maneuvers
Initialize elapsed time data to 0
Initialize()
Save current SpaceObject epochs
Setup Stopping Conditions
Publish initial data
Ready to Propagate
Validate associated SpaceObject epochs
Load derivative model and initialize propagators
Store epoch and direction information
Setup Stopping Conditions
Publish initial data
Ready to Propagate

Figure 22.5: Final Propagator Initialization: PrepareToPropagate()

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Chapter 23

The State Vector for Propagation

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23.1 The MissionState Class

23.1.1 Enumerations used in the MissionState

The MissionState uses several enumerations used to identify propagation components efficiently. This section describes each of these enumerations.

PropMode The PropMode enumeration identifies the type of propagation used with a given set of state elements.

- **ANALYTIC_PROP**
- **INTEGRATE**
- **PRECALCULATED_PROP**

ElementType The ElementType enumeration identifies the kind of component contained in a PropVector

- **CARTESIAN_START**
- **CARTESIAN**
- **EQUINOCTIAL_START**
- **EQUINOCTIAL**
- **STM_START**
- **STM**
- **QUARTERNION_START**
- **QUARTERNION**
- **MASS**
- **USER_DEFINED**
- **UNKNOWN_ELEMENT_TYPE**

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23.1.2 MissionState Attributes

- **Real epoch** The epoch of the state data managed by the MissionState. GMAT requires that all such state data in a MissionState use the same epoch.
- **ObjectArray dataSource** The vector of objects that are propagated
- **std::vector<PropMode> propModes** The propagation mode for each object that is propagated.
- **Integer dimension** Total number of elements that are propagated
- **PropVector thePropVector** The state data to be propagated

23.1.2.1 MissionState Methods

- **bool AddSource(GmatBase* src, PropMode mode, ElementType type, Integer elementId)** Registers an object as a data provider with the MissionState. The mode parameter identifies the type of propagation desired: analytic, numerically integrated, or from an ephemeris source. The type parameter identified the kind of element that is propagated. The elementId parameter is the ID for the start of the data that is propagated. All propagated data must be accessible using the generic access methods defined for GmatBase objects, so that the elementId can be used to access these data.
- **bool Initialize()** Performs preliminary setup of the PropVector prior to propagation.
- **bool PrepareToPropagate()** Completes pre-propagation setup.

23.2 The PropVector Class

Figure 23.1 shows a representative layout of the data in a PropVector for a single spacecraft. The vector displayed here is the PropVector used by a numerical integrator that is modeling the evolution of the spacecraft's trajectory, state transition matrix, and attitude during a finite burn maneuver. When a MissionState object assembles a PropVector, it follows a set of ordering rules designed to make the data in the PropVector fall in a specific order so that access from the propagators is simplified. The general order, as shown in this example, is to place trajectory data first in the vector, followed by associated matrices that evolve along with the trajectory, then attitude data followed by associated attitde matrices, then user defined elements, and finally transitory elements like mass, which only changes (through propagation) during maneuvers.

This ordering can be seen more explicitly in Figure 23.2. The PropVector shown in this figure is a vector constructed for three spacecraft, where the mission needs to propagate the trajectory, state transition matrix, and attitude for all three while maneuvering all three simultaneously.

Figure 23.3 shown another example, where the propagation need not integrate every element of all of the spacecraft. In this example, the trajector is integrated for all three spacecraft. The state transition matrix is only propagated for the first and third spacecraft, the attitude is propagated for the second, and the first spacecraft is depleting mass during a maneuver.

Figure 23.4 **This figure needs updating to include the second PropVector for the trajectory piece** shows a mixed mode propagation, where the trajectory for our three spacecraft is propagated using a precalculated, ephemeris based propagator and the attitude is propagated numerically.

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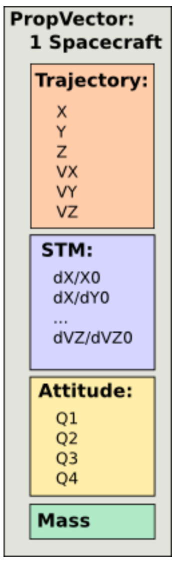

Figure 23.1: Representative Elements of a PropVector

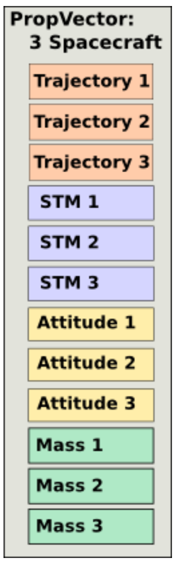

Figure 23.2: Element Arrangement of a PropVector for Three Spacecraft

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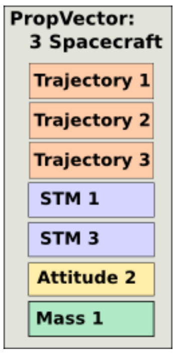

Figure 23.3: Three Spacecraft Arrangement for Select Propagation

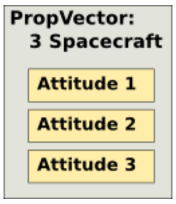

Figure 23.4: PropVector for Attitude Only Propagation on Three Spacecraft

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Chapter 24

Force Modeling in GMAT

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Chapter 22 describes GMAT's propagation subsystem, and introduced the force model container class used to perform precision propagation. This chapter describes the implementation of individual components of the force model.

24.1 Component Forces

$$\mathbf{F} = \mathbf{f}_{grav} + \sum_{bodies} \mathbf{f}_{thirdbodies} + \mathbf{f}_{SRP} + \mathbf{f}_{aero} \tag{24.1}$$

24.1.1 Gravity from Point Masses

$$a_{pm} = -\frac{\mu}{r^3}\vec{r} \tag{24.2}$$

24.1.2 Aspherical Gravity

24.1.3 Solar Radiation Pressure

$$a_{SRP} = -P_{\odot} C_R \frac{R_{AU}^2}{R_{\odot}^2} \frac{A}{m} \frac{\vec{r}_{\odot}}{r_{\odot}^3} \tag{24.3}$$

24.1.4 Atmospheric Drag

$$a_{drag} = -\frac{1}{2}\frac{C_d A}{m} \rho v_{rel}^2 \frac{\vec{v}_{rel}}{v_{rel}} \tag{24.4}$$

24.1.5 Engine Thrust

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Chapter 25

Maneuver Models

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Chapter 26

Mission Control Sequence Commands

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26.1 Command Overview

Users model the evolution of spacecraft over time in GMAT using a mission control sequence that consists of a series of commands. These commands are used to propagate the spacecraft, model impulsive maneuvers, turn thrusters on and off, make decisions about how the mission should evolve, tune parameters, and perform other tasks required to perform mission analysis. This chapter describes the core components of the system that implement this functionality. Chapter 27 provides a more in depth examination of the specific commands implemented in GMAT, providing details about the implementation of each.

26.2 Structure of the Sequence

The mission control sequence is designed to present users with a configurable, flexible mechanism for controlling the GMAT model. Commands may manipulate modeled components, control model visualization and other output data, determine the order of subsequent operations through looping or branching, tune parameters to meet mission criteria, or group commands together to be executed as a single block. Each GMAT Sandbox is assigned its own mission control sequence[1]. This design feature drives the late binding features of objects in the GMAT Sandbox (see Section 5.2.2), which, in turn, places demands for late binding support on the GMAT commands. The following paragraphs provide an overview of these features. Implementation details are described later in the chapter.

26.2.1 Command Categories

GMAT commands can be broken into four distinct categories: "Regular" commands, Control Logic commands, Solver commands, and Function commands, as described here.

Regular commands are commands that perform a single, isolated operation and do not depend on any other command to operate. Examples of the regular command are the Propagate command and the Maneuver command. The regular commands can appear anywhere in the Mission Control Sequence.

[1]While the current implementation of GMAT has a single Sandbox, GMAT is designed to support multiple sandboxes.

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Control Logic commands are used to perform control flow operations in the Mission Control Sequence. Each control logic command controls a list of commands – called the command subsequence – that is executed by the control logic command when that command determines that execution is needed. All control logic commands are paired with a matching End command. The End commands identify the end of the command subsequence controlled by the control logic command.

GMAT supports three control logic commands: If, While and For, which are paired with the commands EndIf, EndWhile and EndFor. For commands are used to iterate over the subsequence for a fixed number of iterations. If commands provide a mechanism to fork the Mission Control Sequence based on conditions detected during execution. While commands are used to iterate over the command subsequence until some condition is met.

Solver commands are similar to control logic commands in that they manage a command subsequence and use that subsequence to explore how changes in parameters affect the results of executing the subsequence. GMAT has three classes of solver commands: Targeters, Optimizers, and Iterators. Targeters adjust parameters in order to meet a specific set of goals. Optimizers also adjust parameters, in order to find the set that optimizes a problem objective. Iterators are used to observe the results of changes to parameters, so that the statistical behavior or the solution space of the subsequence can be measured and recorded.

One key difference between solver commands and control logic commands is that for the control logic commands, the changes to the spacecraft and other mission components applied during a subsequence run affect subsequent runs of the subsequence. Solvers reset the spacecraft states from one iteration to the next, so that the effect of changes to the input parameters are applied to the same set of initial conditions from one iteration of the subsequence to the next.

Functions are used in GMAT to generalize common tasks, to communicate with MATLAB, and to encapsulate multistep tasks into a single call in a mission. *The function subsystem design will be documented at a later date.*

26.2.2 Command Sequence Structure

The mission control sequence is implemented as a linked list of command objects. The sequence is constructed from a script by appending links to the list as they are constructed by the script interpreter. Commands that control subsequences build the subsequences by managing a child linked list. The child list is constructed by appending links until the related subsequence termination command is encountered, terminating the subsequence list.

Users can also interact with the command sequence from the GMAT GUI; these interactions let users append commands to the sequence, insert commands at intermediate points, and remove commands. Users view the sequence as a hierarchical tree, as shown in Figure 26.1. The mission is modeled by executing the commands in the linked list sequentially. The mission tree shown on the GUI provides a graphical view into the linked list, including the command subsequences for commands that control subsequences. The top node in the tree is the the first link in the list; in the figure, that node is a Propagate command, labeled Propagate1 on the mission tree. The entire linked list consists of seven nodes: Propagate - Propagate - Target - Propagate - Propagate - Target - Propagate. Each of the target nodes controls a subsequence used in the targeting process. The first of these nodes is expanded in the figure to show the subsequence. For this example, the subsequence consists of five links: Vary - Maneuver - Propagate - Achieve - EndTarget.

Rework this piece – it's not currently used GMAT does not restrict the depth of the nesting levels for the commands that control subsequences. The command classes include a counter that monitors the current nesting level in the command sequence. The nesting level is set when the command is added to the linked list. The main command sequence has a nesting level of 0. Subsequences off of the main sequence increment the level to 1; subsequences contained in these subsequences have a nesting level of 2, and so forth. The subsequence termmination commands, typically identified by an "End" prefix, have a nesting level set

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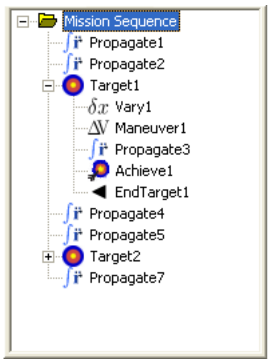

Figure 26.1: GMAT Command Sequence in the GUI

to the same level as the rest of the subsequence, because they are the last command in the subsequence, and therefore exist at the subsequence level.

26.2.3 Command–Sandbox Interactions

When a mission control sequence is run, all of the configured objects used in the run are copied from the Configuration Manager into the Sandbox used for the run. These copies are place into a standard template library (STL) map matching the object names to pointers to the local copies in the Sandbox. These pointers need to be bound to the commands prior to execution of the mission control sequence. This late binding is performed during the initialization phase described below. Additional details about the late bindign strategy implemented in GMAT can be found in Section 5.2.2.

During mission control sequence execution, the commands interact with the object copies to model the interactions dictated for the model, as described in the execution section below. These interactions change the local copies, modeling the evolution of the system. Once the command sequence completes execution (either by finishing the sequence, encountering a "Stop" command, or detecting a user generated stop event), each GMAT command is given the opportunity to complete any pending operations. This final step, described in the Finalization section below, is used to close open file handles, clean up temporarily allocated memory, and perform any other housekeeping tasks needed to maintain the mission control sequence for subsequent user actions.

26.3 The Command Base Classes

Figure 26.2 shows core properties of the base classes used in the Command subsystem. The top level base class, GmatCommand, provides linked list interfaces and methods used to parse command scripts. BranchCommand adds capabilities to implement and execute commands that run subsequences – specifically, the Control Logic, Solver, and Function categories of commands. Additional capabilities required by the Control Logic commands are provided by the ConditionalBranch class. Capabilities shared by all Solvers are implemented in the SolverBranchCommand class.

26.3.1 List Interfaces

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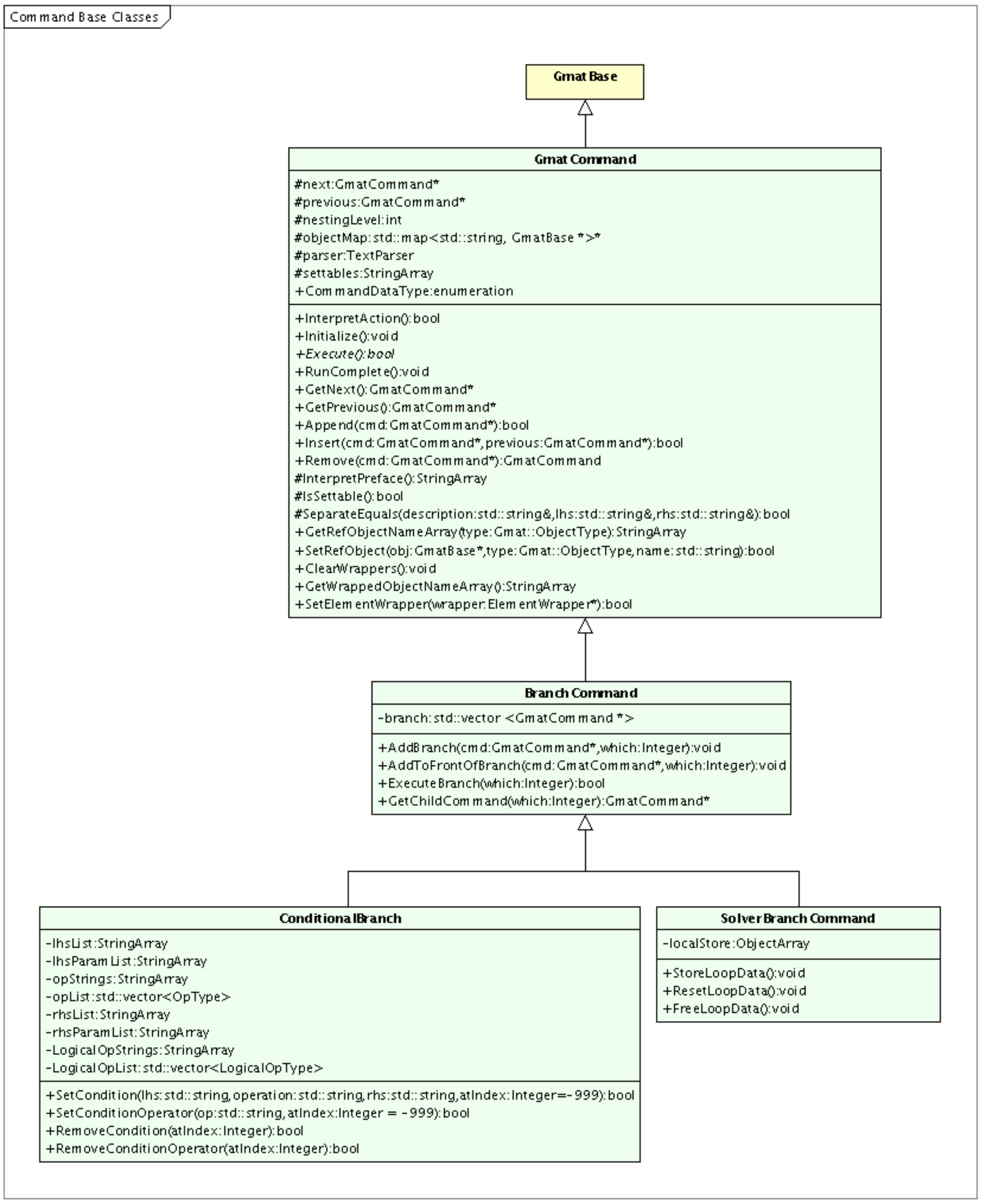
Command Base Classes
GmatBase
GmatCommand
#next:GmatCommand*
#previous:GmatCommand*
#nestingLevel:int
#objectMap:std::map<std::string, GmatBase *>*
#parser:TextParser
#settables:StringArray
+CommandDataType:enumeration
+InterpretAction():bool
+Initialize():void
+Execute():bool
+RunComplete():void
+GetNext():GmatCommand*
+GetPrevious():GmatCommand*
+Append(cmd:GmatCommand*):bool
+Insert(cmd:GmatCommand*,previous:GmatCommand*):bool
+Remove(cmd:GmatCommand*):GmatCommand
#InterpretPreface():StringArray
#IsSettable():bool
#SeparateEquals(description:std::string&,lhs:std::string&,rhs:std::string&):bool
+GetRefObjectNameArray(type:Gmat::ObjectType):StringArray
+SetRefObject(obj:GmatBase*,type:Gmat::ObjectType,name:std::string):bool
+ClearWrappers():void
+GetWrappedObjectNameArray():StringArray
+SetElementWrapper(wrapper:ElementWrapper*):bool
BranchCommand
-branch:std::vector <GmatCommand *>
+AddBranch(cmd:GmatCommand*,which:Integer):void
+AddToFrontOfBranch(cmd:GmatCommand*,which:Integer):void
+ExecuteBranch(which:Integer):bool
+GetChildCommand(which:Integer):GmatCommand*
ConditionalBranch
-lhsList:StringArray
-lhsParamList:StringArray
-opStrings:StringArray
-opList:std::vector<OpType>
-rhsList:StringArray
-rhsParamList:StringArray
-LogicalOpStrings:StringArray
-LogicalOpList:std::vector<LogicalOpType>
+SetCondition(lhs:std::string,operation:std::string,rhs:std::string,atIndex:Integer=-999):bool
+SetConditionOperator(op:std::string,atIndex:Integer = -999):bool
+RemoveCondition(atIndex:Integer):bool
+RemoveConditionOperator(atIndex:Integer):bool
SolverBranchCommand
-localStore:ObjectArray
+StoreLoopData():void
+ResetLoopData():void
+FreeLoopData():void

Figure 26.2: Base Classes in the Command Subsystem

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26.3.2 Object Interfaces

To be filled in

26.3.3 Other Interfaces

To be filled in

26.4 Script Interfaces

The standard script syntax for a command is the command name followed by zero or more text strings separated by white space. Commands that are scripted using this syntax are handled generically in the Interpreter subsystem, as described in Chapter 17[2]. Commands that use more complex scripting than a simple list of elements manage their own parsing in a customized implementation of the InterpretAction() method. This section describes the command base class structures and methods that are used by commands that override InterpretAction() and parse their configurations internally. Parsing for Commands that do not override the InterpretAction() method is handled in the ScriptInterpreter. The methods described in the following text are not used by those Commands.

26.4.1 Data Elements in Commands

Commands can be scripted to describe the actions taken on elements of the model (i.e. objects instantiating GMAT classes), or to manipulate specific data elements of these objects based on the rules encoded into the command. When performing the latter task, the specific data element is accessed using an ElementWrapper helper object that can manipulate data represented by the following types: numbers, object properties, variables, array elements, and Parameter objects. In addition, commands may be construsted in the future that operate on Array objects and strings; the infrastructure needed for these objects is included in the wrapper enumerations, but not yet implemented.

The data wrappers are described in Section 26.4.3[3]. These wrappers are designed to be used by commands when needed to handle single valued Real data elements in the commands. The Gmat namespace includes an enumeration, WrapperDataType, with entries for each of the supported data types. This enumeration is described in Section 9.5.2. The data wrappers are used to standardize the interface to numbers, object properties, variables, array elements, and other Parameter objects to perform the command operations. Arrays and Strings are handled separately by the commands – arrays, because they can have more than one value, and strings, because they do not provide Real number data for use in the commands.

Figure 26.3 shows an overview of the process used to build and validate commands encountered in scripts and on the GUI. The portions of the digram colored orange are performed through calls launched by the ScriptInterpreter. Commands created from the GUI follow the procedure shown in purple. In both cases, once the command has been built and the early binding data has been set, the command is validated using methods provided by the Interpreter base class. The calls made for this validation include calls that build the ElementWrapper members used in the command. These calls are shown in the figure in blue.

The process shown in Figure 26.3 must be performed before the mission control sequence can be executed in a Sandbox. That includes identifying all of the names of configured objects that the sequence will need, creation of any Parameters (performed in the CheckUndefinedReference method) that will be required, and creation of the DataWrappers that will need to be populated during Initialization in the Sandbox.

THe following subsections describe the support methods provided by the Interpreter and GUI subsystems to configure the command objects. These paragraphs are separated to match the three sections of Figure 26.3.

[2]Some commands that do not follow this generic description are also handled in the Interpreters at this writing.
[3]The ElementWrappers use the Adapter design pattern, described in B.5

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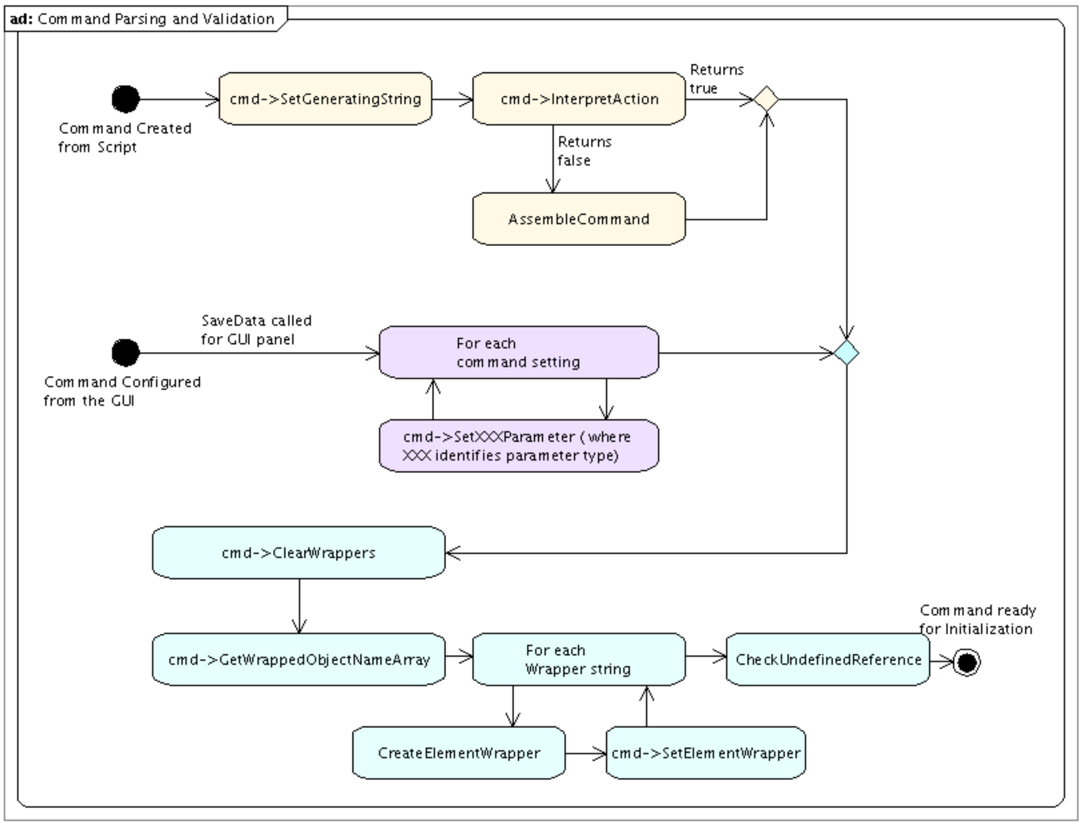
ad: Command Parsing and Validation
Command Created from Script
cmd->SetGeneratingString
cmd->InterpretAction
Returns true
Returns false
AssembleCommand
SaveData called for GUI panel
Command Configured from the GUI
For each command setting
cmd->SetXXXParameter (where XXX identifies parameter type)
cmd->ClearWrappers
cmd->GetWrappedObjectNameArray
For each Wrapper string
CheckUndefinedReference
Command ready for Initialization
CreateElementWrapper
cmd->SetElementWrapper

Figure 26.3: Calls Made in the Interpreters to Build and Validate Commands. Specific calls to the command are prefaced on this diagram with the C++ pointer notation, "cmd->".

26.4.1.1 Scripted Command Configuration: Interpreter Support

Scripted commands are configured using the Interpreter::CreateCommand method called from the ScriptInterpreter while parsing a script. The parsing process followed for commands is described at a high level in Section 17.4.1.4. The Interpreter base class provides several methods that facilitate that process, described here:

- **GmatCommand* CreateCommand(const std::string &type, const std::string &desc, bool &retFlag, GmatCommand *inCmd = NULL)**: The method that drives the command creation process for the ScriptInterpreter. This method takes the generating string for the command as found in the script, and creates an instance of the corresponding GmatCommand object. It then calls InterpretAction() on the command; if that call fails, it calls the Interpreter's AssembleCommand method. Finally, it builds any wrappers needed by the command, and validates that referenced objects used in the command have been created.
- **bool AssembleCommand(GmatCommand *cmd, const std::string &desc)**: Commands that are not internally parsed are configured in this method.

Once this step has been completed, the command has been created and strings have been set decribing all objects and data wrappers referenced by the command. The data wrappers are not yet created; thaqt process is described after the next subsection.

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26.4.1.2 Command Configuration in the GUI

The GMAT GUI configures commands directly, based on the entries made by a user on the GUI panel corresponding to the command. Commands are created when a user inserts them into the mission control sequence, configured with default settings. When a user opens the configuration panel, makes changes, and then applies the changes using either the Apply of OK button, the panel calls an internal method, "SaveData", which passes the data on the panel to the command object.

The data passed into the object identifies all of teh objects referenced by the command. Commands configured by the GUI typically get populated with valid descriptors; as we will see shortly, the validation is repeated after the data wrappers are built, as described in teh next section. All data that requires wrappers is passed into the command as an std::string, using the SetStringParameter method. The command stores these data for use contructing the wrappers.

26.4.1.3 Interpreter Support for Wrappers and Validation

Once GMAT has completed the steps described above, the command is configured with strings describing wrappers and referenced objects, along with any other command specific data needed to fully configure the command. The final steps used configuring the command are shown in blue on Figure 26.3. These steps are all encapsulated in the Interpreter method ValidateCommand. The methods in the Interpreter base class used for wrapper construction and validation are provided here:

- **void ValidateCommand(GmatCommand *cmd)**: The method that executes the steps shown in blue on the figure. This method is called directly from the GUI, and as the final piece of CreateCommand from the ScriptInterpreter.
- **ElementWrapper* CreateElementWrapper(const std::string &description)**: This method takes the descripion of a wrapper object and builds the corresponding wrapper.
- **bool CheckUndefinedReference(GmatBase *obj, bool writeLine = true)**: Method used to verify that all referenced objects needed by the object (in this case, a Command) exist. The command is passed in as the first parameter. The second parameter is a flag indicating if the line number in the script should be written; for commands, that flag is left at its default true value.

CreateElementWrapper Of these methods, the CreateElementWrapper bears additional explanation. The following steps are implemented in that method:

1. Determine if the string is a number. If so, create a NumberWrapper, set its value, and return the wrapper.
2. Check to see if there a parentheses pair in the string. If so, perform the following actions:
   - Check to see if the text preceding the opening paren is an array. If not, throw an exception.
   - Create an ArrayElementWrapper, and set the array name to the text preceding the opening paren.
   - Separate text enclised in the parentheses into row and column strings.
   - Call CreateElementWrapper() for the row and column strings, and set the corresponding wrappers and strings in the ArrayElementWrapper.
   - Return the wrapper.
3. Check to see if there a period in the string. If so, the wrapper needs to be either an ObjectProperty-Wrapper or a ParameterWrapper. Performs these steps to create the correct type:
   - Break apart the string using the GmatStringUtil::ParseParameter method.

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- Find the owner object, and check to see if it has the type provided in the string. If so, create an ObjectPropertyWrapper, otherwise create a ParameterWrapper
- Set the description string.

Return the resulting wrapper.

4. Check to see if the string describes a Variable. If so, create a VariableWrapper, set the description and value, and return the wrapper; otherwise, throw an exception[4].

26.4.2 Command Support for Parsing and Wrappers

The command base class, GmatCommand, includes an instance of the TextParser described in Section 17.3.3, along with an include statement for the GmatStringUtil namespace definition (see Section 10.4 for details of the GmatStringUtil namespace). These inclusions make all of the methods used for general purpose parsing of text from the TextParser and the low level GmatStringUtil namespace functions available for use in command parsing. These elements are used by custom InterpretAction() methods when they are implemented for the commands.

The base class also provides methods used during the creation and validation of the data wrappers. These methods are used by the ScriptInterpreter, interacting with the Moderator in the Interpreter::CreateCommand() method, to validate the objects required by the data wrappers. The methods supplied by the command base class to support data wrappers are described in Section 26.4.4. Before describing these methods, the wrapper classes will be described.

26.4.3 Data Type Wrapper Classes

Many of the commands need to be able to treat all of the usable data types through a common interface. Table 26.1 presents representative examples to the allowed data types in commands. The data type interface used by the commands is captured in the ElementWrapper class, shown with its subclasses in Figure 26.4. Derived classes are available for each of the supported types, using these classes: NumberWrapper, ObjectPropertyWrapper, VariableWrapper, ArrayElementWrapper, and ParameterWrapper. The Array class, when accessed as an entity rather than as a data provider for a single Real number, is handled as a special case by any command designed to work with Array instances. As indicated in the table, no current command uses this capability, though it will be supported in the NonlinearConstraint command in a future release of GMAT. Similarly, strings are handled separately.

The wrapper classes implement the following methods:

- **std::string GetDescription()** Returns the current description string for the wrapper.
- **void SetDescription(const std::string &desc)** Sets the description string.
- **const StringArray &GetRefObjectNames()**: Returns a StringArray containing a list of all reference objects used by the wrapper.
- **bool SetRefObject(GmatBase *obj)**: Passes the a pointer to the reference object into the wrapper so it can be assigned to the correct internal member.
- **void SetupWrapper()**: Takes the description string and breaks it into components for later use.

In addition, each ElementWrapper provides two abstract interfaces that can be used during command execution:

- **Real EvaluateReal()** is used to calculate the current value of the wrapped object, returning a Real number when fired.

[4]A later build will detect and return NULL for Array or String objects, so that they can be handled when needed.

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Table 26.1: Script Examples of Parameters Used in Commands

Type	**Examples**	**Notes**
Number	1, 3.1415927, 3.986004415e5, 6.023e23	Integers and Reals are treated identically
Object Parameter	Sat.X, Burn.V, Thruster.ScaleFactor	Any object parameter
Parameters	Sat.Longitude, Sat.Q4	Any Calculated Parameter
Variables	I, Var	Any Variable object
Array Element	A(2, 3), B(I, J), C(D(1, K), E(F(2, 3), L))	Any array entry. Array row and column indices can be specified using any allowed type
Array	A	An entire array. Arrays are not yet supported in GMAT commands. The NonlinearConstraint command will be updated to use single column arrays (aka vectors) in a later build.
String	"This is a string"	A block of text treated as a single entity.

- **bool SetReal(const Real value)** takes a Real number as input, and sets the wrapped element to that value. It returns a flag indicating success or failure of the data setting operation.

The derived wrapper classes implement these methods (and override the other methods as needed) to access the data structures corresponding to each data type.

26.4.4 Command Scripting Support Methods

The Interpreter subsystem provides the methods needed to construct the data wrapper classes and pass the wrappers into the commands. GmatCommand provides the following methods to support this process:

- **void ClearWrappers()**: Deletes all current wrappers in preparation for a new set of wrapper instances.
- **const Stringarray &GetWrappedObjectNameArray()**: Returns a list of all wrapper descriptions so that the required wrappers can be constructed.
- **bool SetElementWrapper(ElementWrapper *wrapper)**: Sends the wrapper into the command. If the wrapper is set correctly, this method returns true. If the description contained in the wrapper does not match a description in the command, the wrapper is destroyed, and false is returned from this method. All other error result in a thrown exception.

Note that commands own the wrappers passed in, and are responsible for managing the associated memory.

26.5 Executing the Sequence

The mission control sequence is run in a GMAT Sandbox, following a series of steps described in Section 3.2.5. In this section, the command specific steps are described in a bit more detail.

26.5.1 Initialization

26.5.2 Execution

To be filled in

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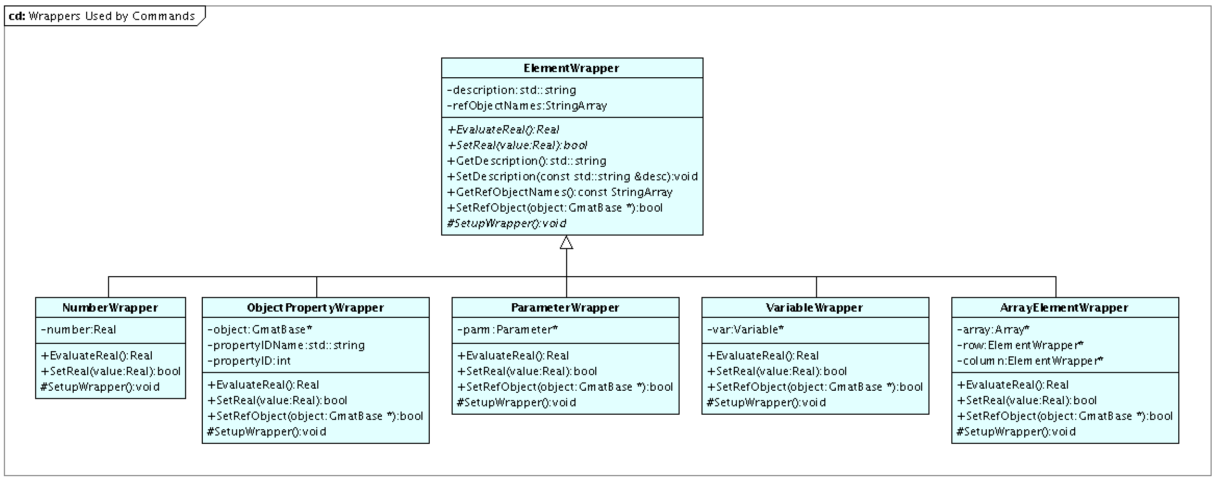
cd: Wrappers Used by Commands
ElementWrapper
-description:std::string
-refObjectNames:StringArray
+EvaluateReal():Real
+SetReal(value:Real):bool
+GetDescription():std::string
+SetDescription(const std::string &desc):void
+GetRefObjectNames():const StringArray
+SetRefObject(object:GmatBase *):bool
#SetupWrapper():void
NumberWrapper
-number:Real
+EvaluateReal():Real
+SetReal(value:Real):bool
#SetupWrapper():void
ObjectPropertyWrapper
-object:GmatBase*
-propertyIDName:std::string
-propertyID:int
+EvaluateReal():Real
+SetReal(value:Real):bool
+SetRefObject(object:GmatBase *):bool
#SetupWrapper():void
ParameterWrapper
-parm:Parameter*
+EvaluateReal():Real
+SetReal(value:Real):bool
+SetRefObject(object:GmatBase *):bool
#SetupWrapper():void
VariableWrapper
-var:Variable*
+EvaluateReal():Real
+SetReal(value:Real):bool
+SetRefObject(object:GmatBase *):bool
#SetupWrapper():void
ArrayElementWrapper
-array:Array*
-row:ElementWrapper*
-column:ElementWrapper*
+EvaluateReal():Real
+SetReal(value:Real):bool
+SetRefObject(object:GmatBase *):bool
#SetupWrapper():void

Figure 26.4: Parameter Wrappers Used by Commands

26.5.3 Finalization

To be filled in

26.5.4 Other Details

To be filled in

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Chapter 27

Specific Command Details

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Chapter 26 provided an introduction and description of the GMAT command classes and their usage when building a Mission Control Sequence. In this chapter, the command classes are described on a class by class level.

27.1 Command Classes

Figure 27.1 shows the command classes incorporated into GMAT at this writing. The base class elements GmatCommand, BranchCommand, ConditionalBranch, and SolverBranchCommand are described in Chapter 26. This chapter looks at the details of the derived classes shown in the figure, providing implementation specifics for these commands. The following paragraphs review the role played by the command base classes and identify pertinent utilities supplied by these bases that the derived classes use to implement their capabilities.

27.1.1 The GmatCommand Class

Every entry in the mission control sequence is implemented as a class derived from GmatCommand. This base class defines the interfaces used for the linked list structures that implement the control sequence. The `next` and `previous` members implement the links for the list structure.

Commands are initialized in the Sandbox, as described in Section 5.2.2.1. They contain three data structures, set by the Sandbox, that are used to set pointers correctly prior to execution. These structures, `objectMap`, `solarSys`, and `publisher`, are the structures managed by the Sandbox to run a misison control sequence. The `objectMap` and `solarSys` are the local copies of the configured objects and space environment used when running the model, and need to be accessed and used to set the pointers required in the commands to run in the Sandbox. This setup is performed in the command's Initialize() method. The `publisher` member is a pointer to the global GMAT Publisher, used to send data to the Subscriber subsystem.

Each GmatCommand implements the Execute() method defined in GmatCommand. This method, along with the internal supporting data structures and support methods, distinguish one command from another. Execute() performs the actions built into the command, manipulating the configured objects to make the model evolve in the Sandbox.

The GmatCommand class provides a generic implementation of the InterpretAction() method, used when parsing lines of script. Derived classes that need special handling for this parsing override InterpretAction() to implement the parsing. The GmatCommand base includes an instance of the TextParser so that derived commands have the facilities provided for parsing.

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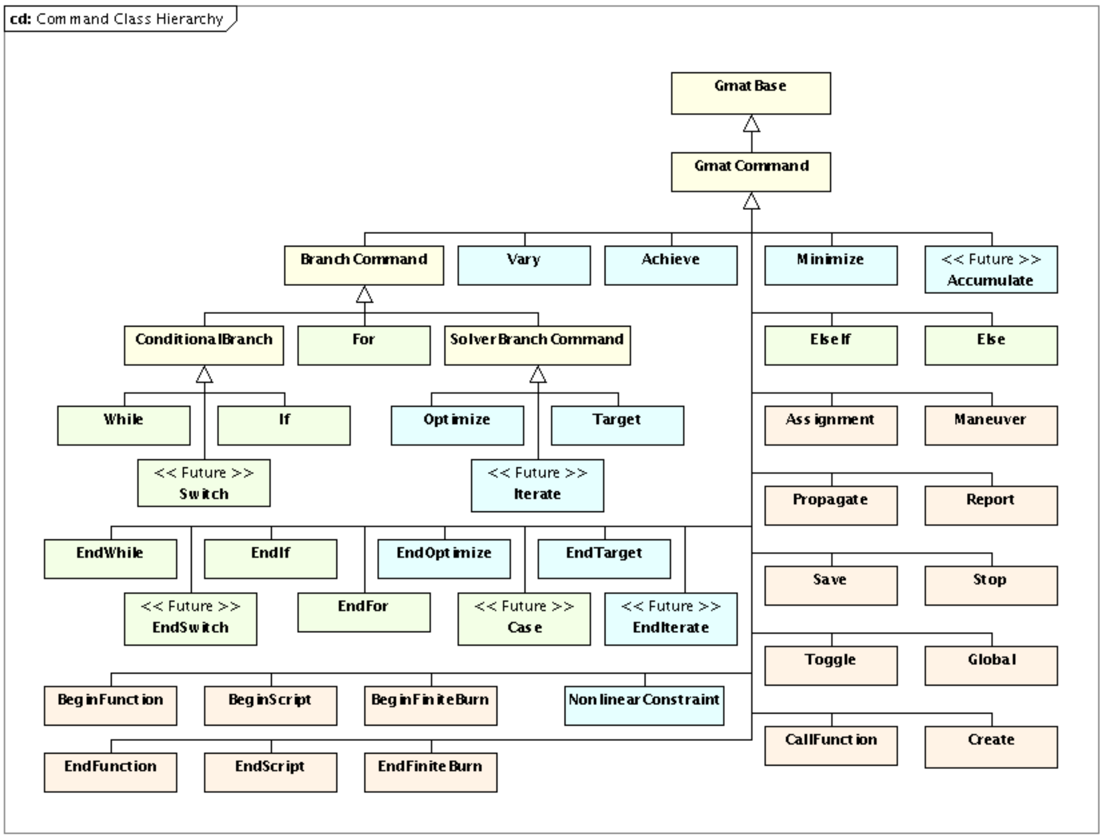

Figure 27.1: GMAT Command Classes.
Classes shown in yellow are base classes, green are control flow commands, blue are commands related to Solvers, and orange are stand alone commands.

27.1.2 Branch Commands

Nesting in the mission control sequence is implemented through the BranchCommand base class. This class, derived from GmatCommand, adds one or more branches to the main misison sequence. The core feature os the BranchCommands is the ability to execute these branches when conditions dictate that the branch should execute. This feature provides users with the ability to execute commands conditionally, to loop over a set of commands, and to run routines that tune the mission to meet or optimize selected goals.

27.1.2.1 Conditional Branch Commands

Some branch commands need the ability to evaluate conditions in order to determine if a branch should be executed. THe ConditionalBranch class provides the structures needed to identiofy and evaluate these conditions.

27.1.2.2 Solver Commands

The Solver subsystem uses several commands designed to interoperate with the Solvers. Because of the close linkage between these commands and the corresponding solvers, the description for these commands

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is given in Section 28.7.1. The commands defined in that section are the branch commands Iterate/EndIterate, Target/EndTarget, and Optimize/EndOptimize, and the GmatCommands Vary, Achieve, Minimize, NonlinearConstraint, Gradient, and TBD commands associated with the scanners.

The nature of the problem encountered when running the Solvers requires that the sytates of many of the objects defined in the Sandbox be stored at the start of the Solver execution, so that they can be reset as the Solver iterates over the variables used to perform its tasks. The SolverBranchCommand class provides the data structures and methods needed to maintain these states while the Solvers are performing their tasks.

27.1.3 Functions

To be filled in

27.2 Command Details

27.2.1 The Assignment Command

Assignment commands implement the methods necessary for users to pass data into and between objects, and to create copies of objects at specific points in the model, for use in the mission control sequence. Assignment commands are used to set one or more object properties while executing the mission control sequence. As can be see in Table 27.1, the command has the general form

$$\texttt{LHS} = \texttt{RHS} \tag{27.1}$$

where the `LHS` entry is a single object or object property, and the `RHS` entry is a number, object or object property, or equation.

Table 27.1: Assignment Command

Script Syntax: `GMAT Arg1 = Arg2;`

Command Description	
`Arg1`	Default: N/A . Options:[Spacecraft Parameter, Array element, Variable, or any other single element user defined parameter]: The `Arg1` option allows the user to set `Arg1` to `Arg2`. Units: N/A.
`Arg2`	Default: N/A . Options:[Spacecraft Parameter, Array element, Variable, any other single element user defined parameter, or a combination of the aforementioned parameters using math operators]: The `Arg2` option allows the user to define `Arg1`. Units: N/A.

Script Examples

% Setting a variable to a number
```
GMAT testVar = 24;
```
% Setting a variable to the value of a math statement
```
GMAT testVar = (testVar2 + 50)/2;
```

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27.2.2 The Propagate Command

Propagation is controlled in the Mission Control Sequence using the Propagate command, which has syntax described in Table 27.2.

Table 27.2: Propagate Command

ScriptSyntax

```
Propagate Mode BackProp PropagatorName(SatList1,{StopCondList1}) ...
BackPropPropagatorName(SatListN,{StopCondListN})
```

Option	Option Description
BackProp	Default: None. Options: [Backwards or None]: The BackProp option allows the user to set the flag to enable or disable backwards propagation for all spacecraft in the the SatListN option. The Backward Propagation GUI check box field stores all the data in BackProp. A check indicates backward propagation is enabled and no check indicates forward propagation. In the script, BackProp can be the word Backwards for backward propagation or blank for forward propagation. Units: N/A.
Mode	Default: None. Options: [Synchronized or None]: The Mode option allows the user to set the propagation mode for the propagator that will affect all of the spacecraft added to the SatListN option. For example, if synchronized is selected, all spacecraft are propagated at the same step size. The Propagate Mode GUI field stores all the data in Mode. In the script, Mode is left blank for the None option and the text of the other options available is used for their respective modes. Units: N/A.
PropagatorName	Default: DefaultProp. Options: [Default propagator or any user-defined propagator]: The *PropagatorName* option allows the user to select a user defined propagator to use in spacecraft and/or formation propagation. The Propagator GUI field stores all the data in *PropagatorName*. Units: N/A.
SatListN	Default: DefaultSC. Options: [Any existing spacecraft or formations, not being propagated by another propagator in the same Propagate event. Multiple spacecraft must be expressed in a comma delimited list format.]: The SatListN option allows the user to enter all the satellites and/or formations they want to propagate using the *PropagatorName* propagator settings. The Spacecraft List GUI field stores all the data in SatListN. Units: N/A.
StopCondListN /Parameter	Default: DefaultSC.ElapsedSecs =. Options: [Any single element user accessible spacecraft parameter followed by an equal sign]. The StopCondListN option allows the user to enter all the parameters used for the propagator stopping condition. See the StopCondListN/Condition Option/Field for additional details to the StopCondListN option. Units: N/A.

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Table 27.2: Propagate Command . . . continued

`StopCondListN` /Condition	Default: 8640.0. Options: [Real Number, Array element, Variable, spacecraft parameter, or any user defined parameter]. The `StopCondListN` option allows the user to enter the propagator stopping condition's value for the `StopCondListN` Parameter field. Units: Dependant on the condition selected.

Script Examples

```
% Single spacecraft propagation with one stopping condition
% Syntax #1
Propagate DefaultProp(DefaultSC, {DefaultSC.ElapsedSecs = 8640.0});

% Single spacecraft propagation with one stopping condition
% Syntax #2
Propagate DefaultProp(DefaultSC) {DefaultSC.ElapsedSecs = 8640.0};

% Single spacecraft propagation by one integration step
Propagate DefaultProp(DefaultSC);

% Multiple spacecraft propagation by one integration step
Propagate DefaultProp(Sat1, Sat2, Sat3);

% Single formation propagation by one integration step
Propagate DefaultProp(DefaultFormation);

% Single spacecraft backwards propagation by one integration step
Propagate Backwards DefaultProp(DefaultSC);

% Two spacecraft synchronized propagation with one stopping condition
Propagate Synchronized DefaultProp(Sat1, Sat2, {DefaultSC.ElapsedSecs = 8640.0});

% Multiple spacecraft propagation with multiple stopping conditions and propagation settings
% Syntax #1
Propagate Prop1(Sat1,Sat2, {Sat1.ElapsedSecs = 8640.0, Sat2.MA = 90}) ...
Prop2(Sat3, {Sat3.TA = 0.0});

% Multiple spacecraft propagation with multiple stopping conditions and propagation settings
% Syntax #2
Propagate Prop1(Sat1,Sat2) {Sat1.ElapsedSecs = 8640.0, Sat2.MA = 90} ...
Prop2(Sat3) {Sat3.TA = 0.0};
```

Each Propagate command identifies one or more PropSetup[1], consisting of an integrator and forcemodel defined to work together. Each PropSetup identifies one or more SpaceObject that it is responsible for advancing through time. This propagation framework allows users to model the motion of one or more SpaceObjects using different propagation modes, and to advance the SpaceObjects to specific points on the SpaceObject's trajectories.

[1]The object used in this role in GMAT is an instance of the PropSetup class. On the GUI and in GMAT scripting, the keyword used for PropSetup instances is "Propagator." In this document I'll use the class name, PropSetup, when referring to these objects.

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27.2.2.1 Propagation Modes

The Propagate command provides several different modes of propagation based on the settings passed into the command. These modes are described in the following list:

- **Unsynchronized Propagation** Unsynchronized propagation is performed by executing the PropSetups assigned to a Propagate command independently, allowing each PropSetup to find its optimal step without regard for other PropSetups assigned to the command.
- **Synchronized Propagation** Synchronized propagation steps the first PropSetup assigned to the command using its optimal step, and then advances the remaining PropSetups by the same interval, so that the epochs for all of the PropSetups remain synchronized during integration.
- **Backwards Propagation** GMAT usually integrates SpaceObjects so that the epoch of the SpaceObject increases. Integration can also be performed so that the epoch decreases, modeling motion backwards in time.
- **Propagation to Specific Events** Propagation can be performed in GMAT until specific events occur along a SpaceObject's trajectory. When the one of these specified events occurs, the Propagate command detects that a condition requiring termination of propagation has occurred, finds the time step required to reach the epoch for that termination, and calls the PropSetups to propagate the SpaceObjects for that period.
- **Single Step Propagation** When no specific events are specified as stopping conditions, the Propagate command takes a single propagation step and exits.

27.2.2.2 The Propagation Algorithm

Figure 27.2 shows the basic process implemented in the Propagate command. Propagation usually consumes the bulk of the time required to run a mission in GMAT. Because of this feature, the Propagate command was written to support execution across several steps in the Sandbox, so that the Sandbox can poll for user interruption during propagation. There are several initialization steps required at the start of propagation that should not be performed when reentering the command from a polling check in the Sandbox. These steps are performed in the PrepareToPropagate() method identified in the figure.

Once the Propagate command is ready to perform propagation, the force models used in propagation are initialized to the start of the step about to be taken, and then the PropSetups take a single integration step. The resulting integrated states are passed into the relevant SpaceObjects through calls to the ForceModel's UpdateSpaceObject methods.

The next action depends on the propagation stopping mode: if the Propagate command is operating in single step mode, propagation is complete and control exits the propagation loop. Otherwise, the stopping conditions are evaluated and compared to the desired stopping events. If no stopping conditions have been passed or met, the integrated state data is passed to GMAT's Publisher for distribution. The command then determines if an interrupt check is required; if so, control is returned to the Sandbox for the check, otherwise, the propagation loop resumes with an update to the ForceModel.

If a stopping condition was triggered, it is first tested to ensure that the triggered stopping condition is not an artifact of a previous propagation execution. This test is only performed during the first propagation step of a new execution. If the stopping condition passes this validation, control leaves the main propagation loop and enters the control logic implemented to terminate propagation at a specific stopping event, as described in the next section.

Once the propagation has been terminated, any transient forces set during propagation are cleared from the force models, command summary data is set when running with stopping conditions, and execution is completed.

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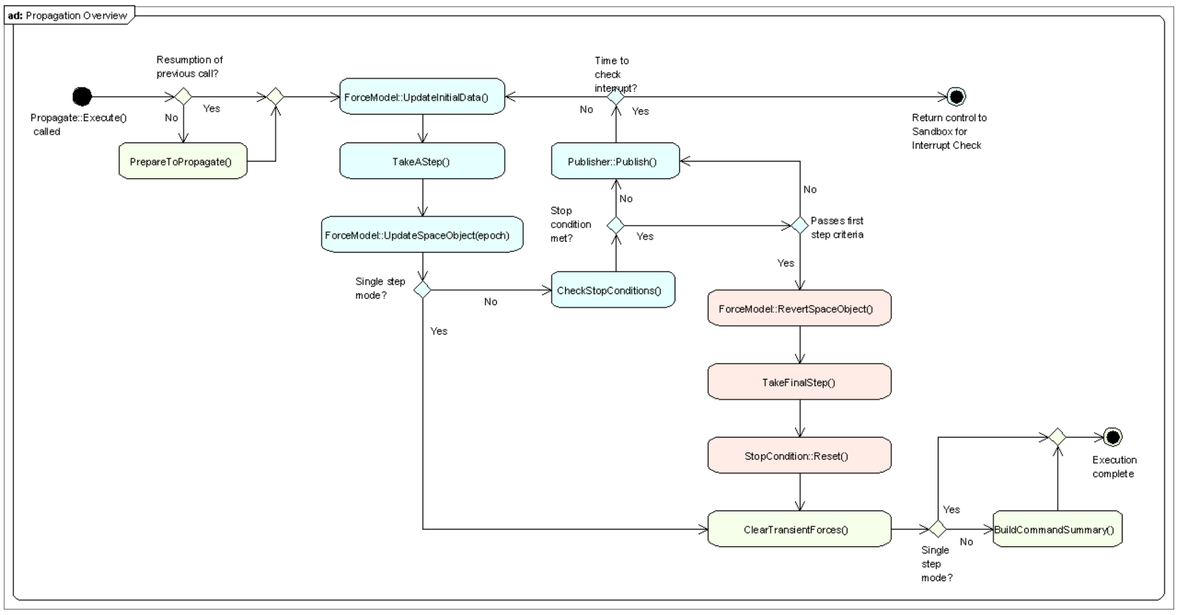

Figure 27.2: Executing the Propagate Command
The core propagation code is shown in blue. Steps taken during startup and shutdown are colored green. Steps used when stopping propagation at specific events are shown in red; additional details for the stopping condition algorithm are described below and shown in Figure 27.3.

27.2.2.3 The Stopping Algorithm

Propagation performed to reach specific events is terminated at points within a fixed tolerance of those events. The algorithm employed to take this final step is shown in Figure 27.3. Propagation used time as the independent parameter to evolve the states of the propagated SpaceObjects, so the stopping condition problem can be reduced to finding the time step that moves the SpaceObjects from the propagated state immediately prior to the desired event up to that event. The steps shown in the figure are used to find that time step, and to advance the SpaceObject states by that amount.

Stopping Condition Evaluation. The top portion of the figure shows the basic stopping condition evaluation procedure in the command. First the force model is prepared for a propagation step. If the stopping condition is a time based condition, the time step is estimated by subtracting the desired time from the current time. Stopping conditions that are not time based are estimated using a cubic spline algorithm, designed to avoid knots at the second and fourth points used when building the splines (see the description of the not-a-knot cubic spline in [MathSpec]). The steps performed when running the cubic spline are shown in the central portion of the figure and described below.

After the time step needed to reach the desired event has been estimated, the SpaceObjects are propagated using that time step. The resulting values for the stopping parameters are calculated and compared to the desired stop values. If the result is not within the stopping tolerance for the propagation, a further refinement is made to the time step estimate using a secant based implementation of Newton's method, described below and illustrated in the bottom portion of the figure.

Once the final propagation step has been performed to acceptable tolerance, the resulting propagated states are applied to the SpaceObjects. The Publisher is passed the new state data and instructed to empty

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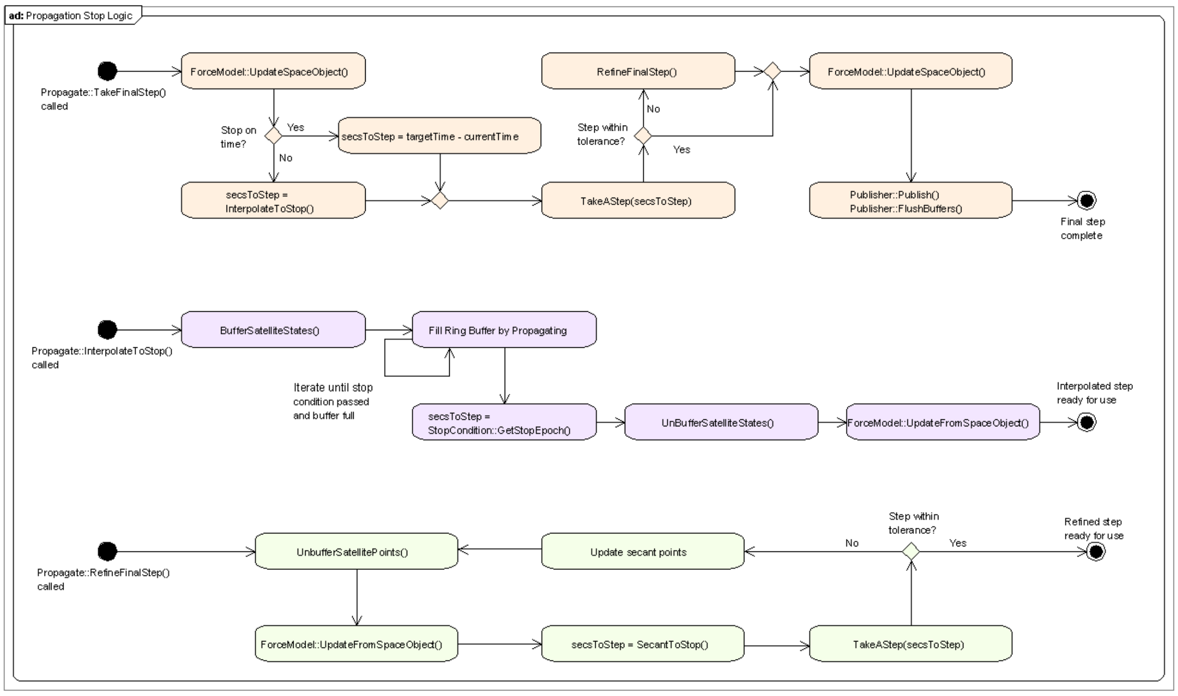
ad: Propagation Stop Logic
Propagate::TakeFinalStep() called
ForceModel::UpdateSpaceObject()
Stop on time?
Yes
No
secsToStep = targetTime - currentTime
secsToStep = InterpolateToStop()
TakeAStep(secsToStep)
Step within tolerance?
No
Yes
RefineFinalStep()
ForceModel::UpdateSpaceObject()
Publisher::Publish()
Publisher::FlushBuffers()
Final step complete
Propagate::InterpolateToStop() called
BufferSatelliteStates()
Fill Ring Buffer by Propagating
Iterate until stop condition passed and buffer full
secsToStep = StopCondition::GetStopEpoch()
UnBufferSatelliteStates()
ForceModel::UpdateFromSpaceObject()
Interpolated step ready for use
Propagate::RefineFinalStep() called
UnbufferSatellitePoints()
Update secant points
Step within tolerance?
No
Yes
Refined step ready for use
ForceModel::UpdateFromSpaceObject()
secsToStep = SecantToStop()
TakeAStep(secsToStep)

Figure 27.3: Algorithm Used to Stop Propagation
The core algorithm is shown in orange, in the sequence at the top of the figure. The initial estimate of the time step needed to reach the stop epoch is performed using a cubic spline algorithm; this sequence is shown in purple in the center of the diagram. If further refinements are needed, they are made using a secant algorithm, shown in the lower, green portion of the figure.

its data buffers. This completes the stopping algorithm.

Cubic Spline Details. The heart of the stop time estimation for events that are not time based is the not-a-knot cubic spline algorithm. The problem solved using this algorithm inverts the roles of the independent variable – the propagation time – and the dependent variable – the parameter that is advancing to reach some specific event – so that the desired time step can be generated based on the desired event value. Since we already know the time step that advances the SpaceObject states from one side of the desired event to the other, we have the time steps that bracket the stop time, and we need only refine this time using the spline interpolator.

The spline algorithm requires five pairs of data points to estimate this time. These data points are generating by propagating the SpaceObjects across the time interval that brackets the stop event in four equally spaced steps, evaluating the stop parameter after each step. These values and associated times, along with the parameter value and time at the start of the process, are used by the spline to estimate the time step needed to reach the target event. The implementation details, as shown in the figure, are described in the following paragraphs.

Before performing the necessary propagations, the SpaceObject states at the start of the procedure are

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buffered so that they can be restored later. The SpaceObjects are then propagated for a minimum of four steps, checking to ensure that the stop event is actually crossed. If the desired event is not crossed, additional propagation steps – up to a maximum of four additional steps – are allowed in order to continue searching for the condition required for stopping. If the event is still not encountered, and exception is thrown and execution terminates.

Once the spline buffer has been filled with values that bracket the stop event, the spline algorithm is called to get the time step that is estimated to produce target value. This time step is stored, the buffered states are reset on the SpaceObjects, and the force model is reset in proparation for a final propagation step. This completes the spline interpolation portion of the stopping condition evaluation.

Additional Refinements using a Secant Solver. For most stopping reqirements encountered in GMAT, the not-a-knot cubic spline solution described above is sufficiently accurate. However, there are cases in wich the propagation needs further refinement to meet mission requirements. In those cases, the cubic spline solution is refined using a secant based root finder. The resulting algorithm, shown in the bottom portion of Figure 27.3, is described in the following paragraphs.

The data in the force model at this point in the process is the propagated state data generated using the time step obtained from the cubic spline. Before proceding, these data are replaced with the state data at the start of the final step.

The next estimate, t_2, for the desired time step is made using the target parameter value, v_T, the calculated parameter value, v_0 at the epoch t_0 of the initial state and the value, v_1, obtained after the spline step, t_1, was applied using the formula

$$t_2 = v_T \frac{t_1 - t_0}{v_1 - v_0}. \tag{27.2}$$

This formula is evaluated in the SecantToStop method. The resulting time step is then applied to the SpaceObjects. If the resulting parameter value is withing acceptable tolerance, the refinement algorithm terminates. If not, the results from this new step are stored, the state data and force model are reset, and a new time step is calculated using the equation

$$t_{n+1} = v_T \frac{t_n - t_{n-1}}{v_n - v_{n-1}}. \tag{27.3}$$

This process repeats until either an integration step is taken that meets the propagator tolerance requirements, or an unacceptable number of attempts have been made and failed. The Propagate command will make 50 such attempts before raising an exception and termminating execution.

27.2.2.4 The Startup and Shutdown Routines

There are several steps that need to be applied before and after propagation to ensuree htat propagation uses and releases data that depends on the current state of the mission control sequence. The following paragraphs destribe these steps.

During startup , the Propagate command updates the object pointers and data structures to match the current state of the objects in the mission. *More to come here.*

Upon completion of propagation, the Propagate command resets its internal flags indicating that the command is ready to be called at a new point in the mission and clears any transient forces that have been set for the current propagation. If the command is not running in single step mode, the states of the SpaceObjects are accessed and stored in the command summary buffers for display on user request. (This operation is moderately expensive computationally, so it is not performed in single step mode.) This completes execution of the Propagate command.

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27.2.2.5 Propagate Command Attributes and Methods

The class design for the Propagate command is shown in Figure 27.4.

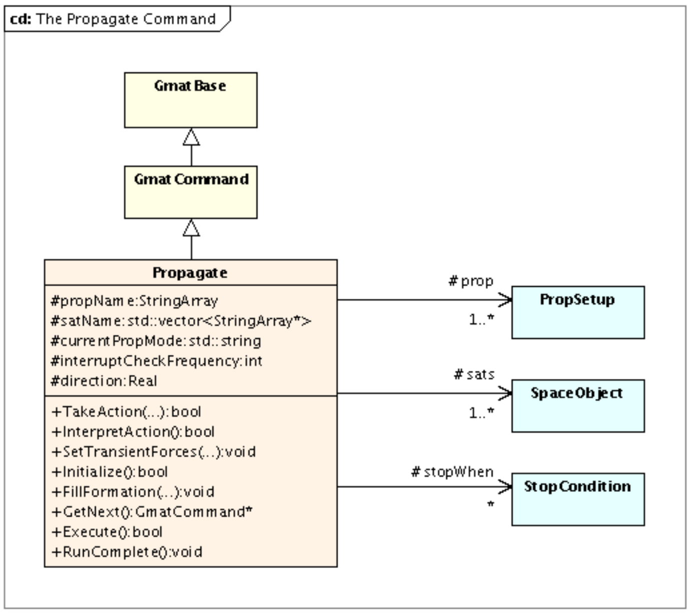

Figure 27.4: Propagate Command Details

Class Attributes Each Propagate command instance implements the following data elements:

- **StringArray propName**: List of the PropSetups used in this command.
- **std::vector<StringArray*> satName**: A vector of lists of SpaceObjects. There is a 1:1 correspondence between the propName members and the satName StringArrays. In addition, each of these StringArrays must have at least one member, and that member must be the name of a SpaceObject.
- **std::string currentPropMode**: The propagation mode setting for the PropSetups. This string tracks whether the propagation is synchronized or not[2].
- **Real direction**: The propagation direction: 1.0 to propagate forwards in time, -1.0 to propagate backwards.
- **int interruptCheckFrequency**: The number of steps the PropSetup will take before returning control to the Sandbox. This setting is used to allow the Sandbox to poll for interrupts from the user, as described in Section 5.2.3.
- **std::vector<PropSetup *> prop**: The PropSetups used in this instance.
- **std::vector<SpaceObject *> sats**: The SpaceObjects propagated by the PropSetups.

[2]GMAT currently supports two propagation modes, synchronized – specified by the keyword "Synchronized", and unsynchronized, the default setting. Backwards propagation is treated separately, though the "BackProp" keyword is parsed as a propagation mode.

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- **std::vector<StopCondition *> stopWhen**: The stopping conditions used to determine when propagation should terminate. If no stopping conditions are specified, the PropSetups fire the mminimum number of times allowed – one time in unsynchronized mode, and just enough times to meet the synchronization constraint in synchronized mode.

Methods The public methods implemented in the Propagate command are itemized below:

- **bool TakeAction(const std::string &action, const std::string &actionData)**: Performs actions specific to propagation. The Propagate command defines three actions:
  - *Clear*: Clears the arrays of reference objects used by the instance. Clearing can occur for two distinct types of objects:
    - Propagator: Clears the lists of PropSetups, propagated SpaceObjects, and the associated StringArrays.
    - StopCondition: Clears the lists of stopping conditions, SpaceObjects used for stoppign, and any associated StringArrays.
  - *SetStopSpacecraft*: Adds a named SpaceObject to the list of SpaceObjects used for stopping.
  - *ResetLoopData*: Resets the PropSetups to their startup values so that Solvers obtain consistent results when iterating to a solution.
- **void FillFormation(SpaceObject* so, StringArray owners, StringArray elements)**: Fills in the components of a formation recursively.
- **GmatCommand* GetNext()**: Returns the next command that should be executed. Propagate overrides the implementation provided by GmatCommand so that interrupt polling can occur without abnormally terminating propagation.
- **bool InterpretAction()**: The parser for the Propagate command, overridden from the default implementation to handle all of the variations Propagate supports.
- **void SetTransientForces(std::vector<PhysicalModel*> *tf)**: Tells the Propagate command about the current list of transient forces, so taht the command can incorporate active transient forces into the force model in the PropSetups.
- **bool Initialize()**: Performs initialization in the Sandbox prior to execution of the command.
- **bool Execute()**: Performs the propagation.
- **void RunComplete()**: Cleans up the command structures after completion of propagation.

27.2.3 The Create Command

27.2.4 The Target Command

27.2.5 The Optimize Command

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Chapter 28

Solvers

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28.1 Overview

GMAT implements several algorithms used to tune mission models, so that specific mission goals can be defined and achieved from within the mission sequence. The subsystem used for this mission parameter tuning is the Solver subsystem.

Each of the solvers in GMAT can be described as a finite state machine taking the input state of the GMAT objects in a mission and changing the states of user specified parameters to achieve desired goals. Each solver executes a series of GMAT commands as part of this solution finding algorithm; the differences between the different solvers comes from the approach taken to find this solution.

28.2 Solver Class Hierarchy

Each solver takes a section of a mission sequence, and manipulates variables in that subsequence in order to evaluate how those changes affect the modeled mission. The results of the changes are collected in the Solver, reported to the user if desired, and possibly used to drive subsequent actions in the mission sequence.

The Solver subsystem can be decomposed into three broad categories of algorithms: scanners, targeters, and optimizers. The distinguishing characteristics of these different algorithms can be summarized as follows:

- **Scanners** are used to perform studies of the behavior of the the system as the variables change, in order to collect statistical data about how the system behaves in the neighborhood of the variables defined for the problem. A scanner does not have an inherent set of goals; rather, the intention of a scanner is to evaluate how changes in the system variables affect the behavior of the system over time.

- **Targeters** are used to find solutions that satisfy a set of goals to within some user defined set of tolerances. In other words, a targeter is seeking an exact solution, and stops searching for that solution when the achieved results of the targeter all fall to within a specified tolerance of those goals.

- **Optimizers** are used to find the configuration of the variables that best satisfies a set of user goals, subject, optionally, to a set of constraints. Optimizers function by seeking the minimum of a user defined function of parameters, subject to these constraints.

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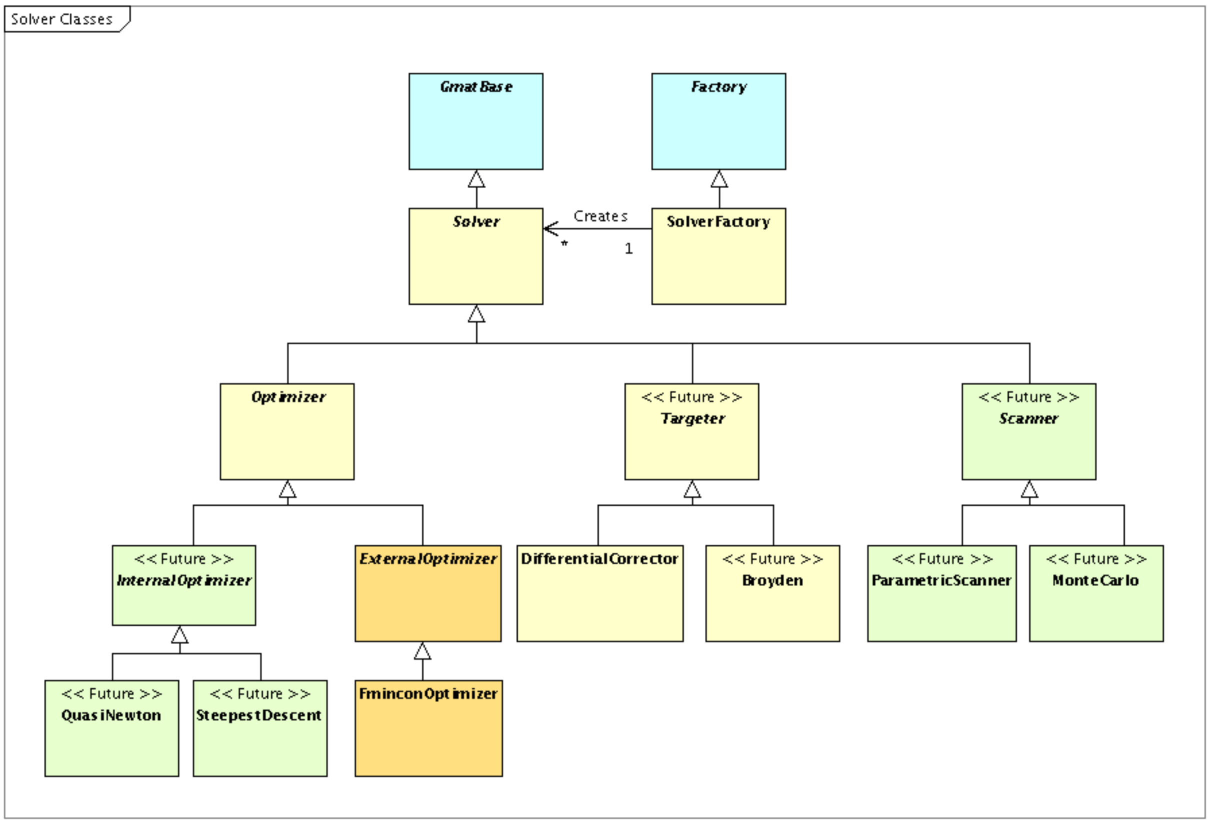

Figure 28.1: The Solver Subsystem

Figure 28.1[1] shows the class hierarchy for the GMAT solvers, including a number of planned extensions that are not yet scheduled for implementation, identified by the «future» label. The base class, Solver, contains the core elements required to implement the solver finite state machine. These elements are assembled differently to implement different classes of solvers, as described in the following sections.

The Solver class hierarchy shown here identifies two scanners, two targeters (the DifferentialCorrector and Broyden targeters), and three optimizers. The scanners, ParametericScanner and MonteCarlo, are planned enhancements to GMAT that are not currently scheduled for implementation. The DifferentialCorrector is a targeter used extensively at Goddard Space Flight Center and other locales to find solutions to targeting goals; Broyden's method, another targeter slated for implementation in GMAT, solves similar problems. The SteepestDescent and QuasiNewton optimizers are planned enhancements that will be built as native algorithms in the GMAT code base. The FminconOptimizer is an optimizer implemented in the MATLAB Optimization Toolbox. GMAT uses the MATLAB interface to communicate with this component through the ExternalOptimizer class.

28.3 The Solver Base Class

Core elements of the Solver class are shown in Figure 28.2. This class contains the infrastructure required to run a solver state machine. The class provides default implementations for methods run at each state,

[1]**Note:** The current implementation of the differential corrector does not yet conform to the class structure defined here because the intermediate class, Targeter, is not yet implemented.

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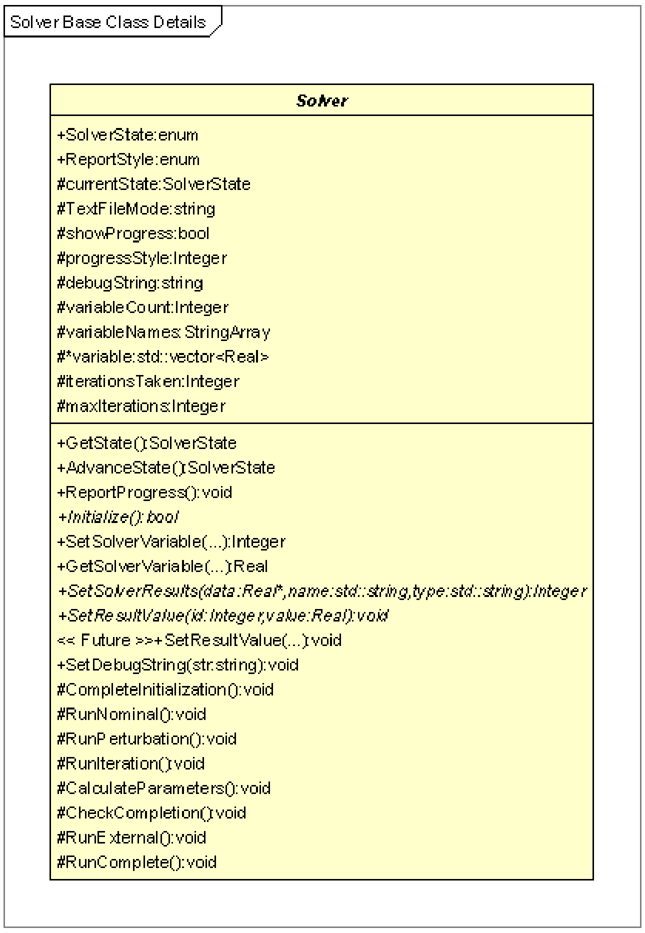
Solver Base Class Details
Solver
+SolverState:enum
+ReportStyle:enum
#currentState:SolverState
#TextFileMode:string
#showProgress:bool
#progressStyle:Integer
#debugString:string
#variableCount:Integer
#variableNames: StringArray
#*variable:std::vector<Real>
#iterationsTaken:Integer
#maxIterations:Integer
+GetState():SolverState
+AdvanceState():SolverState
+ReportProgress():void
+Initialize():bool
+SetSolverVariable(...):Integer
+GetSolverVariable(...):Real
+SetSolverResults(data:Real*,name:std::string,type:std::string):Integer
+SetResultValue(id:Integer,value:Real):void
<< Future >>+SetResultValue(...):void
+SetDebugString(str:string):void
#CompleteInitialization():void
#RunNominal():void
#RunPerturbation():void
#RunIteration():void
#CalculateParameters():void
#CheckCompletion():void
#RunExternal():void
#RunComplete():void

Figure 28.2: The Solver Base Class

and abstract interfaces for the methods used by the GMAT Command classes.

28.3.1 Solver Enumerations

The Solver base class contains two public enumerations used evaluate the status of the solver objects during a run and to control the style of the diagnostic reports generated by the solver. The SolverState enumeration is used to represent the finite states in the solver's state machine. It can be set to any of the following values:

- **INITIALIZING**: The entry state for the state machine, this state is used to set the initial data and object pointers for the state machine.
- **NOMINAL**: The nominal state is used to evaluate the behavior of the solver subsequence using the current best guess at the values of the variables.
- **PERTURBING**: Many solver algorithms work by applying small perturbations to the nominal values of the variables, and collecting the resulting affects on the solver subsequence. This state is used to perform those perturbations.

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- **ITERATING**: The Scanners perform a series of runs at calculated values of the variables. This state is used to iterate over those values.
- **CALCULATING**: The CALCULATING state is used to perform algorithm specific calculations in preparation for the next pass through the solver subsequence.
- **CHECKINGRUN**: This state is used to evaluate the current results of the solver run, and to determine if the solver algorithm has accomplished its goals.
- **RUNEXTERNAL**: The state used to launch an external solver which controls the solution process.
- **FINISHED**: This final state is used to report the results of the solver run, and to perform any final adjustments required to use those results in the rest of the mission sequence.
- **UNDEFINED_STATE**: A value used to indicate a fault, and as a special case for the solver text file.

The states actually used by a solver are algorithm dependent; no given algorithm is likely to use all of the states represented by this enumeration.

The ReportStyle enumeration is used to set the level of reporting performed while a solver is executing. This enumeration is used to represent the following styles of reporting:

- **NORMAL_STYLE** The default report style, set using the string "Normal".
- **CONCISE_STYLE** A compact report style, set using the string "Concise".
- **VERBOSE_STYLE** A report style generating lots of data, useful for analyzing the details of a run, set using the string "Verbose".
- **DEBUG_STYLE** A report style useful for debugging solver algorithms, set using the string "Debug".

Each solver has a member parameter, the "ReportStyle", used to set the reporting style. The ReportProgress method, described below, is used to generate the text for a report.

28.3.2 Solver Members

The Solver base class contains the following member data elements:

Class Attributes

- **SolverState currentState**: The current state of the solver, one of the members of the SolverState enumeration.
- **std::string textFileMode**: The string representation for the output mode, set to one of the following: "Compact", "Normal", "Verbose", or "Debug".
- **bool showProgress**: A flag used to toggle the progress report on or off.
- **Integer progressStyle**: An integer representation of the report style, taken from the ReportStyle enumeration.
- **std::string debugString**: A string used in the progress report when in Debug mode.
- **Integer variableCount**: The number of variables used in the current problem.
- **StringArray variableNames**: A string array containing the name of each variable.

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- **std::vector<Real> variable**: The array of current values for the variables used by the solver.
- **Integer iterationsTaken**: The number of iterations taken by the current run of the solver.
- **Integer maxIterations**: The maximum number of iterations through the subsequence allowed for the solver.

All solvers must provide implementations of these five pure virtual methods:

Abstract Methods

- **bool Initialize()**: Used to set object pointers and validate internal data structures. GMAT initializes all of the commands in the solver subsequence before executing this method, so all of the variable data and result data structures have been registered when this method is called.
- **Integer SetSolverVariables(Real *data, const std::string &name)**: This is the variable registration method, used to pass in parameter data specific to variables used in the solver algorithm. This method is used by the Vary Command during initialization to set up the solver variables for a run. The return value from the method is the index in the solver array for the variable, or -1 if the variable could not be registered. The parameters in the method are used to set the details for the variables:

  data: An array containing the initial value for the variable. This array may also contain additional algorithm specific variable settings; for instance, the perturbation for the variable, and the minimum and maximum values for the variable, and the maximum allowed step for changes to the variable.

  name: The string name associated with the variable.
- **Real GetSolverVariable(Integer id)**: Used to obtain the current value of a variable from the solver. The Vary command uses this method to refresh the current value for a variable during a solver subsequence run. The parameter, *id*, is the index of the requested variable in the solver's variable array.
- **Integer SetSolverResults(Real *data, const std::string &name, const std::string &type)**: This is the method used to register the values returned from the solver subsequence to the solver. It is used to pass in parameter data specific to the subsequence run outputs, so that the solver has the data needed to initialize and track the results of an iteration through the subsequence. For targeters, the Achieve command uses this method to set up targeter goals. Optimizers use this method to set up the connection to the objective function and constraints. Scanners use this method to report the products of each scanning run.

  data: An array containing settings for the solver result, if applicable. An example of the type of data in this field is the acceptable tolerance for a targeter goal.

  name: The string name associated with the solver result.

  type: The string name associated with the type of solver result. This field defaults to the empty string, and is only used when a solver needs to distinguish types of resultant data.
- **void SetResultValue(Integer id, Real value)**: Used to report data calculated while running the subsequence to the Solver. Commands specific to the different algorithms use this method to pass data into a solver; for example, for the differential corrector, the Achieve command passes the achieved data to the solver using this method. Optimizers use this method to send the value of the objective function, and constraints, and, if calculated, the gradient of the objective function and Jacobian of the constraints. Scanners use this method to receive the data that is being measured, so that meaningful statistics can be calculated for the scanning run.

Each solver contains the following methods, which have default implementations:

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Methods

- **SolverState GetState()**: Retrieves the current SolverState for the solver.
- **SolverState AdvanceState()**: Executes current state activities and then advances the state machine to the next SolverState.
- **void ReportProgress()**: Writes the current progress string to the GMAT message interface, which writes the string to the log file and message window.
- **void SetResultValue(Integer id, std::vector<Real> values)**: Used to report multiple data values in a vector, calculated while running the subsequence, to the solver. Note that this is an overloaded method; there is also an abstract SetResultValue method which sets a single Real value. The default implementation of this method is empty; solvers that need it should provide an implementation tailored to their needs.
- **void SetDebugString(std::string str)**: Sets the string contents for the debug string.
- **void CompleteInitialization()**: Finalizes the initialization of the solver. This method is executed when the state machine is in the INITIALIZING state.
- **void RunNominal()**: Executes a nominal run of the solver subsequence. This method is executed when the state machine is in the NOMINAL state.
- **void RunPerturbation()**: Executes a perturbation run of the solver subsequence. This method is executed when the state machine is in the PERTURBING state.
- **void RunIteration()**: Executes one run of the solver subsequence and increments the iteration counter. This method is executed when the state machine is in the ITERATING state.
- **void CalculateParameters()**: Performs algorithm specific calculations for the solver. This method is executed when the state machine is in the CALCULATING state.
- **void CheckCompletion()**: Checks to see if the solver has completed its tasks. This method is executed when the state machine is in the CHECKINGRUN state.
- **void RunExternal()**: Launches an external process that drives the solver. This method is executed when the state machine is in the RUNEXTERNAL state.
- **void RunComplete()**: Finalizes the data from the solver subsequence and sets up the corresponding data for subsequent steps in the GMAT mission sequence. This method is executed when the state machine is in the FINISHED state.

28.4 Scanners

TBD – This section will be completed when the first scanner is scheduled for implementation.

28.5 Targeters

Given a mapping from a set of variables to a set of results,

$$M(x) \longrightarrow R \tag{28.1}$$

Targeting is the process of finding the value of a set of variables x_G, such that the mapping $M(x_G)$ produces a desired set of results, G:

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$$M(x_G) \longrightarrow G \tag{28.2}$$

The targeting problem is a search for an exact solution. Numerically, the targeting problem is met when a set of variables x_n is found that satisfies the conditions

$$M(x_n) \longrightarrow R_n \qquad \text{such that} \quad |G - R_n| \le \delta \tag{28.3}$$

where δ is the vector of tolerances for the resulting quantities.

The targeting problem is typically formulated as a series of steps proceding from an initial guess to a solution, as outlined here:

1. Generate an initial guess $x_i = x_0$
2. Evaluate $M(x_i) = A_i$
3. Compare A_i with the goals, G. If $|G - A_i| \le \delta$, go to step 6
4. Using the targeter algorithm, calculate new values for the variables $x_i = T(x_{i-1}; A_{i-1})$.
5. Go to step 2
6. Report the results and exit.

28.5.1 Differential Correction

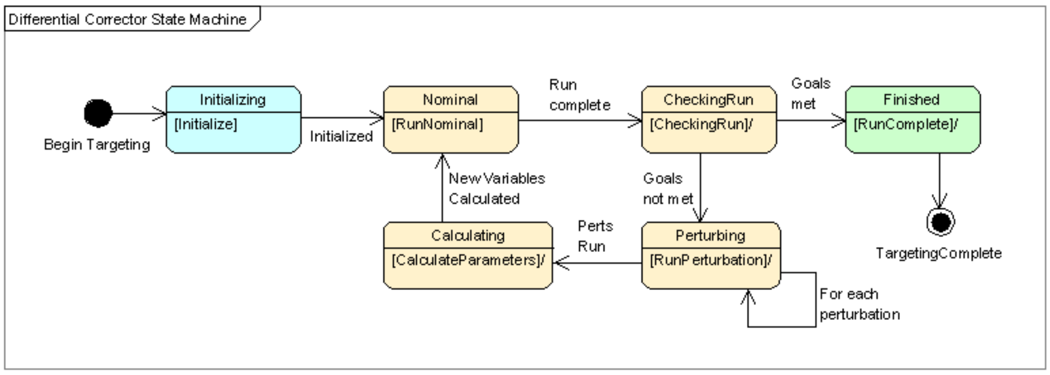

Figure 28.3: State Transitions for the Differential Corrector

28.5.1.1 Scripting a Differential Corrector

```
%----------------------------------------------------------------
%------------------ Create core objects --------------------------
%----------------------------------------------------------------
Create Spacecraft sat;

Create ForceModel DefaultProp_ForceModel;
GMAT DefaultProp_ForceModel.PrimaryBodies = {Earth};
```

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```

Create Propagator DefaultProp;
GMAT DefaultProp.FM = DefaultProp_ForceModel;

Create ImpulsiveBurn TOI;
GMAT TOI.Axes = VNB;
Create ImpulsiveBurn GOI;
GMAT GOI.Axes = VNB;

%-----------------------------------------------------------------
%---------------- Create and Setup the Targeter ------------------
%-----------------------------------------------------------------
Create DifferentialCorrector DC;
GMAT DC.TargeterTextFile = targeter_DefaultDC.data;
GMAT DC.MaximumIterations = 25;
GMAT DC.UseCentralDifferences = false;

%-----------------------------------------------------------------
%------------------- Create and Setup a plot ---------------------
%-----------------------------------------------------------------
Create XYPlot watchTargeter;
GMAT watchTargeter.IndVar = sat.A1ModJulian;
GMAT watchTargeter.Add = {sat.RMAG};
GMAT watchTargeter.Grid = On;
GMAT watchTargeter.TargetStatus = On;

%*****************************************************************
%-------------------The Mission Sequence--------------------------
%*****************************************************************

%  The targeting sequences below demonstrates how to use a
%  differential corrector in GMAT to construct a Hohmann transfer
%  between two circular, co-planar orbits by targeting first one
%  maneuver to raise.apogee, and then a second maneuver to
%  circularize.

%  Start by spending some time in the initial orbit
Propagate DefaultProp(sat, {sat.ElapsedSecs = 86400});
Propagate DefaultProp(sat, {sat.Periapsis});

%  Target the apogee raising maneuver
Target DC;
   Vary DC(TOI.V = 0.5, {Pert = 0.0001, MaxStep = 0.2, Lower = 0, Upper = 3.14159});
   Maneuver TOI(sat);
   Propagate DefaultProp(sat, {sat.Apoapsis});
   Achieve DC(sat.Earth.RMAG = 42165, {Tolerance = 0.1});
EndTarget;  % For targeter DC

%  Propagate for 1.5 orbits on the transfer trajectory
Propagate DefaultProp(sat, {sat.Periapsis});
Propagate DefaultProp(sat, {sat.Apoapsis});
```

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```

%  Target the circularizing maneuver
Target DC;
   Vary DC(TOI.V = 0.5, {Pert = 0.0001, MaxStep = 0.2, Lower = 0, Upper = 3.14159});
   Maneuver TOI(sat);
   Propagate DefaultProp(sat, {sat.Periapsis});
   Achieve DC(sat.Earth.SMA = 42165, {Tolerance = 0.1});
EndTarget;  % For targeter DC

%  Propagate for an additional day
Propagate DefaultProp(sat, {sat.ElapsedSecs = 86400});
```

28.5.2 Broyden's Method

TBD – This section will be completed when the Broyden's method is scheduled for implementation.

28.6 Optimizers

Optimization is the process of taking a function $f(x)$ of a set of variables x, and changing the values of those variables to move the function to a minimum. The function f is called the objective function. *Constrained optimization* adds a set of constraints that must simultaneously be satisfied. More succinctly, the optimization problem can be written

$$\min_{x \in R^n} f(x) \qquad \text{such that } \begin{cases} c_i(x) = 0 \text{ and} \\ c_j(x) \geq 0 \end{cases} \tag{28.4}$$

The constraint functions, c, specify additional conditions that need to be satisfied in order for the problem to be solved. The constraints can be broken into two categories. Constraints that need to be met exactly, the c_i constraints in equation 28.4, are referred to as equality constraints. Constraints that only need to satisfy some bounding conditions, represented here by c_j, are called inequality constraints.

Numerically, the optimization problem is solved when either the gradient of the objective function falls below a specified value while the constraints are met to a given tolerance, or when the constraints are met and the solution point x is unchanging during subsequent iterations. The optimization problem is can be formulated as a series of steps proceeding from an initial guess to a solution, similar to a targeting problem:

1. Generate an initial guess $x_i = x_0$
2. Evaluate $f(x_i)$ and constraints
3. Evaluate the gradient of the objective function at x_i and the constraint Jacobians. This step usually involves either an analytic calculation or iterating the $f(x)$ calculation with small perturbations.
4. Check to see if x_i is a local minimum or unchanging, and if the constraints are met. If so, go to step 8.
5. Use the optimizer algorithm to calculate a new search direction.
6. Step in the search direction to a minimal value in that direction. This is the new value for x_i.
7. Go to step 3
8. Report the results and exit.

Figure 28.4 shows the state transitions for a typical optimization algorithm that follows this procedure.

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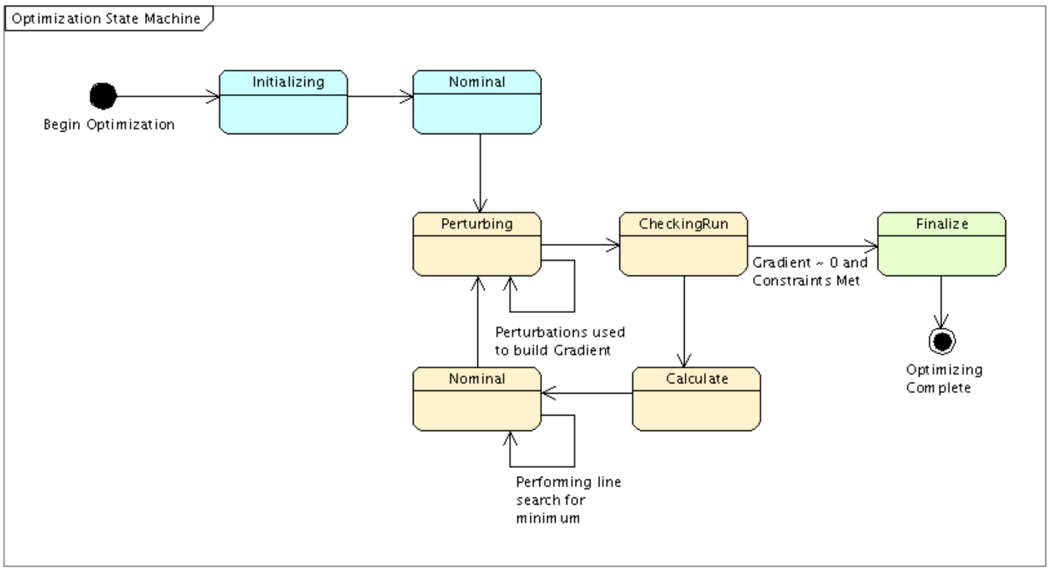
Optimization State Machine
Begin Optimization
Initializing
Nominal
Perturbing
CheckingRun
Finalize
Gradient ~ 0 and Constraints Met
Perturbations used to build Gradient
Optimizing Complete
Nominal
Calculate
Performing line search for minimum

Figure 28.4: State Transitions for Optimization

28.6.1 The Optimizer Base Class

All optimizers require an objective function that changes based on the values of the variables in the problem. In addition, when analytic gradients of the objective function can be calculated, the optimization procedure can be streamlined to incorporate these data. Optimizers that include constraints also need data structures to store the constraint data. Storage support for all of these values is built into the Optimizer base class, shown in Figure 28.5. The computation of these parameters is provided in the optimization specific commands, described later in this chapter. The members of this base class serve the following purposes:

Class Attributes

- **std::string objectiveFnName**: The name of the objective function data provider. This member defaults to the string "Objective", but users can override that value by setting this data member.
- **Real cost**: The latest value obtained for the objective function.
- **Real tolerance**: Optimizers have converged on a solution when the magnitude of the gradient of the cost function is smaller that a user specified value. This parameter holds that value. Note that GMAT can pass this parameter into external optimizers as one of the parameters in the *options* data member.
- **bool converged**: A boolean flag used to detect when the optimizer has reached an acceptable value for the objective function and, if applicable, the constraints.
- **StringArray eqConstraintNames**: The names of the equality constraint variables.
- **std::vector<Real> eqConstraintValues**: The most recent values obtained for the equality constraints.
- **StringArray ineqConstraintNames**: The names of the inequality constraint variables.
- **std::vector<Real> ineqConstraintValues**: The most recent values obtained for the inequality constraints.

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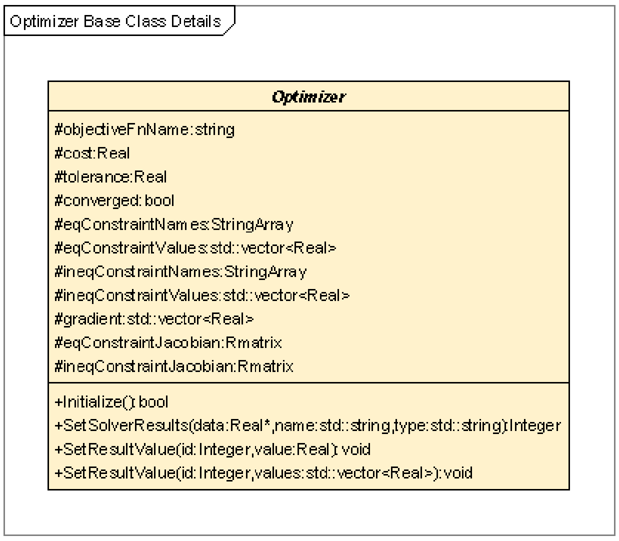
Optimizer Base Class Details
Optimizer
#objectiveFnName:string
#cost:Real
#tolerance:Real
#converged:bool
#eqConstraintNames:StringArray
#eqConstraintValues:std::vector<Real>
#ineqConstraintNames:StringArray
#ineqConstraintValues:std::vector<Real>
#gradient:std::vector<Real>
#eqConstraintJacobian:Rmatrix
#ineqConstraintJacobian:Rmatrix
+Initialize():bool
+SetSolverResults(data:Real*,name:std::string,type:std::string):Integer
+SetResultValue(id:Integer,value:Real):void
+SetResultValue(id:Integer,values:std::vector<Real>):void

Figure 28.5: The Optimizer Base Class

- **std::vector<Real> gradient**: «Future» The most recently calculated gradient of the objective function.

- **Rmatrix eqConstraintJacobian**: «Future» The most recently calculated Jacobian of the equality constraints.

- **Rmatrix ineqConstraintJacobian**: «Future» The most recently calculated Jacobian of the inequality constraints.

Methods The methods shown in Figure 28.5 provide implementations of the methods in the Solver base class. These methods are described below:

- **bool Initialize()**: Used to set object pointers and validate internal data structures. GMAT initializes all of the commands in the optimizer subsequence in the Optimize::Initialize() method, called on the command sequence during Sandbox initialization. After performing this initialization, the Optimize command calls this method, so data structures can be prepared for all of the variable data and result data elements registered during command subsequence initialization.

- **Integer SetSolverResults(Real *data, const std::string &name, const std::string &type)**: Used to register parameter data needed by the optimizer to evaluate the behavior of a subsequence run. For optimizers, the Minimize and NonLinearConstraint commands use this method to set up the connection to the objective function and constraints. Future releases will implement the Gradient, EqConstraintJacobian, and IneqConstraintJacobian commands, which will also use this method.

  data: An array containing settings for the output parameter.

  name: The string name associated with the parameter.

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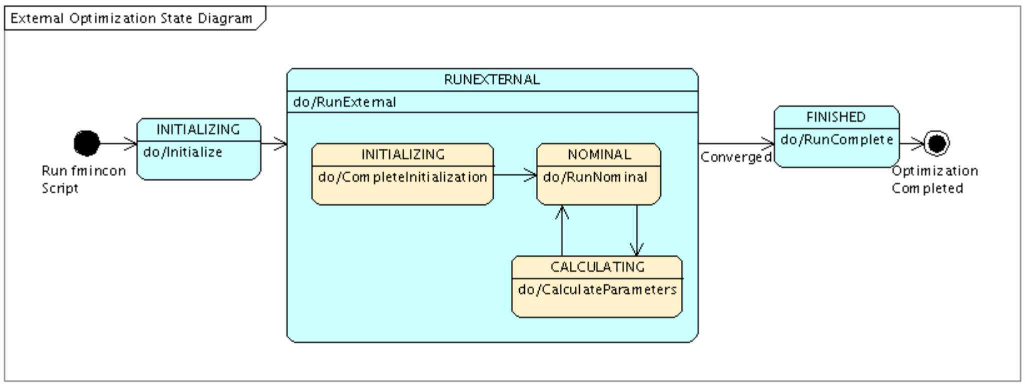

Figure 28.6: GMAT state transitions when running the FminconOptimizer Optimizer

type: The string name associated with the type of resultant used in the optimizer. Valid options are “Objective”[2], “EqConstraint”, “IneqConstraint”, “ObjGradient”, “EqConstraintJacobian”, and “IneqConstraintJacobian”.

- **void SetResultValue(Integer id, Real value)**: Used to report data, calculated while running the subsequence, to the optimizer. The Minimize and NonLinearConstraint commands use this method to set the current values of the objective function and constraints.
- **void SetResultValue(Integer id, std::vector<Real> values)**: «Future» Used to report multiple data values in a vector, calculated while running the subsequence, to the optimizer. When implemented, the Gradient and Jacobian commands will report data to the optimizers using this method.

Each of these methods may be overridden based on the needs of the derived optimizers.

28.6.2 Internal GMAT optimizers

TBD – This section will be completed when the first internal optimizer is scheduled for implementation.

28.6.2.1 The Steepest Descent Optimizer

TBD – This section will be completed when the steepest descent optimizer is scheduled for implementation.

28.6.2.2 The Quasi-Newton Optimizer

TBD – This section will be completed when the quasi-Newton optimizer is scheduled for implementation.

28.6.3 External Optimizers

The optimizers described in Section 28.6.2 are coded directly into the system. GMAT also provides access to the MATLAB Optimization Toolbox[opttools] through a set of interfaces designed for this purpose.

28.6.3.1 External Optimizer State Transitions

GMAT has the ability to incorporate optimizers coded outside of the system, as long at those optimizers provide communications interfaces that can be interfaced to GMAT. These outside processes are called

[2]If more than one command attempts to register an objective function in the same optimizer loop, GMAT will throw an exception stating that the optimization problem is ill defined because there is more than one objective function.

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"external optimizers." A typical finite state machine used to perform optimization using an external optimizer is shown in the state transitions diagram for the fmincon optimizer from MATLAB's Optimization Toolbox, Figure 28.6. The state machine for fmincon will be used in what follows to provide an overvie of external optimization; other external processes would adapt this machine to meet their needs.

The optimization process starts in an INITIALIZING state. When the AdvanceState() method is called in this state, the object references necessary for the optimization run are set. This step includes passing the pointer to the Optimize command at the start of the optimization loop to the GmatInterface that MATLAB uses to communicate with GMAT. The Optimize command includes a method, ExecuteCallback(), used when the fmincon optimizer needs to run the optimizer subsequence and gather the resulting data.

Once initialization has been performed, the state transitions to the RUNEXTERNAL state. This state calls MATLAB with the appropriate parameters needed to run the optimizer using the FminconOptimizationDriver MATLAB function, a driver function tailored to fmincon described below. At this point, control for the optimization process has been transferred to MATLAB. The fmincon optimizer makes calls back into GMAT when it needs to collect data from the optimizer subsequence. These calls are passed to the ExecuteCallback() method registered in the initialization process, above. ExecuteCallback() uses the Optimize command to run the nested state transitions shown in the figure. The nested states start by setting up and running the mission subsequence, performed in the NOMINAL state. Once the subsequence has been run, the data gathered during the run are collected and any processing needed on the GMAT side is performed. This data collection is performed in the CALCULATING state. This completes the iteration of the nested state machine; the nested state is set back to NOMINAL in preparation for the next call from MATLAB. The collected data are passed to MATLAB, and used by fmincon to determine the next action to be taken. If fmincon has not yet found an optimal solution, it calculates new values for the variables, and passes them into GMAT for another pass through the nested state machine. This process repeats until fmincon has found a solution or reached another terminating condition.

Once fmincon has completed execution, it sends an integer flag to GMAT indicating how the optimization process was terminated[3] and returns control to GMAT. This return of control results in a transition into the FINISHED state. GMAT performs the tasks required at the end if the optimization, and then continues running the mission sequence. Details of all of these steps are provided in the discussion discussion of fmincon optimization below.

28.6.3.2 Class Hierarchy for the External Optimizers

External optimizers are coded using the classes shown in Figure 28.7. One set of external optimizers, the functions in the Optimization Toolbox, is accessed using the MATLAB interface built into GMAT. Those functions, in turn, use calls through the GmatServer code to access spacecraft specific models in GMAT. Future extensions to GMAT may use other interfaces for external optimizers.

28.6.3.3 The ExternalOptimizer Class

All external optimizers are derived from the ExternalOptimizer class. The design illustrated in Figure 28.7 shows this class, along with one subclass, the FminconOptimizer, and the interfaces used to communicate with MATLAB. When necessary, similar interfaces will be written for communications with other external programs. External optimizers add the functionality needed to open the interfaces to the external programs. Classes derived form this class implement the state transitions functions used in the external optimization nested state machine. The ExternalOptimizer class elements are described here:

Class Attributes

[3]See the Optimization Toolkit documentation for the meaning of this flag's values; in general, if the flag is greater than zero, the optimization process was successful.

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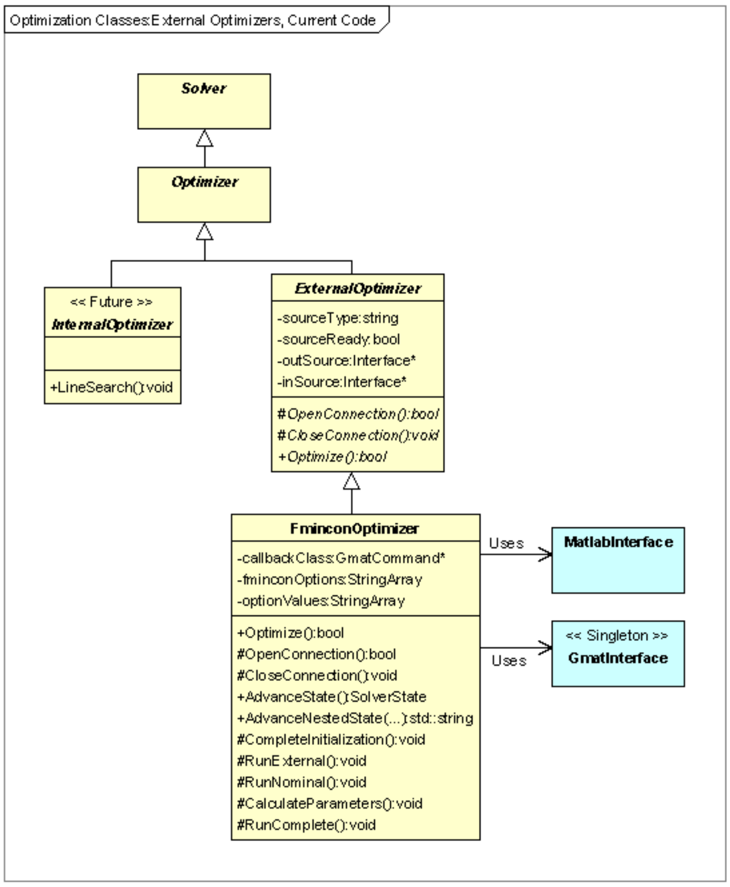

Figure 28.7: GMAT Classes Used with External Optimizers

- **std::string sourceType**: String indicating the type of external interface that is used. The only external interface supported in the current code is a MATLAB interface, so this string is always set to "MATLAB" in the current GMAT code.
- **bool sourceReady**: A flag indicating the state of the interface; this flag is set to true if the interface was opened successfully and the supporting structures needed by the interface were found[4].
- **outSource**: A pointer to the Interface object that is used to make calls to the external interface.
- **inSource**: A pointer to the Interface object that is used to receive calls from the external interface[5].

All external optimizers must provide implementations of these pure virtual methods:

Abstract Methods

[4]An example of the "supporting structures": if the external interface is an FminconOptimizer, then the MATLAB system and the Optimization Toolkit must both be available for use, and the MATLAB files that establish the calls into GMAT must also be accessible from MATLAB.

[5]In the current code, two pointers are necessary: one to a MatlabInterface object, and a second to the GmatServer used for calls from MATLAB to GMAT. Future builds may combine these interfaces.

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- **bool OpenConnection()**: The method used to open the interfaces between GMAT and the external program. This method, called during initialization, opens the interface and verifies that the external program is ready to interact with GMAT.
- **void CloseConnection()**: Closes the connections to the external program.
- **bool Optimize()**: Calls the external optimizer, starting the optimization process. When the process terminates, this method also terminates, returning a true value if the process reported success and a false value if the process failed.

Note that in both of the connection configuration methods, the interface interaction preserves the interface state as needed for other objects: for example, if the interface is already open either at the GMAT level because of user interactions or from previous initialization, then it does not open again; the open interface is used. Similarly, the interface is closed only if it is not in use elsewhere – either globally by GMAT, or by another object that is still using the interface.

28.6.3.4 The FminconOptimizer Class

Fmincon is an implementation of sequential quadratic programming, implemented in MATLAB. GMAT interfaces with fmincon using a class, the FminconOptimizer class, to coordinate the calls to MATLAB to access the optimizer. For the purposes of this discussion, the MATLAB optimizer fmincon will be referenced by the MATLAB function name, "fmincon"; the GMAT class that wraps that optimizer for use by GMAT will be referenced by the class name, "FminconOptimizer."

The class members for the FminconOptimizer are described here.

Class Attributes

- **GmatCommand *callbackClass**: A class that implements the ExecuteCallback method used by the external process.
- **StringArray fminconOptions**: The table of parameters that can be set on the fmincon optimizer.
- **StringArray optionValues**: The current settings for the fmincon options.

Each FminconOptimizer contains the following methods, which have default implementations:

Methods

- **bool Optimize()**: The entry point for fmincon based optimization, this method is used to call MATLAB with the settings needed for fmincon.
- **bool OpenConnection()**: If necessary, launches the MATLAB engine and starts the GmatServer, and then sets the engine pointer on the FminconOptimizer.
- **void CloseConnection()**: If appropriate, closes the MATLAB engine and/or the GmatServer.
- **SolverState AdvanceState()**: This method is used to run the outer state machine. It manages 3 states: the INITIALIZING state, the RUNEXTERNAL state, and the FINISHED state.
- **std::string AdvanceNestedState(std::vector<Real> vars)**: This method is called by the Optimize command to run the nested state machine, and managed the transitions between the NOMINAL and CALCULATING states. The input parameter here is a vector of the variable values used for the nested state machine run. The return value for this method is the resultant data from the nested run, serialized for transport to the external process.

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- **void CompleteInitialization()**: The method run in INITIALIZING state, which sets the callback class pointer for the GmatInterface and prepares the GMAT side of the system for optimization.
- **void RunExternal()**: The method run in the RUNEXTERNAL state which builds the data stores needed for the optimization loop, and then calls Optimize to hand program control to MATLAB.
- **void RunNominal()**: The method that sets up the data structures for a run of the optimizer subsequence. The Optimize command uses AdvanceState to run this method immediately before running the optimization subsequence.
- **void CalculateParameters()**: The method that gathers the resultant data from the subsequence run and massages it into form for transport to MATLAB.
- **void RunComplete()**: The method that finalizes the optimization, writing resultant data to the solver log file and releasing any temporary data structures that were used in the optimization process.

28.6.3.5 Interface Classes: Details for the FminconOptimizer

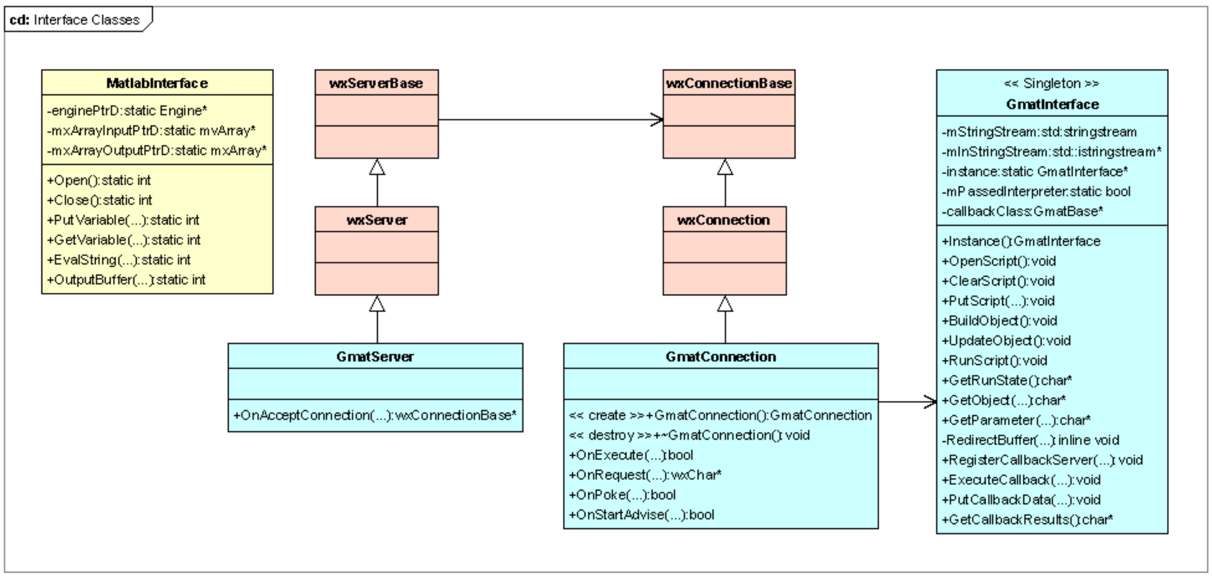
cd: Interface Classes
MatlabInterface
-enginePtrD:static Engine*
-mxArrayInputPtrD:static mvArray*
-mxArrayOutputPtrD:static mxArray*
+Open():static int
+Close():static int
+PutVariable(...):static int
+GetVariable(...):static int
+EvalString(...):static int
+OutputBuffer(...):static int
wxServerBase
wxServer
GmatServer
+OnAcceptConnection(...):wxConnectionBase*
wxConnectionBase
wxConnection
GmatConnection
<< create >>+GmatConnection():GmatConnection
<< destroy >>+~GmatConnection():void
+OnExecute(...):bool
+OnRequest(...):wxChar*
+OnPoke(...):bool
+OnStartAdvise(...):bool
<< Singleton >>
GmatInterface
-mStringStream:std:stringstream
-mInStringStream:std::istringstream*
-instance:static GmatInterface*
-mPassedInterpreter:static bool
-callbackClass:GmatBase*
+Instance():GmatInterface
+OpenScript():void
+ClearScript():void
+PutScript(...):void
+BuildObject():void
+UpdateObject():void
+RunScript():void
+GetRunState():char*
+GetObject(...):char*
+GetParameter(...):char*
-RedirectBuffer(...):inline void
+RegisterCallbackServer(...):void
+ExecuteCallback(...):void
+PutCallbackData(...):void
+GetCallbackResults():char*

Figure 28.8: Interface Classes used by the FminconOptimizer

The current implementation of interfaces in GMAT used to communicate with MATLAB are shown in Figure 28.8[6]. Details of this implementation are provided in Chapter 19. These paragraphs point out the pertinent features used when running an external optimizer.

The Optimize command, described later, is used to control the state transitions used when running the state machine. This command is used to advance the state machine by calling the AdvanceState method on the optimizer. External optimizers use a state, the RUNEXTERNAL state, to pass control from GMAT to the external process. The Optimize command implements a method named ExecuteCallback which provides the entry point from the external process back into the GMAT system so that spacecraft modeling commands

[6]There are currently two separate MATLAB interfaces, and both are used for this work. The interface from MATLAB to GMAT uses code from the wxWidgets library. Because of this implementation, external optimizers running in MATLAB cannot be used with the command line versions of GMAT.

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Table 28.1: Options for the FminconOptimizer Solver

Option	**Type**	**Values**	**Description**
DiffMaxChange	Real	value > 0.0	Maximum allowed change in the variables.
DiffMinChange	Real	0.0 < value <= DiffMaxChange	Minimum allowed change in the variables.
MaxFunEvals	Integer	value > 0	Maximum number of function evaluations before terminating.
MaxIter	Integer	value > 0	
TolX	Real	value > 0.0	Variable change tolerance required to declare convergence.
TolFun	Real	value > 0.0	Gradient tolerance required to declare convergence.
DerivativeCheck	String	On, Off	Toggle for fmincon derivative checking.
Diagnostics	String	On, Off	Toggle used to turn dignostics on for fmincon.
Display	String	Iter, Off, Notify, Final	Level of output generated from fmincon.
GradObj	String	On, Off	Toggle to turn on gradients calculated in GMAT.
GradConstr	String	On, Off	???

can be executed buy the external process. The GmatInterface contains members designed to manage this callback process. These members, a pointer and several methods, are described here[7]:

Class Attributes

- **GmatCommand *callbackClass**: A class that implements the ExecuteCallback method used by the external process.

Methods

- **void RegisterCallbackServer(GmatCommand *cbClass)**: Method used to identify the command that implements ExecuteCallback.
- **void ExecuteCallback()**: The method called from the GMAT server to run the callback method.
- **void PutCallbackData(std::string data)**: Method used to set the input data for the callback function. For optimization, this method is called to pass in the variable data.
- **char* GetCallbackResults()**: Method used to retrieve the results of the callback. For optimization, this method retrieves the value of the objective function and constraints, and other optional data when it becomes available.

The entry point to the optimization process is the Optimize command, described below. When this command is executed, the FminconOptimizer refreshes the data needed for optimization, and passes that data across the interface to MATLAB. These data are stored in the FminconOptimizer's

There are many different parameter settings available for MATLAB's fmincon optimizer. Table 28.1 shows the fmincon options supported by GMAT. The option table is contained in the fminconOptions StringArray. Settings for these options are collected in the optionValues member and passed from GMAT into MATLAB when the optimization loop starts execution.

[7]Note that this is not the full description of the GmatInterface class. That description is in Chapter 19.

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28.6.3.6 Control Flow in the FminconOptimizer

Figures 28.9a through 28.9c show the sequence of method calls made on the GMAT objects to run the MATLAB based fmincon optimizer. The Optimization Toolbox contains several other optimization functions that may be incorporated into future versions of GMAT if the need arises; they will use a similar control flow when implemented.

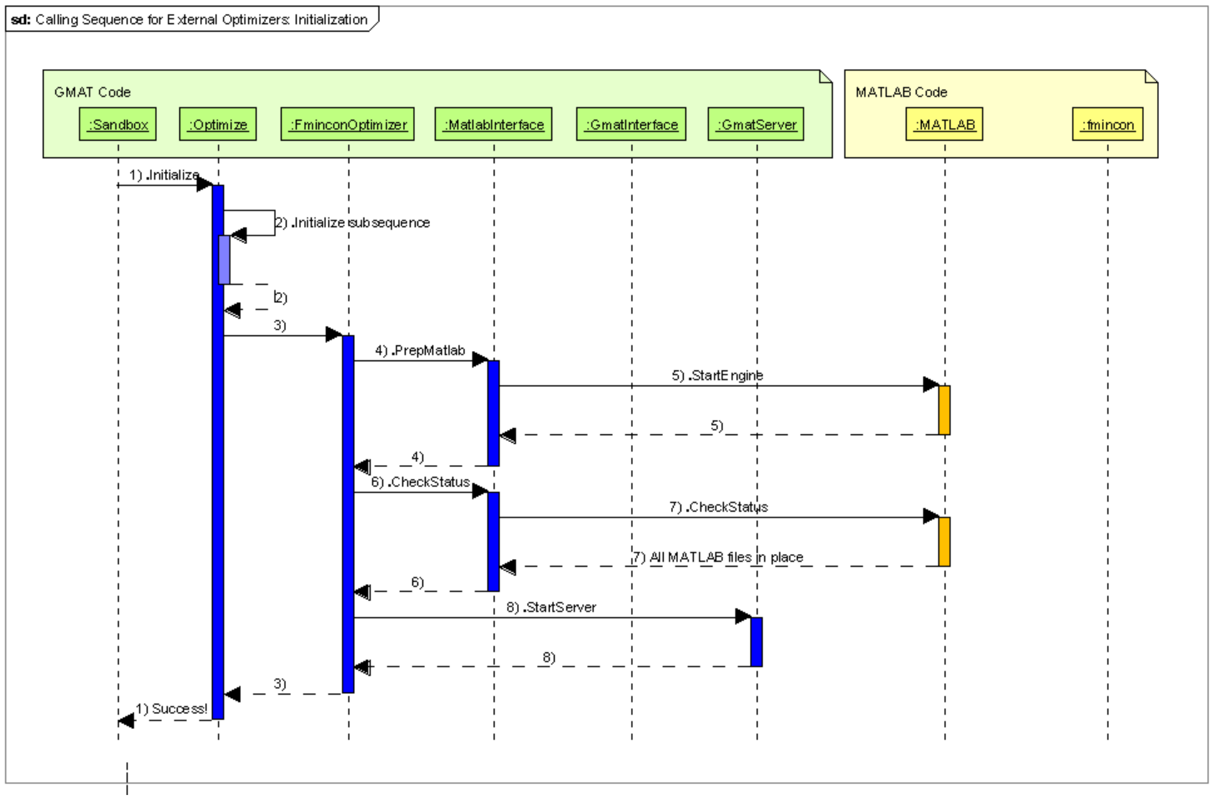

Figure 28.9a: Initialization Call Sequence for MATLAB's fmincon Optimizer

The event sequence shown in these figures consists of two pieces. Initialization (Figure 28.9a) is used to set all of the object pointers in place that are needed for the optimization, and to prepare the optimizer's internal data structures for the optimization process. This step includes the initialization and validation of the interfaces used to access the external optimizer. In the illustrated example, the input and output interfaces GMAT uses to communicate with MATLAB are started, and the MATLAB side of the interface validates the presence of the MATLAB scripts and functions needed to run the optimizer. This step is performed when the GMAT Sandbox initializes the mission sequence prior to a run.

Once initialization has completed, the Sandbox starts executing the mission sequence. The mission sequence proceeds until the Optimize command is ready to be run. Figure 28.9b picks up at that point, and shows the steps taken to perform the optimization with fmincon from within the control sequence. These steps include the execution of the nested state machine, described shortly. Once the sequence shown in this figure finishes running, the optimization process has completed, and the remainder of the mission control sequence is run.

The details of the nested state machine run, including the execution of the optimizer subsequence, are shown in Figure 28.9c. When ExecuteCallback() is called on the Optimize command, the command queries

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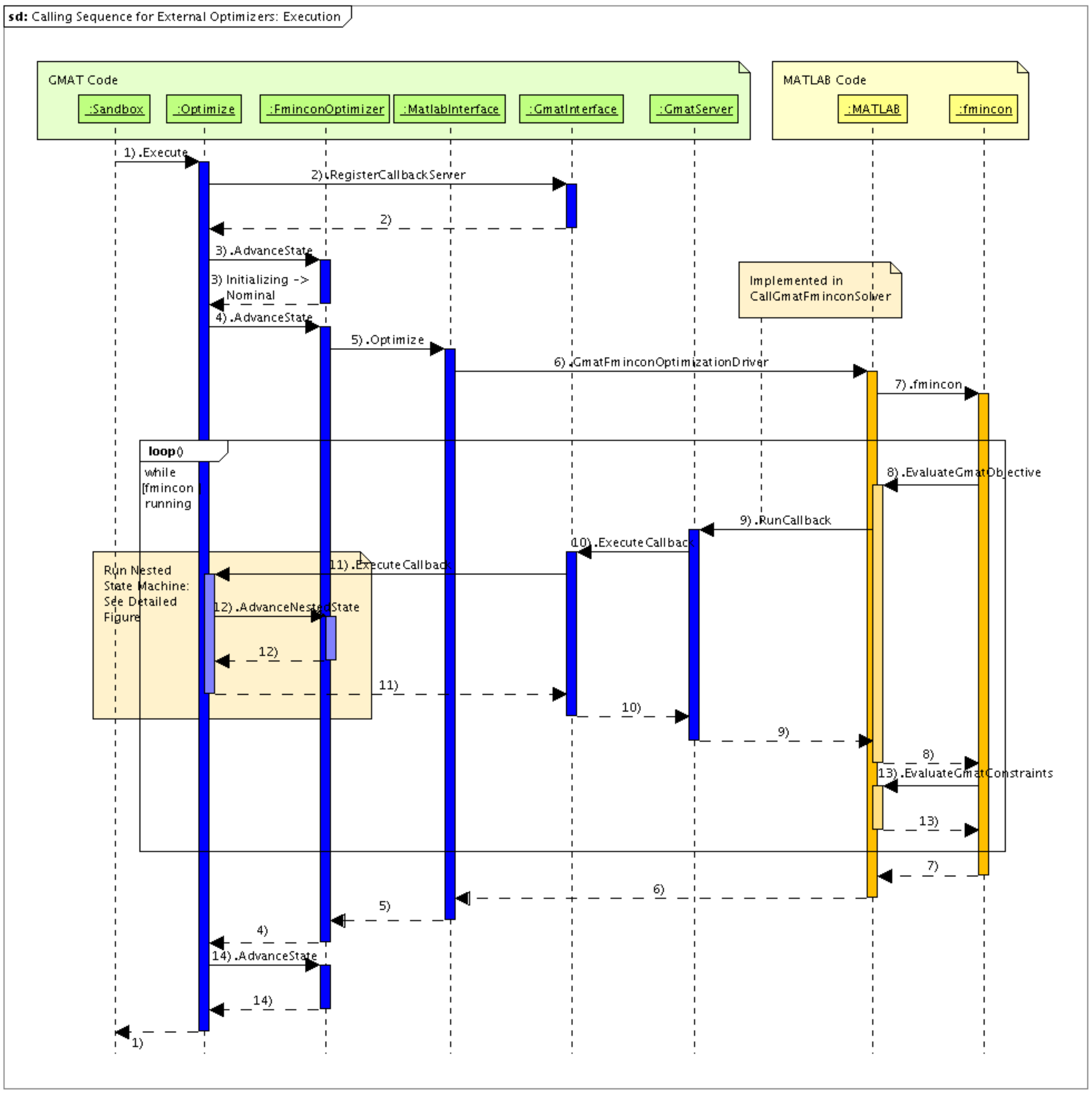

Figure 28.9b: Execution Call Sequence for MATLAB's fmincon Optimizer

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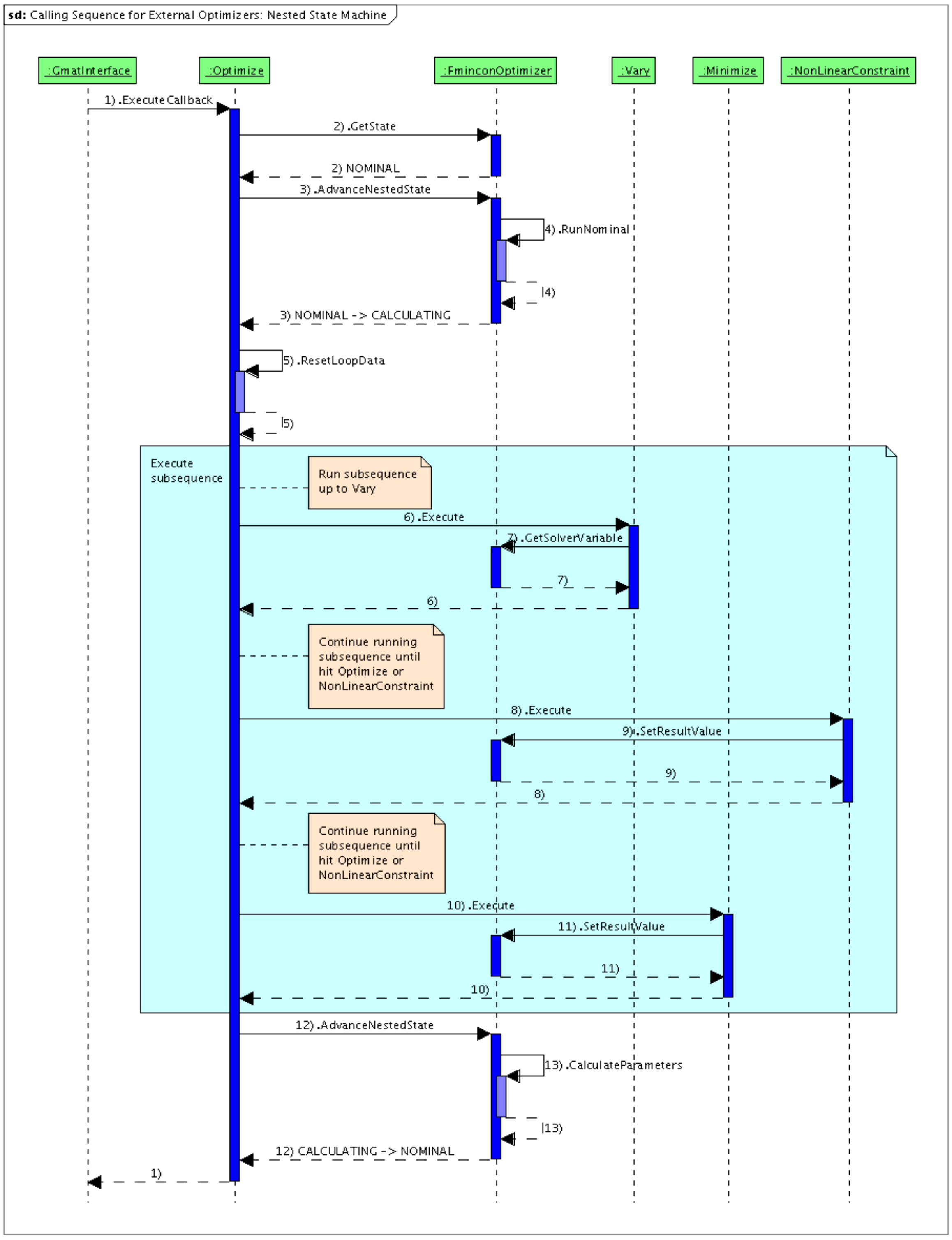

Figure 28.9c: FminconOptimizer Nested State Transition Details

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the FminconOptimizer to determine the current state of the nested state machine. The returned state should be either INITIALIZING or NOMINAL.

The action taken when the nested state is in the INITIALIZING state is not shown in the figure. When that state is encountered, the Optimize command calls AdvanceNestedState on teh FminconOptimizer and the FminconOptimizer executes its CompleteInitialization() method. The nested state machine then transitions into the NOMINAL state. Upon return from this process, the Optimize command executes the StoreLoopData() method, which saves the spacecraft state data at the start of the optimization loop. It then proceeds to run the nested state machine.

When the nested state is in the NOMINAL state, the Optimize command calls the FminconOptimizer's AdvanceNestedState() method, which executes the RunNominal() method to prepare the optimizer for execution of a nominal run through the subsequence. The state of the nested state maching changes from NOMINAL to CALCULATING. Upon the return from the AdvanceNestedState() method, the Optimize command sets the GMAT objects up for a run of the optimization subsequence by executing the ResetLoopData() method. It then begins execution of the optimization subsequence.

The execution of the optimizer subsequence depends on the order of the commands contained in the subsequence. All GMAT commands include a method, Execute(), that fire the command. Like ann GMAT command sequences and subsequences, the commands in the optimization subsequence are stored as a linked list of GmatCommand objects. The Optimize command runs the subsequence by starting at the begining of this linked list and firing the Execute() method on each command in the list. The list is navigated using the GetNext() method on the command. The subsequence is terminated when the GetNext() method returns a pointer to the Optimize command.

The actions shown in Figure 28.9c should be treated as a guideline for how the optimization specific commands in the subsequence interact with the FminconOptimizer. Each time a Vary command is executed, it retrieves its variable value from the FminconOptimizer using the GetSolverVariable() method and sets the value of the associated variable. The Execute() method on the Minimize command evaluates the objective function, and sends the resulting value to the FmminconOptimizer using the SetResultValue() method. Similarly, when a NonLinearConstraint command is executed, the constraint is evaluated and the value is sent to the FminconOptimizer using SetResultValue(). The order in which these actions occur is the order in which they appear in the subsequence.

When the mission subsequence has finished execution, the Optimize command retrieves the results of the subsequence run from the FminconOptimizer and returns these data to the GmatInterface so that they can be passed back to MATLAB.

28.6.3.7 MATLAB Support Files

The fmincon code in MATLAB is driven from a set of three high level MATLAB function files and a fourth lower level function. The three high level files implement these functions:

1. **GmatFminconOptimizationDriver.m** manages the call into the optimizer from GMAT

2. **EvaluateGMATObjective.m** gathers data and executes the callback function into GMAT, obtaining the data calculated in GMAT and returning the value of the objective function and optionally its gradient

3. **EvaluateGMATConstraints.m** accesses the values for the constraints, returned in the call to EvaluateGMATObjective.

These three MATLAB files are listed here. GMAT starts a fmincon run by calling the GmatFminconOptimizationDriver function as a MATLAB function. The actual MATLAB function syntax is encapsulated in the FminconOptimizer; the user does not set up the function objects or the CallFunction commands. GmatFminconOptimizationDriver takes four inputs: a vector containing the initial values of the variables that are being optimized, an array containing the options specified by the user for the optimizer, as described

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in Table 28.1, and two vectors defining the lower and upper bounds on the variables. The function returns a vector to GMAT containing the optimized values of the variables. The MATLAB file[8] is listed here:

```
function [X] = GmatFminconOptimizationDriver(X0, Opt, Lower, Upper)

%  function GmatFminconOptimizationDriver(X0, Opt, Lower, Upper)
%
%  Description:  This function is called from GMAT to drive the fmincon
%  optimizer.
%
%  Variable I/O
% -------------------------------------------------------------------------
%  Variable Name       I/O     Type        Dimens.     Description/Comments
%
%  X0                  I       array       nx1         Column vector of
%                                                      initial values for
%                                                      independent
%                                                      variables
%
%  Opt                 I       string                  Name of GMAT
%                                                      FminconOptimizer
%                                                      object.  This is the
%                                                      the options structure used
%                                                      by fmincon.
%
%  Lower               I       array       nx1         Lower bound on the
%                                                      values of X
%
%  Upper               I       array       nx1         Upper bound on the
%                                                      values of X
%
%  X                   O       array       nx1         Column vector of
%                                                      final values for
%                                                      independent
%                                                      variables
%
%  Notes:  n is the number of independent variables in X
%          neq is the number of nonlinear equality constraints
%          nineq is the number of nonlinear inequality constraints
% -------------------------------------------------------------------------
%
%  External References: fmincon, EvaluateGMATObjective,
%                       EvaluateGMATConstraints, CallGMATfminconSolver
%
%  Modification History
%
%  06/15/06, D. Conway, Created
```

[8]This file, and all of the other MATLAB files, are read in verbatim from the working files to ensure accuracy in the transcription. If you are missing any of the required files, they can be reproduced from the text presented here.

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```
% --- Declare global variables
global NonLinearEqCon NLEqConstraintJacobian NonLinearIneqCon ...
    NLIneqConstraintJacobian

X = fmincon(@EvaluateGMATObjective, X0, [], [], [], [], Lower, Upper, ...
    @EvaluateGMATConstraints, Opt)

% Apply the converged variables
CallGMATfminconSolver(X, 'Converged')
```

MATLAB's fmincon optimizer uses two user supplied MATLAB functions when optimizing a problem: one that evaluates the objective function and, optionally, its gradient, and a second that evaluates problem constraints and the related Jacobians. For GMAT's purposes, those two functions are defined in the other two files listed above, EvaluateGMATObjective.m and EvaluateGMATConstraints.m.

EvaluateGMATObjective passes the values of the variables calculated in fmincon to GMAT using the low level CallGMATfminconSolver function, described below, and waits for GMAT to return the data calculated off of these variables. The variables passed to GMAT are used when running the commands in the solver subsequence. When GMAT receives the call from MATLAB and sets the current variable values in the FminconOptimizer used for the mission. Then the mission subsequence is executed one command at a time. Vary commands in the subsequence query the FminconOptimizer for the corresponding variable values, and the NonLinearConstraint and Minimize, and, eventually, Gradient and Jacobian commands set their calculated values on the FminconOptimizer as they are executed. Once the solver subsequence finishes running, these calculated values are returned to MATLAB in the return vectors defined for the function. Here is the MATLAB file that implements EvaluateGMATObjective:

```
function [F,GradF] = EvaluateGMATObjective(X)

%  function [F,GradF] = EvaluateGMATObjective(X)
%
%  Description:  This function takes the nondimensionalized vector of
%  independent variables, X, and sends it to GMAT for evaluation of the
%  cost, constraints, and derivatives.  If derivatives are not calculated
%  in GMAT, then an empty matrix is returned.
%
%  Variable I/O
% -------------------------------------------------------------------------
%  Variable Name        I/O     Type         Dimens.        Description/
%                                                           Comments
%
%  X                     I     array         n x 1          Column vector
%                                                           of Independent
%                                                           variables
%
%  F                     O     array         1 x 1          Cost function
%                                                           value
%
%  GradF                 O     array         n x 1  or []   Gradient of
%                                                           the cost f'n
%
%  NonLinearEqCon        O   global array    neq x 1 or []  Column vector
%                                                           containing
%                                                           nonlinear
```

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```
%                                                           equality
%                                                           constraint
%                                                           values.
%
%  JacNonLinearEqCon      O   global array    n x neq or []  Jacobian of the
%                                                           nonlinear
%                                                           equality
%                                                           constraints
%
%  NonLinearIneqCon       O  global array     nineq x1 or [] Column vector
%                                                           containing
%                                                           nonlinear
%                                                           inequality
%                                                           constraint
%                                                           values.
%
%  JacNonLinearIneqCon    O  global array   n x ineq or []   Jacobian of the
%                                                           nonlinear
%                                                           inequality
%                                                           constraints
%
%  Notes:  n is the number of independent variables in X
%          neq is the number of nonlinear equality constraints
%          nineq is the number of nonlinear inequality constraints
% --------------------------------------------------------------------------
%
%  External References: CallGMATfminconSolver
%
%  Modification History
%
%  06/13/06, S. Hughes, Created


% --- Declare global variables
global NonLinearIneqCon, JacNonLinearIneqCon, NonLinearEqCon, ...
       JacNonLinearEqCon

% --- Call GMAT and get values for cost, constraints, and derivatives
[F, GradF, NonLinearEqCon, JacNonLinearEqCon, NonLinearIneqCon, ...
    JacNonLinearIneqCon] = CallGMATfminconSolver(X);
```

When control returns to MATLAB from GMAT, all of the data fmincon needs is available for consumption. The value of the objective function, along with its gradient if calculated, are returned directly to fmincon. The constraint and Jacobian data are stored in global MATLAB variables so that they can be sent to fmincon when the optimizer requests them. The EvaluateGMATConstraints function provides the interface fmincon needs to access these data. It is shown here:

```
function [NonLinearIneqCon, JacNonLinearIneqCon, NonLinearEqCon, ...
                                     JacNonLinearEqCon] = EvaluateGMATConstraints(X)

%  function [F,GradF] = EvaluateGMATConstraints(X)
%
```

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```
%  Description:  This function returns the values of the contraints and
%  Jacobians.  Empty matrices are returned when either a constraint type
%  does not exist, or a Jacobian is not provided.
%
%  Variable I/O
% ---------------------------------------------------------------------
%  Variable Name       I/O     Type         Dimens.        Description/
%                                                          Comments
%
%  X                   I     array         n x 1          Column vector of
%                                                          Independent
%                                                          variables
%
%  NonLinearEqCon       O   global array    neq x 1 or []  Column vector
%                                                          containing
%                                                          nonlinear
%                                                          equality
%                                                          constraint
%                                                          values.
%
%  JacNonLinearEqCon    O   global array    n x neq or []  Jacobian of the
%                                                          nonlinear
%                                                          equality
%                                                          constraints
%
%  NonLinearIneqCon     O  global array     nineq x1 or [] Column vector
%                                                          containing
%                                                          nonlinear
%                                                          inequality
%                                                          constraint
%                                                          values.
%
%  JacNonLinearIneqCon  O  global array   n x ineq or []   Jacobian of the
%                                                          nonlinear
%                                                          inequality
%                                                          constraints
%
%  Notes:  n is the number of independent variables in X
%          neq is the number of nonlinear equality constraints
%          nineq is the number of nonlinear inequality constraints
% ---------------------------------------------------------------------
%
%  External References: CallGMATfminconSolver
%
%  Modification History
%
%  06/13/06, S. Hughes, Created

global NonLinearIneqCon, JacNonLinearIneqCon, NonLinearEqCon, ...
       JacNonLinearEqCon
```

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The low level callback function, CallGMATfminconSolver, uses the MATLAB server interface in GMAT to run the solver subsequence. This function is contained in the MATLAB file shown here:

```
function [F, GradF, NonLinearEqCon, JacNonLinearEqCon, ...
    NonLinearIneqCon, JacNonLinearIneqCon] = ...
    CallGMATfminconSolver(X, status)

% function [F, GradF, NonLinearEqCon, JacNonLinearEqCon, ...
%    NonLinearIneqCon, JacNonLinearIneqCon] = CallGMATfminconSolver(X)
%
% Description:  This is the callback function executed by MATLAB to drive
% the GMAT mission sequence during fmincon optimization.
%
%
```

28.6.3.8 Scripting the fmincon Optimizer

A sample script for the FminconOptimizer is shown here:

```
%-----------------------------------------------------------------
%------------------ Create core objects --------------------------
%-----------------------------------------------------------------
Create Spacecraft Sat;
...
Create ForceModel DefaultProp_ForceModel;
...
Create Propagator DefaultProp;
GMAT DefaultProp.FM = DefaultProp_ForceModel;
...
Create ImpulsiveBurn dv1;
Create ImpulsiveBurn dv2;
...
%-----------------------------------------------------------------
%-----------------Create and Setup the Optimizer------------------
%-----------------------------------------------------------------
Create fminconOptimizer SQPfmincon
GMAT SQPfmincon.DiffMaxChange = 0.01;    % Real number
GMAT SQPfmincon.DiffMinChange = 0.0001;  % Real number
GMAT SQPfmincon.MaxFunEvals   = 1000;    % Real number
GMAT SQPfmincon.MaxIter       = 250;     % Real number
GMAT SQPfmincon.TolX          = 0.01;    % Real number
GMAT SQPfmincon.TolFun        = 0.0001;  % Real number
GMAT SQPfmincon.DerivativeCheck = Off;   % {On, Off}
GMAT SQPfmincon.Diagnostics     = On;    % {On, Off}
GMAT SQPfmincon.Display         = Iter   % {Iter, Off, Notify, Final}
GMAT SQPfmincon.GradObj         = Off;   % {On, Off}
GMAT SQPfmincon.GradConstr      = Off;   % {On, Off}

%*****************************************************************
%-------------------The Mission Sequence--------------------------
%*****************************************************************

```

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```
% The optimization sequence below demonstrates how to use an SQP
% routine in GMAT to show that the Hohmann transfer is the optimal
% transfer between two circular, co-planar orbits.
Optimize SQPfmincon

   % Vary the initial maneuver using the optimizer, and apply the maneuver
   Vary SQPfmincon(dv1.Element1 = 0.4, {Upper = 2.0, Lower = 0.0, cm = 1, cf = 1});
   Maneuver  dv1(Sat);

   % Vary the tranfer time of flight using the SQP optimizer
   Vary SQPfmincon( TOF = 3600 );
   Propagate DefaultProp(Sat, {Sat.ElapsedSecs = TOF});

   % Vary the second maneuver using the optimizer, and apply the maneuver
   Vary SQPfmincon(dv2.Element1 = 0.4 , {Upper = 2.0, Lower = 0.0});
   Maneuver  dv2(Sat);

   % Apply constraints on final orbit, and define cost function
   NonLinearConstraint SQPfmincon(Sat.SMA = 8000);
   NonLinearConstraint SQPfmincon(Sat.ECC = 0);
   Minimize SQPfmincon(dv1.Element1 + dv1.Element2);

EndOptimize
```

28.7 Command Interfaces

The GMAT solvers are driven from a number of commands tailored to the solver algorithms. The solver specific commands are shown in Figure 28.10. Each category of solver is used to drive a sequence of commands that starts with the keyword associated with the solver: “Target” for the targeters, “Iterate” for the scanners, and “Optimize” for the optimizers. The solver used for the sequence is identified on this initial line. Each solver sequence is terminated with a corresponding end command: “EndTarget” for the targeters, “EndIterate” for the scanners, and “EndOptimize” for the optimizers. The commands enclosed between these keywords define the variables used in the solver, the conditions that the solver is designed to evaluate, ancillary conditions that need to be met (e.g. constraints for the optimizers), and the sequence of events that the model runs when solving the scripted problem. This section describes the features of the commands that interact directly with the Solvers to solve mission specific tasks. The general layout and methods used by all commands are provided in Chapter 26.

28.7.1 Commands Used by All Solvers

Figure 28.10 shows the classes used by the GMAT solvers. Classes shown in purple on this figure are used by targeters, in blue by scanners, and in green by optimizers. The classes shown in yellow are base classes, and the command in orange – the Vary command – is used by all solvers. The solver specific commands, shown in Figure 28.11, are described in the following paragraphs. The scripting and options for the commands are presented first, followed by a brief description of the steps take during initialization and execution of the commands.

28.7.1.1 Solver Loop Commands

Each solver defines a mission subsequence that starts with a command, identified by the keyword “Target”, “Iterate”, or “Optimize”, followed by the name of an instantiated solver. These commands are collectively

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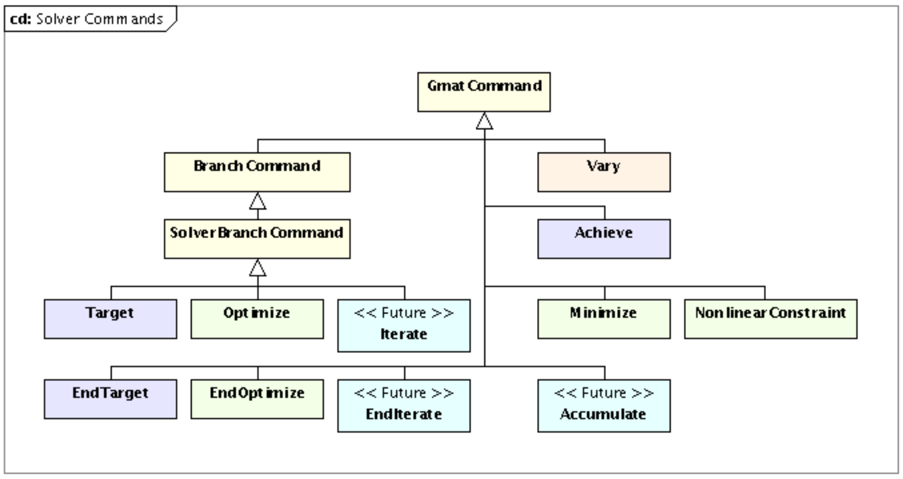

Figure 28.10: Command Classes used by the Solvers

called the "loop entry commands" in the text that follows. The commands that are evaluated when running the solver subsequence follow this line in the order in which they are executed. The solver subsequence is terminated with a corresponding loop exit command, one of "EndTarget", "EndIterate", or "EndOptimize", selected to match the loop entry command line. The format for a solver loop can be written

```
<LoopEntryCommand> <SolverName>
   <Solver Subsequence Commands>
<LoopExitCommand>
```

All solver subsequences must contain at least one `Vary` command so that the solver has a variable to use when running its algorithm. Targeter commands also require at least one `Achieve` command, specifying the goal of the targeting. Scanners require at least one `Accumulate` command, defining the data that is collected during the iterative scan driven by the algorithm. Optimizers are required to define one – and only one – objective function, using the `Minimize` command.

When the Solver hierarchy includes the option to drive the solution process from an external solver, the loop entry command must also supply a method used for the external process to call back into GMAT to run the solver subsequence. This method, ExecuteCallback(), is currently only supported by the optimizers.

The solver loop command members shown in the figure fill these roles:

Data Elements

- **std::string iteratorName, targeterName, optimizerName**: The name of the solver used for this solver loop.
- **Solver* iterator, targeter, optimizer**: The Solver used for this solver loop.

Methods

- **bool Initialize()**: Sets member pointers, initializes the solver subsequence, and then initalizes the Solver.
- **bool Execute()**: Runs the Solver state machine, and executes the solver subsequence when the state machine requires it.

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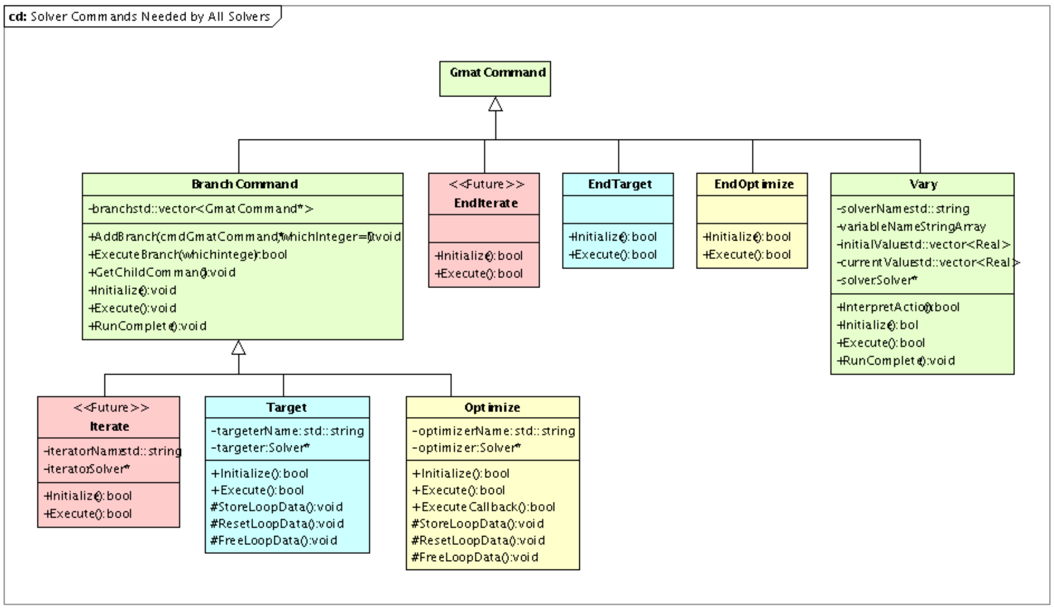

Figure 28.11: Command Classes Required by All Solvers

- **bool ExecuteCallback()**: For external solvers[9], this method runs the nested state machine through one iteration.
- **void StoreLoopData()**: Constructs objects used to store the object data at the start of a Solver subsequence, so that the data can be reset each time the subsequence is run. These objects are initialized to the values of the objects at the start of the execution of the Solver loop.
- **void ResetLoopData()**: Resets the subsequence data to their initial values prior to the run of the solver subsequence.
- **void FreeLoopData()**: Releases the objects constructed in the StoreLoopData() method. This method is called after a Solver has completed its work, immediately before proceeding to the next command in the mission sequence.

Initialization During initialization, the loop entry commands use the Sandbox's local object map to find the solver used in the loop. That solver is cloned and the clone is stored in a local variable. The loop entry command then walks through the list of commands in its subsequence and passes the pointer to the solver clone into each command that needs the pointer; these commands are those shown as solver specific in Figure 28.10. The branch command Initialize() method is then called to complete initialization of the commands in the solver subsequence.

Execution The loop entry commands execute by performing the following series of events:

1. If the "commandExecuting" flag is false:

   Store the current states for all spacecraft and formations

   Retrieve and store the entry data for the solver

[9]Currently only applicable for Optimizers

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Set the “commandExecuting” flag to true and the and “commandComplete” flag to false

Retrieve the current solver state

2. If the command is currently running the solver subsequence, take the next step in that run. This piece is required to let the user interrupt the execution of a run; when the subsequence is running, it periodically returns control to the Sandbox so that the user interface can be polled for a user interrupt.
3. If the subsequence was not running, perform actions that the subsequence needs based on the current solver state. These actions may be restoring spacecraft data to the entry data for the solver loop, starting a run in the mission subsequence, preparing to exit the solver loop, other algorithm specific actions, or taking no action at all.
4. Call AdvanceState() on the solver.
5. Write out solver report data.
6. Return control to the Sandbox.

28.7.1.2 Vary

The Vary command is used by all solvers to define the variables used by the solver, along with parameters appropriate to the variable. A typical Vary command has the format

```
Vary <SolverName>(<variable> = <initialValue>, {<parameter overrides>})
```

The `<SolverName>` should be the same solver object identified when the solver loop was opened. The solver must be identified in each Vary command, so that nested solvers can assign variables to the correct solver objects[10].

The Vary command has the following parameters that users can override:

- **Pert**: Defines the perturbation applied to the variable during targeting or scanning. This parameter has no effect when using the FminconOptimizer. (TBD: the effect for other optimizers.)
- **Lower** (Default: Unbounded): The minimum allowed value for the variable.
- **Upper** (Default: Unbounded): The maximum allowed value for the variable.
- **MaxStep** (Default: Unbounded): The largest allowed singel step that can be applied to the variable.
- **AdditiveScaleFactor** (Default: 0.0): The additive factor, A, defined in equation 28.5.
- **MultiplicativeScaleFactor** (Default: 1.0): The multiplicative factor, M, defined in equation 28.5.

Parameters are set by assigning values to these keywords. For example, when setting a perturbation on a maneuver component `Mnvr.V`, using the targeter dcTarg, the scripting is

```
Vary dcTarg(Mnvr.V = 1.5, {Pert = 0.001});
```

where the initial value for the velocity component of the maneuver is 1.5 km/s, and the targeter applies a perturbation of 1 m/s (0.001 km/s) to the maneuver when running the targeting algorithm.

The scale factor parameters are used to rescale the variables when passing them to the solvers. Scaling of the variables and other elements in a solver algorithm can be used to ensure that the steps taken by a targeter or optimizer are equally sensitive to variations in all of the parameters defining the problem, and

[10]A similar constraint is applied to all solver commands; identifying the solver removes the possibility of misassigning solver data.

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therefore more quickly convergent. When a variable is passed to a solver, the actual value sent to the solver, $\hat{X}_i$, is related to the value of the variable used in the solver subsequence, X_i, by the equation

$$\hat{X}_i = \frac{X_i + A}{M} \tag{28.5}$$

where A is the value set for the AdditiveScaleFactor, and M is the value of the MultiplicativeScaleFactor. This equation is inverted when the variable is set from the solver, giving

$$X_i = M\hat{X}_i - A \tag{28.6}$$

All solvers work with the scaled value of the variable data. When a variable value is retrieved from the Solver, the Vary command applies equation 28.6 to the retrieved value before using it in the mission subsequence.

The Vary command members shown in the figure fill these roles:

Data Elements

- **std::string solverName**: The name of the solver that uses this variable.
- **Solver *solver**: A pointer to the Solver.
- **std::string variableName**: The name of the variable fed by this command.
- **<see text> initialValue**: The initial value for the variable. This can be a number, a piece of object data, a Parameter, or an array element.
- **Real currentValue**: The current or most recent value of the variable.

Methods

- **bool InterpretAction()**: Parses the command string and builds the references needed during initialization and execution.
- **bool Initialize()**: Sets the member pointers and registers the variables with the Solver.
- **bool Execute()**: Queries the Solver for the current variable values, and sets these values on the corresponding objects.
- **bool RunComplete()**: Cleans up data structures used in the solver loop.

Initialization At initialization, the Vary command registers its variable with the solver by calling the SetSolverVariable() method. The scaled initial value of the variable (normalized using equation 28.5), along with the associated parameters, are all passed into the solver with this call. That method returns the solver's integer index for the variable, which is stored in a member of the Vary command.

Execution When the Vary command executes, it queries the solver for the current value of the variable using the GetSolverVariable() method. That method passes back the value of the variable that should be used in the current run of the solver subsequence. The value is unnormalized using equation 28.6 and then used to set the value of the variable for later use in the solver subsequence.

28.7.2 Commands Used by Scanners

Scanners are used to collect statistical data by iterating the scanner subsequence for a user specified number of passes. The data collected is identified using the Accumulate command, shown in Figure 28.12 and described here.

TBD – This section will be completed when the first scanner is scheduled for implementation.

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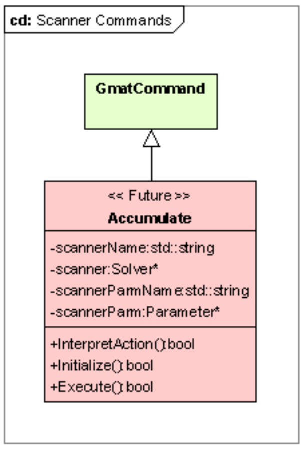

Figure 28.12: Command Classes Used by Scanners

28.7.3 Commands Used by Targeters

Targeters are used to change the variables so that the mission reaches some user specified set of goals. These goals are identified using the Achieve command, shown in Figure 28.13 and described here.

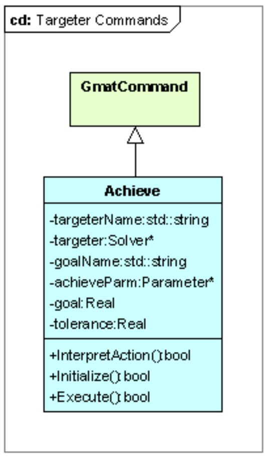

Figure 28.13: Command Classes Used by Targeters

28.7.3.1 Achieve

The Achieve command is used by targeters to define the goals of the targeting sequence. Achieve commands occur inside of a targeter subsequence. They set the targeter goals using scripting with the syntax

```
Achieve <TargeterName>(<goalParameter> = <goalValue>, {Tolerance = ToleranceValue})
```

The targeter named in the command must match the targeter named in the Target command that starts the targeter subsequence. The goalParameters is a GMAT Parameter that produces a Real value. The

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GoalValue and the ToleranceValue each consist of either a number, a Parameter, or an array element, again, producing a Real number.

The Achieve command members shown in the figure fill these roles:

Data Elements

- **std::string targeterName**: The name of the Targeter associated with this goal.
- **Solver *targeter**: The Targeter that is trying to meet the goal specified by this command.
- **std::string goalName**: The name of the parameter that is evaluated for this goal.
- **Parameter *achieveParm**: The parameter that is evaluated for comparison with the goal.
- **Real goal**: The goal of the targeting run associated with the achieveParm.
- **Real tolerance**: The measure of how close the achieved value needs to be to the goal.

Methods

- **bool InterpretAction()**: Parses the command string and builds the references needed during initialization and execution.
- **bool Initialize()**: Sets the member pointers and registers the goals with the Targeter.
- **bool Execute()**: Evaluates the value of the achieveParm, and sends this value to the Targeter.

Initialization During Initialization, the Achieve command sets its internal member pointers and registers with the Targeter.

Execution When the Achieve command is executed, the parameter that calculates the current value for the targeter goal is evaluated, and that value is sent to the Targeter.

28.7.4 Commands Used by Optimizers

All optimizers require exactly one Minimize command. Optimizers may also specify other data used in optimization; specifically, commands exist to specify nonlinear constraints, gradient data, and Jacobian data.

28.7.4.1 Minimize

The Minimize command has the syntax

```
Minimize <OptimizerName>(<ObjectiveFunction>)
```

As in the other solver commands, the solver identified in the command, <OptimizerName>, is the same optimizer as was identified in the loop entry command, an Optimize command in this case. The parameter passed inside the parentheses, identified as <ObjectiveFunction> here, returns a scalar Real value that represents the current value of the objective function. This function is contained in a GMAT a Variable.

The Minimize command members shown in the figure fill these roles:

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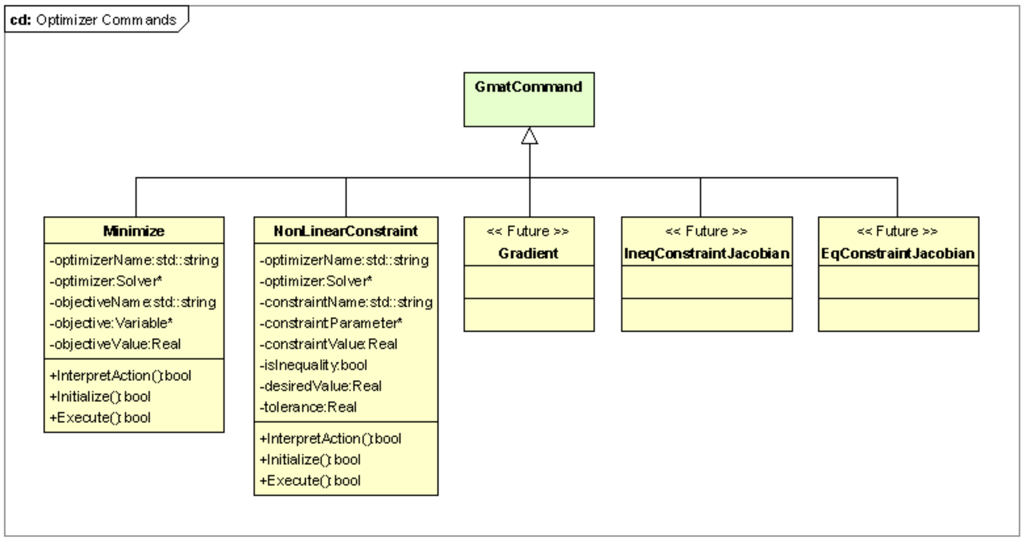

Figure 28.14: Command Classes Used by Optimizers

Data Elements

- **std::string optimizerName**: The name of the Optimizer that owns this objective.
- **Solver *optimizer**: A pointer to the Optimizer.
- **std::string objectiveName**: The name of the variable used to evaluate the objective function.
- **Variable *objective**: The variable used for the objective function.
- **Real objectiveValue**: The current or most recent value of the objective function.

Methods

- **bool InterpretAction()**: Parses the command string and builds the references needed during initialization and execution.
- **bool Initialize()**: Sets the member pointers and registers the objective function with the Optimizer.
- **bool Execute()**: Evaluates the value of the objective function, and sends this value to the optimizer.

Initialization The Optimizer used by the Minimize command is set by the Optimize loop entry command prior to initialization of this command. When initialization is called for the Minimize command, the Variable providing the objective function value is found in the Sandbox's local object map and the pointer is set accordingly. The Minimize command then registers with the Optimizer using the SetSolverResults method. The Optimizer sets its member data structure accordingly, and throws an exception if more than one objective attempts to register.

Execution When the Minimize command is executed, the Real value of the objective function is evaluated by calling the Variable's EvaluateReal method. The resulting value of the objective function is passed to the Optimizer using the SetResultValue method.

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28.7.4.2 NonLinearConstraint

The NonlinearConstraint command has the syntax

```
NonlinearConstraint <OptimizerName>(<ConstraintSpecification>)
```

Here the OptimizerName is the name of the Optimizer identified in the Optimize loop entry command.
The <ConstraintSpecification> has the form

```
<ConstraintParameter>  <operator>  <ConstraintValue>
```

<ConstraintParameter> is a Parameter, Variable, or object property. The operator is either an equal sign ("=") for equality constraints, or a "<=" specification for inequality constraints. The constraint value is a Real number settig the target value of the constraint.

The NonlinearConstraint command members shown in the figure fill these roles:

Data Elements

- **std::string optimizerName**: The name of the Optimizer that owns this constraint.
- **Solver *optimizer**: A pointer to the Optimizer.
- **std::string constraintName**: The name of the object providing the constraint value.
- **Parameter *constraint**: The object providing the constraint value.
- **Real constraintValue**: The current or most recent value of the constraint.
- **bool isInequality**: A flag indicating is the constraint is an inequality constraint.
- **Real desiredValue**: The desired value, or right hand side, of the constraint equation.
- **Real tolerance**: Currently unused, this is a measure of how close the calculated value for the constraint needs to be to the actual value for equality constraints.

Methods

- **bool InterpretAction()**: Parses the command string and builds the references needed during initialization and execution.
- **bool Initialize()**: Sets the member pointers and registers the constraint with the Optimizer.
- **bool Execute()**: Evaluates the value of the constraint, and sends this value to the optimizer.

Initialization The Optimizer used by the NonlinearConstraint command is set by the Optimize loop entry command prior to initialization of this command. When initialization is called for the NonlinearConstraint command, the object that is evaluated for the constraint is retrieved from the Sandbox's local object map. The constraint specification is parsed, setting the constraint type and data in the NonlinearConstraint command. Finally, all of the constraint information is collected and registered with the Optimizer using the SetSolverResults method.

Execution When the NonlinearConstraint command is executed, the Real value of the constraint is evaluated, and the resulting value of the constraint is passed to the Optimizer using the SetResultValue method.

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28.7.4.3 Gradient

The Gradient command is used to send the gradient of the objective function to an optimizer. This command, a future enhancement, will be implemented when state transition matrix calculations are incorporated into GMAT.

28.7.4.4 NLIneqConstraintJacobian

This command is used to set the Jacobian of the nonlinear inequality constraints for an optimizer. This command, a future enhancement, will be implemented when state transition matrix calculations are incorporated into GMAT.

28.7.4.5 NLEqConstraintJacobian

This command is used to set the Jacobian of the nonlinear equality constraints for an optimizer. This command, a future enhancement, will be implemented when state transition matrix calculations are incorporated into GMAT.

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Chapter 29

SolverUtilities

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GMAT's Solver classes may require one or more of several routine utility functions in order to proceed towards the dictated solution. These functions include calculation of gradients and Jacobians, Hessians, and systematic searches in a specified direction (aka "Line searches") for minima, and other routines common to the solver algorithms. For each of these utilities, users can provide their own implementation – analytic or numerical – or use an algorithm implemented in the class.

This chapter describes the interfaces for these solver utilities and the implementation of the algorithms internal to GMAT. It also provides information about how user specified implementations are used in GMAT.

29.1 Overview

29.2 Gradient Calculations

29.3 Jacobian Calculations

29.4 Hessian Calculations

29.5 Line Searches

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Chapter 30

Inline Mathematics in GMAT

Darrel J. Conway
Thinking Systems, Inc.

GMAT provides a flexible mechanism that lets users place both scalar and matrix computations into the command sequence for a mission. This mechanism is implemented in a set of classes described in this chapter.

30.1 Scripting GMAT Mathematics

Mathematics in GMAT scripts follow the conventions established in MATLAB; an equation consists of an object on the left side of an equals sign, with an equation on the right. Equations can be entered either in script files, or using a panel on the graphical user interface. Parentheses are used to set the precedence of operations when the normal precedence rules are not valid. Table 30.1 lists the operators implemented in GMAT. The table is arranged in order of operator precedence; operators higher in the table are evaluated before operators that appear lower in the table. Users can override this order through selective use of parentheses.

Mathematics in GMAT are scripted using the same syntax as assignments. Three samples of the scripting for the operations in Table 30.1 are provided here to and discussed in the design presentation to help explain how GMAT manipulates its internal data structures to perform scripted mathematics.

Example 1: Basic Arithmetic

In this simplest example, a user needs to write script to perform the calculation of the longitude of periapsis,

$$\Pi = \Omega + \omega \tag{30.1}$$

for the spacecraft named sat. The scripting for this calculation is straight forward:

```
Create Spacecraft sat;
Create Variable arg
GMAT arg = sat.RAAN + sat.AOP
```

Example 2: More Complicated Expressions

This snippet calculates the separation between two spacecraft, using the Pythagorean theorem:

$$\Delta R = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2} \tag{30.2}$$

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Table 30.1: Operators and Operator Precedence in GMAT

Operator or Function	**Implemented Cases**	**Comments**	**Example**
Evaluate Conversion Functions	DegToRad, RadToDeg	Converts between radians and degrees	DegToRad(sat.RAAN)
Evaluate Matrix Operations	transpose and ', det, inv and ^(-1), norm		mat', det(mat)
Evaluate Math Functions	sin, cos, tan, asin, acos, atan, atan2, log, log10, exp, sqrt	Angles in the trig functions are in radians	sin(DegToRad(sat.TA))
Exponentiation	^	Powers are any real number	sin(radTA)^0.5
Multiplication and Division	* /		sat.RMAG / sat.SMA
Addition and Subtraction	+ -		sat.RAAN + sat.AOP

This is a useful example because, as we will see, it exercises the parser to ensure that operations are performed in the correct order. The script for this example is, again, pretty simple:

```
Create Spacecraft sat1, sat2;
Create Variable sep
GMAT sep = sqrt((sat1.X-sat2.X)^2 + (sat1.Y-sat2.Y)^2 + (sat1.Z-sat2.Z)^2)
```

Example 3: Matrix Computations

This final example is more complex, and exercises both operator ordering and matrix computations to calculate a component of the analytic gradient of a function used in optimization. This script snippet assumes that GMAT can calculate the State Transition Matrix and provide users with access to the corresponding 3x3 submatrices of it. The scripting for that calculation is:

```
% This script snippet uses the following definitions for pieces of the
% State Transition Matrix (STM):
%    Sat.Phi is a 6x6 matrix that is the spacecraft STM
%    Sat.PhiA is the upper left 3x3 portion of the STM
%    Sat.PhiB is the upper right 3x3 portion of the STM
%    Sat.PhiC is the lower left 3x3 portion of the STM
%    Sat.PhiD is the lower right 3x3 portion of the STM

Create Spacecraft Sat1, Sat2
Create Array Svec[3,1] Svecdot[3,1] S[1,1] dSdotdR[1,3]

For I = 1: 100
   % Step the spacecraft
   Propagate LowEarthProp(Sat1,Sat2);

   % Calculate the relative position and velocity vectors
```

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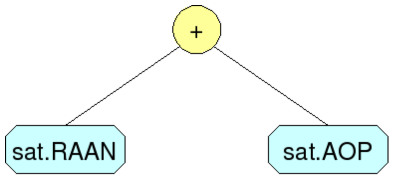

Figure 30.1: Tree View of the Longitude of Periapsis Calculation

```
      GMAT Svec(1,1) = Sat2.X - Sat1.X;
      GMAT Svec(2,1) = Sat2.Y - Sat1.Y;
      GMAT Svec(3,1) = Sat2.Z - Sat1.Z;
      GMAT Svecdot(1,1) = Sat2.VX - Sat1.VX;
      GMAT Svecdot(2,1) = Sat2.VY - Sat1.VY;
      GMAT Svecdot(3,1) = Sat2.VZ - Sat1.VZ;

      % Calculate range
      GMAT S =  norm(Svec);

      % Calculate the change in the range rate due to a change in the
      % initial position of sat1
      GMAT dSdotdR = 1/S*( Svecdot' - Svec'*Svecdot*Svec'/S^2 )*(- Sat1.PhiA )...
                     + Svec'/S*(-Sat1.PhiC);
   EndFor;
```

The last expression here, dsDotdR, will be used in the design discussion.

30.2 Design Overview

When GMAT encounters the last line of the first script snippet:

```
   GMAT arg = sat.RAAN + sat.AOP
```

it creates an assignment command that assigns the results of a calculation to the variable named arg. The right side of this expression – the equation – is converted into GMAT objects using an internal class in GMAT called the MathParser. The MathParser sets up custom calculations by breaking expressions – like the ones scripted in the preceding section – into a tree structure using a recursive descent algorithm. This decomposition is performed during script parsing when the user is running from a script file, and during application of user interface updates if the user is constructing the mathematics from the GMAT graphical user interface. GMAT stores the tree representation of the mathematics in an internal object called the MathTree. During script execution, the MathTree is populated with the objects used in the calculation during mission initialization in the Sandbox. The equation is evaluated when the associated Assignment command is executed by performing a depth-first traversal of the tree to obtain the desired results. The algorithms implemented here are extensions of the approach presented in chapter 40 of [schildt].

The tree based structure of the computations enforces the operator precedence rules tabulated above. In this section the construction and evaluation of the trees for the examples is presented, and the classes used in this process are introduced. The sections that follow this overview present the classes in a more systematic manner, discuss how the scripting is parsed to create the GMAT objects used in evaluation, and then tie these pieces together by discussing how the constructed objects interact as a program executes.

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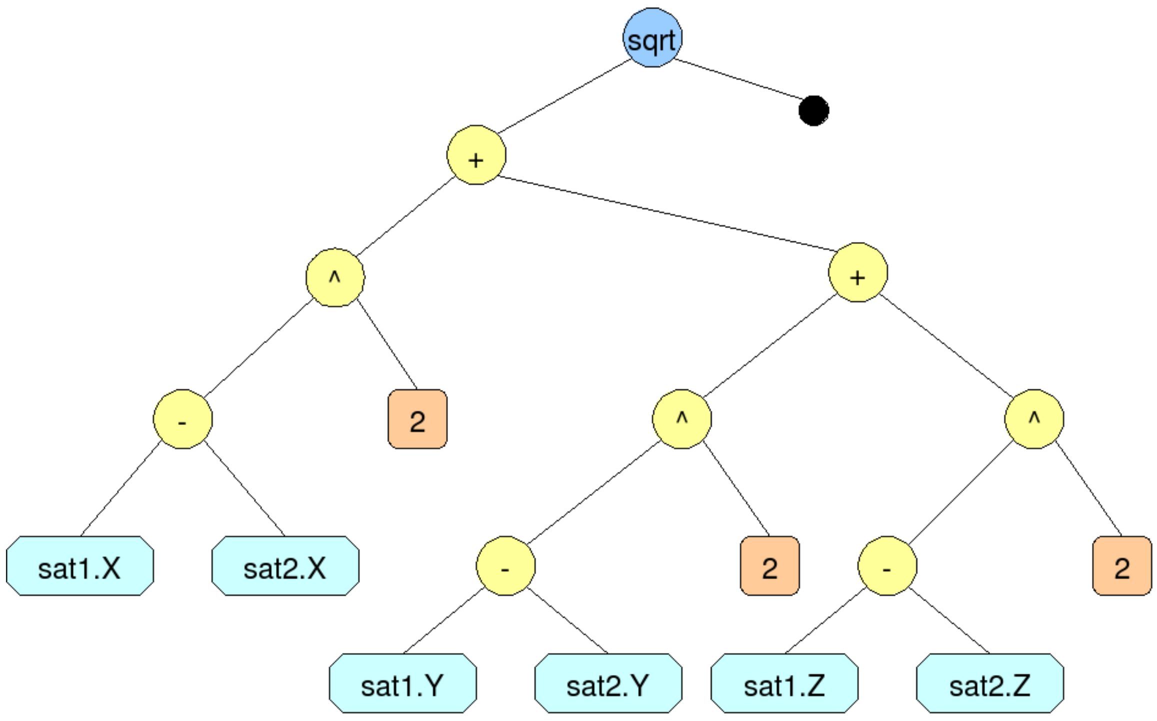

Figure 30.2: Tree View of the Satellite Separation Calculation

Figure 30.1[1] shows the tree generated for the longitude of periapsis calculation scripted above. This simplest example illustrates the layout of the tree in memory that results from a simple arithmetic expression. The GMAT MathParser class is fed the right side of the expression from the script – in this case, that is the string "sat.RAAN + sat.AOP". This string is passed to the recursive descent code, which breaks it into three pieces – two expressions that can be evaluated directly, and an operator that combines these expressions. These pieces are stored in an internal class in GMAT called the MathTree. The expressions "sat.RAAN" and "sat.AOP" are placed into the "leaves" of the tree, while the addition operator is placed in the top, "internal" node. The leaf nodes are all instances of a class named "MathElement", and the internal nodes, of classes derived from a class named "MathFunction". When the assignment command containing this construct is executed, each of the leaves of the tree is evaluated, and then combined using the code for the addition operator.

The second example, illustrated in Figure 30.2, provides a more illustrative example of the parsing and evaluation algorithms implemented in GMAT. This tree illustrates the equation encoded in example 2:

```
GMAT sep = sqrt((sat1.X-sat2.X)^2 + (sat1.Y-sat2.Y)^2 + (sat1.Z-sat2.Z)^2)
```

Each node in the MathTree can be one of three types: a function node, an operator node (both of these types are embodied in the MathFunction class), or an element node (in the MathElement class). The element nodes are restricted to being the leaf nodes of the tree; the internal nodes are all either function nodes or operator nodes.

Each MathElement node consists of two separate pieces; a string containing the text of the expression represented by the node, and either a pointer to the object that embodies that expression or, for constants,

[1]In this figure and those that follow, the components that can be evaluated into Real numbers are drawn on elongated octagons, and the operators are drawn in a circle or ellipse. Matrices are denoted by a three-dimensional box. Empty nodes are denoted by black circles, and numbers, by orange squares with rounded corners.

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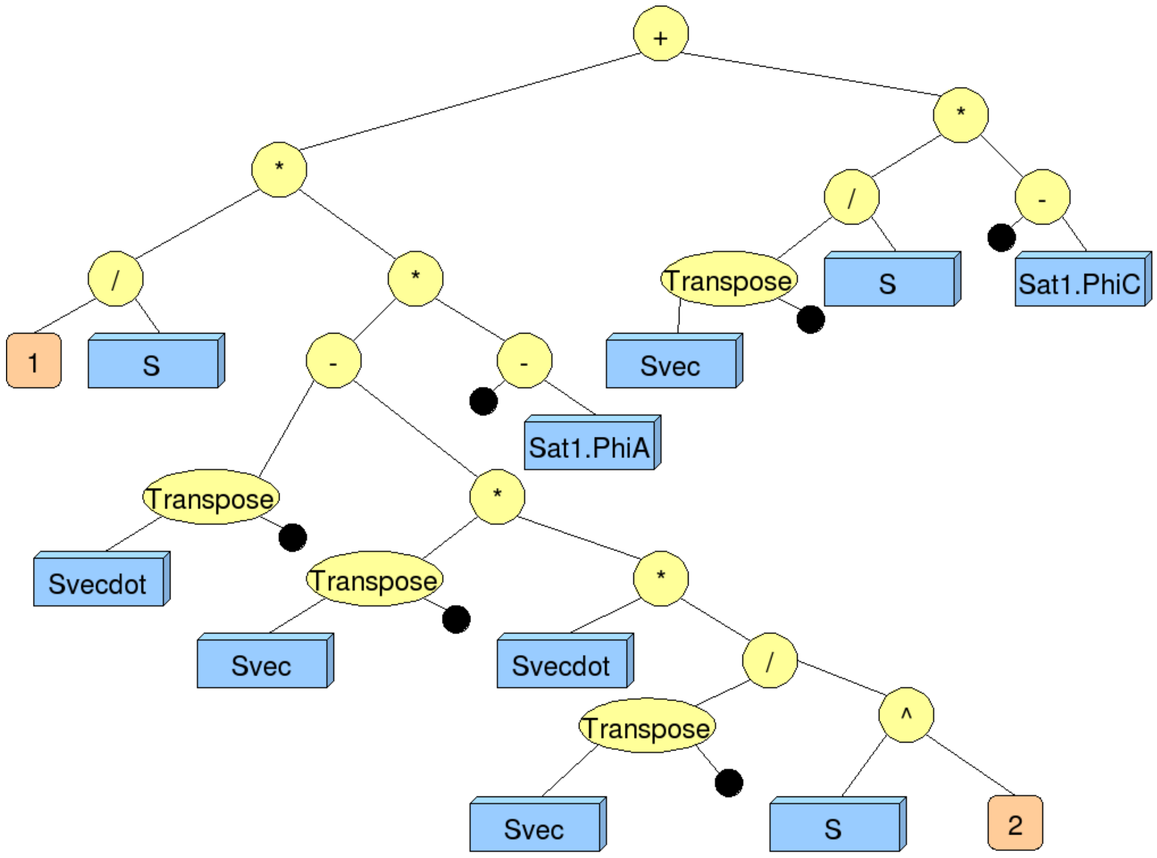

Figure 30.3: Tree View of the Matrix Calculation in Example 3

a local member containing the value of the expression. The pointer member is initially set to NULL when the MathElement node is constructed during script parsing. When the script is initialized in the GMAT Sandbox, these pointers are set to the corresponding objects in the Sandbox's configuration. Each time the assignment command associated with the MathTree executes, an Evaluate() method is called on the MathTree, as described below.

The function and operator nodes consist of several pieces as well. Each of these nodes contain subnode pointers that identify the input value or values needed for the node evaluation, and a method that performs the actual mathematics involved in the evaluation. The mathematical operations for each of these nodes is coded to work on either a scalar value or a matrix; the specific rules of implementation are operator specific.

The Evaluate() method for the MathTree calls the Evaluate() method for the topmost node of the tree. This method call is evaluated recursively for all of the subnodes of the tree, starting at the top node. The method checks to see if the node is a leaf node or an internal node. If it is a leaf node, it is evaluated and the resulting value is returned to the object that called it. If it is an internal node, it evaluates its subnodes by calling Evaluate() first on the left node, then on the right node. Once these results are obtained, they are combined using the mathematical algorithm coded for the node, and the resulting value is then returned to the calling object.

Finally, the gradient component scripted in the third example:

```
GMAT dSdotdR = 1/S*( Svecdot' - Svec'*Svecdot*Svec'/S^2 )*(- Sat1.PhiA )...
               + Svec'/S*(-Sat1.PhiC);
```

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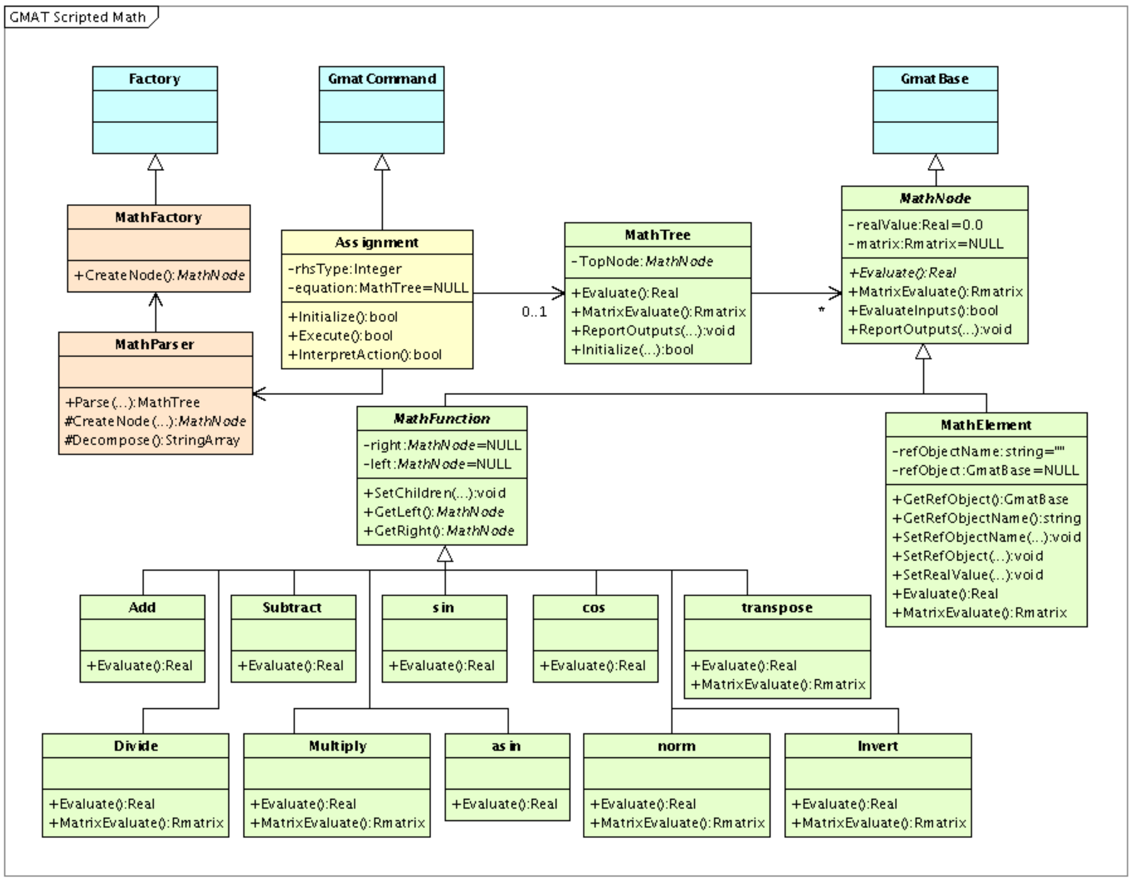

Figure 30.4: Classes Used to Implement GMAT Mathematics

produces Figure 30.3. Evaluation for this tree proceeds as outlined above, with a few variations. Instead of calling the Evaluate() method for the nodes in the tree, expressions that use matrices call the MatrixEvaluate method. Another wrinkle introduced by the matrix nature of this example is that the internal nodes now have an additional requirement; each node needs to determine that the dimensionality of the subnodes is consistent with the requested operations. This consistency check is performed during initialization in the Sandbox, using the ValidateInputs() method. MatrixEvaluate may perform additional checks during execution, so that singularities in the computation can be flagged and brought to the attention of the user.

30.3 Core Classes

Figure 30.4 shows the class hierarchy implemented to perform the operations described above, along with some of the core members of these classes. The core classes used in GMAT to perform mathematical operations are shown in green in this figure, while the helper classes used to setup the binary tree structure are shown in orange. The MathTree and its nodes are all owned by instances of the Assignment command, shown in yellow in the figure. Core GMAT classes are shaded in blue. The main features of these classes are shown here, and discussed in the following paragraphs. At the end of this section, the principal elements of the base classes are collected for reference.

The MathTree class is the container for the tree describing the equation. It contains a pointer to the

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topmost node of the tree, along with methods used to manipulate the tree during initialization and execution. This class is used to provide the interface between the tree and the Assignment command.

Each node in a MathTree is derived from the MathNode class. That base class provides the structures and methods required by the MathTree to perform its functions. There are two classes derived from the MathNode base: MathElement and MathFunction. The MathElement class is used for leaf nodes, and can store either a numerical value, a matrix, or a GMAT object that evaluates to a floating point number – for example, a Parameter, or a real member of a core GMAT object. MathFunction instances are used to implement mathematical operators and functions. The left and right subnodes of these nodes contain the function or operator operands. Subnodes are evaluated before the operator is evaluated, producing results that are used when evaluating the function.

The MathNode base class contains two members that are used to check the compatibility of operands during initialization. The EvaluateInputs() method checks the return dimensions of the subnodes of the node, and returns true if either the node is a MathElement or if the subnodes are compatible with the current node's Evaluate() and MatrixEvaluate() methods. The ReportOutputs() method is called on subnodes to obtain the dimensions of matrices returned from calls to MatrixEvaluate(). That method provides an interface used by the EvaluateInputs() method to perform its evaluation.

One additional item worth mentioning in the MathNode base class is the implementation of the Matrix-Evaluate() method. The Evaluate() method is pure virtual, and therefore not implemented in the base class. MatrixEvaluate(), on the other hand, is implemented to apply the Evaluate() method element by element to the matrix members. In other words, the default MatrixEvaluate() method implements the algorithm

$$M_{ij} = Op(L_{ij}, R_{ij}) \tag{30.3}$$

where M_{ij} is the [i,j] element of the resultant, L_{ij} is the [i,j] element of the left operand, and R_{ij} is the [i,j] element of the right operand. Most classes derived from the MathFunction class will override this implementation.

The classes implementing mathematical operations are derived from the MathFunction class. Figure 30.4 shows some (but not all) of these derived classes. Operators that have a one to one functional correspondence with MATLAB operations are named identically to the MATLAB function. That means that operators like the transpose operator will violate the GMAT naming conventions, at least for the string name assigned to the class, because the MATLAB operator is lowercase, "transpose", while the GMAT naming convention specified that class names start with an upper case letter.

Operations that can rely on the algorithm presented in equation 30.3 do not need to implement the MatrixEvaluate() method; for the classes shown here, that means that Add, Subtract, sin, cos, and asin only need to implement the Evaluate() method, while Multiply, Divide, transpose, norm and Invert need to implement both the Evaluate() and MatrixEvaluate() methods.

30.3.1 MathTree and MathNode Class Hierarchy Summary

This section describes the top level classes in the MathTree subsystem, summarizing key features and providing additional information about the class members.

30.3.1.1 MathTree

A MathTree object is a container class used to help initialize and manage the tree representing an equation. It standardizes the interface with the Assignment command and acts as the entry point for the evaluation of an equation. It is also instrumental in setting the object pointers on the tree during initialization in the Sandbox. Key members of this class are described below.

Class Attributes

- **topNode**: A pointer to the topmost node in the MathTree.

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Methods

- **Evaluate()**: Calls the Evaluate() method on the topNode and returns the value obtained from that call.
- **MatrixEvaluate()**: Calls the MatrixEvaluate() method on the topNode and returns the matrix obtained from that call.
- **ReportOutputs(Integer &type, Integer &rowCount, Integer &colCount)**: Calls ReportOutputs(...) on the topNode and returns the data obtained in that call, so that the Assignment command can validate that the returned data is compatible with the object that receives the calculated data (i.e. the object on the left side of the equation).
- **Initialize(std::map<std::string,GmatBase*> *objectMap)**: Initializes the data members in the MathTree by walking through the tree and setting all of the object pointers in the MathElement nodes.

30.3.1.2 MathNode

MathNode is the base class for the nodes in a MathTree. Each MathNode supports methods used to determine the return value from the node, either as a single Real number or as a matrix. The MathNodes also provide methods used to test the validity of the calculation contained in the node and any subnodes that may exist. The core MathNode members are listed below.

Class Attributes

- **realValue**: Used to store the most recent value calculated for the node.
- **matrix**: Used to store the most recent matrix data calculated for the node, when the node is used for matrix calculations.

Methods

- **Evaluate()**: An abstract method that returns the value of the node. For MathElements, this method returns the current value of the element, either by evaluating a Parameter and returning the value, accessing and returning an object's internal data, or returning a constant. For MathFunctions, the Evaluate() method appies the function and returns the result. If the encoded function cannot return a Real number, Evaluate() throws an exception.
- **MatrixEvaluate()**: Fills in a matrix with the requested data. For MathFunction objects, this method performs the calculation of the operation and fills in the matrix with the results. The default implementation uses equation 30.3 to fill in the matrix element by element. Operations that do not return matrix values, like norm and determinant, throw exceptions when this method is called. MathElements simply return the matrix associated with the node.
- **EvaluateInputs()**: Checks the inputs to the node to be sure that they are compatible with the calculation that is being performed. For MathElement nodes, this method always returns true if the node was successfully initialized. For MathFunction nodes, this method calls its subnodes and checks to be sure that the subnodes return compatible data for the function.
- **ReportOutputs(Integer &type, Integer &rowCount, Integer &colCount)**: This method tells the calling object the type and size of the calculation that is going to be performed by setting values of the parameters used in the call. The first parameter, 'type', is set to indicate whether the return value will be a matrix or a Real number. 'rowCount' and 'colCount' are set to the dimensions of the matrix if the return value is a matrix, or to 0 if the return value is scalar. This method is used in the EvaluateInputs() method to determine the suitability of subnodes for a given calculation, and by the MathTree class to obtain the size of the answer returned from a complete calculation.

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30.3.1.3 MathElements

The leaf nodes of a MathTree are all instances of the MathElement class. The MathElement class acts as a wrapper for GMAT objects, using the methods defined in the GmatBase base class to set these referenced objects up for the MathElement's use. The GmatBase methods SetRefObject(), SetRefObjectName(), GetRefObject(), and GetRefObjectName() are overridden to set the internal data structures in the node. The other relevant members of this class are listed below.

Class Attributes

- **refObjectName**: Holds the name of the GMAT object that is accessed by this node.
- **refObject**: A pointer to the referenced object. This pointer is set when the MathTree is initialized in the Sandbox.

Methods

- **SetRealValue(Real value)**: Sets the value of the node when it contains a constant.

30.3.1.4 MathFunctions

The internal nodes of a MathTree are all instances of classes derived from MathFunction. This class contains pointers to subnodes in the tree which are used to walk through the tree structure during initialization and evaluation. The relevant members ate described below.

Class Attributes

- **left**: A pointer to the left subnode used in the calculation. MathFunctions that only require a right subnode leave this pointer in its default, NULL setting.
- **right**: A pointer to the right subnode used in the calculation. MathFunctions that only require a left subnode leave this pointer in its default, NULL setting.

Methods

- **SetChildren(MathNode *leftChild, MathNode *rightChild)**: Sets the pointers for the left and right child nodes. If a node is not going to be set, the corresponding parameter in the call is set to NULL.
- **GetLeft()**: Returns the pointer to the left node.
- **GetRight()**: Returns the pointer to the right node.
- **Evaluate()**: In derived classes, this method is overridden to perform the mathematical operation represented by this node.
- **MatrixEvaluate()**: In derived classes that do not use the default matrix calculations (equation 30.3), this method is overridden to perform the mathematical operation represented by this node.

30.3.2 Helper Classes

There are two classes that help configure a MathTree: MathParser and MathFactory. In addition, the Assignment command acts as the interface between a MathTree and other objects in GMAT, and the Moderator provides the object interfaces used to configure the tree. This section sketches the actions taken by these components.

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30.3.2.1 MathParser

The Interpreter subsystem (see Section 18.3) in GMAT includes an interface that can be used to obtain a MathParser object. This object takes the right side of an equation, obtained from either the GMAT GUI or the ScriptInterpreter, and breaks it into a tree that, when evaluated depth first, implements the equation represented by the equation. The MathParser uses the methods described below to perform this task.

Methods

- **Parse(const std::string &theEquation)**: Breaks apart the text representation of an equation and uses the component pieces to construct the MathTree.
- **CreateNode(const std::string &genString)**: Uses the generating string "genString", to create a node for insertion into the MathTree.
- **Decompose(const std::string &composite)**: This method is the entry point to the recursive descent algorithm. It uses internal methods to take a string representing the right side of the equation and break it into the constituent nodes in the MathTree. The method returns the topmost node of the MathTree, configured with all of the derived subnodes.

30.3.2.2 MathFactory

The MathFactory is a GMAT factory (see Chapter 11 that is used to construct MathNodes. It has one method of interest here:

Methods

- **CreateNode(const std::string &ofType)**: Creates a MathNode that implements the operation contained in the string. If no such operator exists, the MathFactory creates a MathElement node and sets the reference object name on that node to the test of the 'ofType' string.

30.3.2.3 The Assignment Command and the Moderator

The Assignment command is the container for the MathTree described in this chapter. All GMAT equations are formatted with a receiving object on the left side of an equals sign, then the equals sign, and then the equation on the right. When the interpreter system is configuring an Assignment command, it detects when the right side is an equation, and passes the string describing the equation into a MathParser. That MathParser proceeds to parse the equation, making calls into the Moderator when a new MathNode is required. The Moderator accesses the MathFactories through the FactoryManager, and obtains MathNodes as required. These nodes are not added to the Configuration Manager, but they are returned to the MathParser for insertion into the current MathTree. Once the tree is fully populated, it is returned to the Assignment command, completing the parsing of the expression.

When the Moderator is instructed to run a mission, it passes the configured objects into the Sandbox, and then initializes the Sandbox. The last step in Sandbox initialization is to initialize all of the commands in the mission sequence. When one of these commands is an Assignment command that includes a MathTree, that command initializes the MathTree after initializing all of its other elements, and then validates that the MathTree is compatible with the object on the left side of the equation. If an error is encountered at this phase, the Assignment command throws an exception that describes the error and includes the text of the command that failed initialization. If initialization succeeds, the Moderator then tells the Sandbox to run the mission. The Sandbox starts at the first command in the mission sequence, and executes the command stream as described in Chapter 26.

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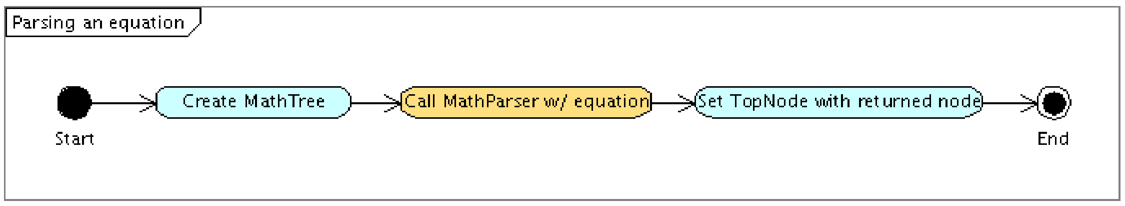

Figure 30.5: Control Flow for Parsing an Equation

30.4 Building the MathTree

Scripted mathematics are constructed using the MathParser class, which builds the binary tree representing the equation that is evaluated by constructing nodes for the tree and placing these nodes into the tree one at a time. Figure 30.5 shows the high level control flow used to create the MathTree. An empty MathTree is created, and then that tree is passed into the MathParser along with the string representation of the equation. The Mathparser takes the MathTree and populates it with MathNodes based on the equation string. The top node of this completed tree is then returned from the parser, and set on the assignment command for use during execution of the mission.

The middle step in the process outlined in Figure 30.5 encapsulates the recursive descent decomposition of the equation. Figure 30.6 provides a more detailed view of this algorithm. The InterpretAction method of the Assignment command determines that the right side of the assignment is an equation, and then creates a MathTree and a MathParser to break this equation into the components needed for evaluation during execution. The MathTree and the equation string are passed into the MathParser.

The MathParser takes the input string, and attempts to break it into three pieces: an operator, a left element, and a right element. Any of these three pieces can be the empty string; if the operator string is empty, only the left string contains data, denoting that the string is used to build a MathElement node, on one of the leaves of the MathTree.

If the operator string is not empty, the operator string is used to build a MathFunction node. MathFunction nodes are used to perform all mathematical operations: basic math like addition, subtraction, multiplication, division, and exponentiation, along with unary negation and mathematical functions. The arguments of the MathFunction are contained in the left and right strings. These strings are passed into the MathParser's Parse method for further decomposition, and the process repeats until all of the strings have been decomposed into operators and the MathElement leaf nodes. If either string is empty, the corresponding child node on the MathFunction is set to NULL.

Once a leaf node has been constructed, that node is set as the left or right node on the operator above it. Once the left and right nodes are set on a MathFunction, that node is returned as a completed node to the calling method, terminating that branch of the recursion. When the topmost node has its child nodes filled in, the MathParser returns from the recursion with the completed MathTree.

30.5 Program Flow and Class Interactions

The preceding section describes the construction of the MathTree that represents an equation. The parsing described above places the instances of the MathFunction nodes into the MathTree, along with the string names of the MathElement nodes. The objects evaluated in the MathElement nodes are not placed into the MathTree, because those elements depend on local objects in the GMAT Sandbox when a script is executed. This section explains how those objects are placed into the MathTree in the Sandbox, and then evaluated to complete a calculation for an Assignment command.

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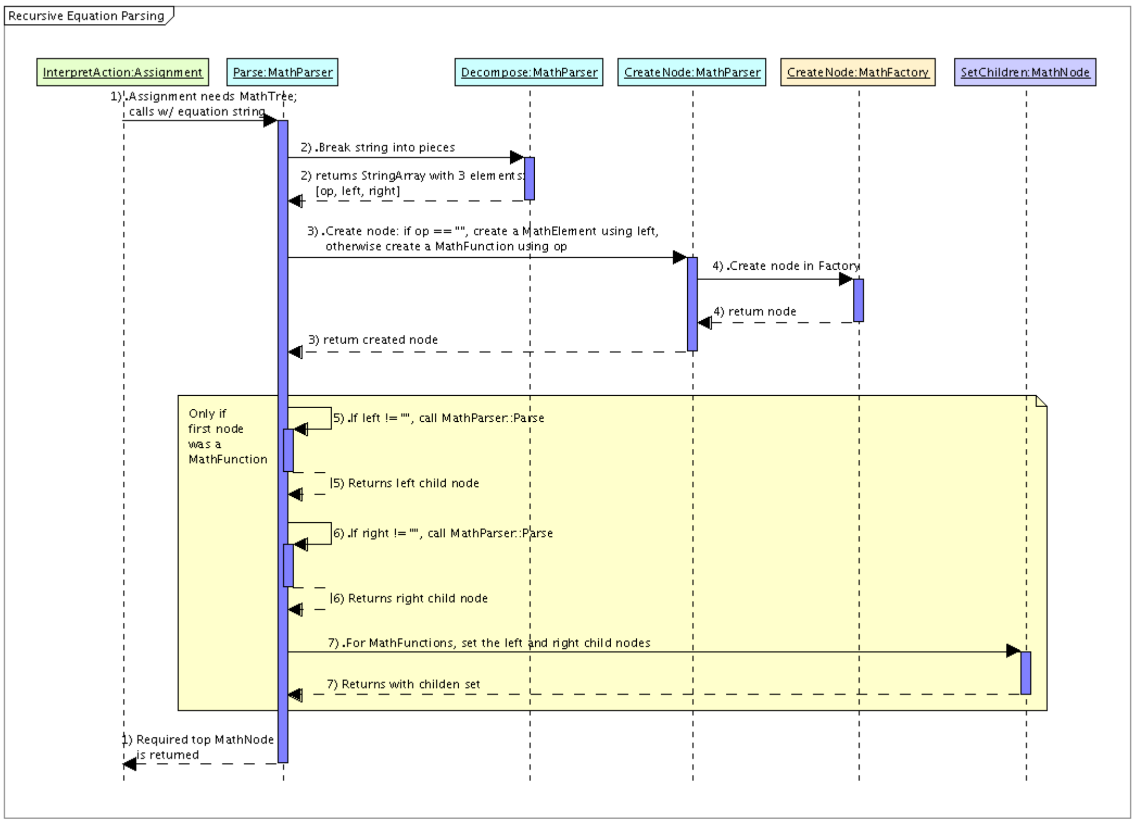
Recursive Equation Parsing
InterpretAction:Assignment
Parse:MathParser
Decompose:MathParser
CreateNode:MathParser
CreateNode:MathFactory
SetChildren:MathNode
1) .Assignment needs MathTree; calls w/ equation string
2) .Break string into pieces
2) returns StringArray with 3 elements: [op, left, right]
3) .Create node: if op == "", create a MathElement using left, otherwise create a MathFunction using op
4) .Create node in Factory
4) return node
3) return created node
Only if first node was a MathFunction
5) .If left != "", call MathParser::Parse
5) Returns left child node
6) .If right != "", call MathParser::Parse
6) Returns right child node
7) .For MathFunctions, set the left and right child nodes
7) Returns with childen set
1) Required top MathNode is returned

Figure 30.6: Parser Recursion Sequence

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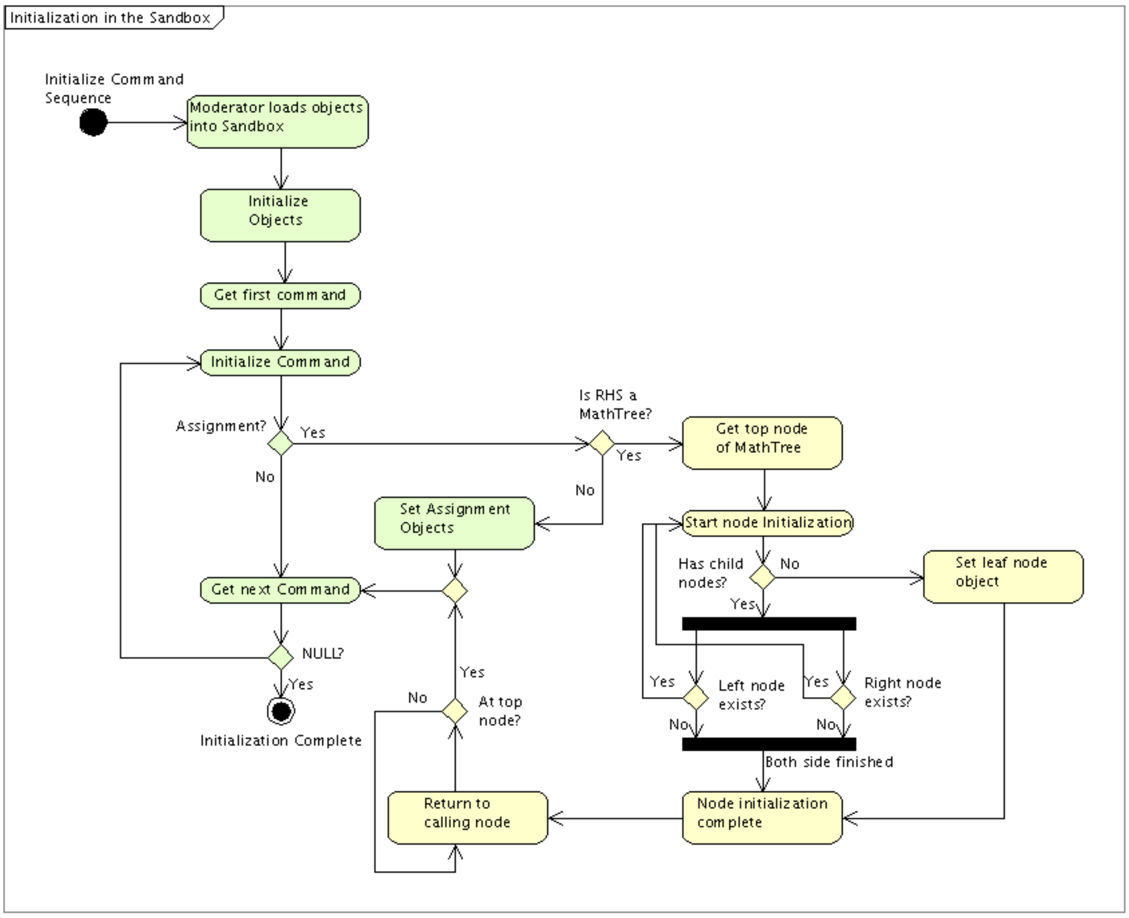

Figure 30.7: MathTree Initialization in the Sandbox

30.5.1 Initialization

Figure 30.7 shows the process of initialization of the Command Sequence in the Sandbox, with a focus on the MathTree initialization. Section 5.2.2.1 describes the general initialization process in the Sandbox. Sandbox initialization proceeds as described there, initializing the objects and then the command sequence. When the command in the sequence is an Assignment command containing in-line mathematics, the Assignment command performs the details shown here to initialize the MathTree. The command first accesses the top node of the MathTree. If that node has subnodes, those subnodes are initialized iteratively until a MathElement node is encountered.

When a MathElement node is encountered, that node is queried for its referenced object's name. If the node returns a name, that object's pointer is accessed in the local object map owned by the Sandbox and set on the node using the SetRefObject() method. If the reference object name is empty, the node is a numerical constant, and no further initialization is required.

When all of the subnodes of a MathFunction node have been initialized, that node validates that the dimensionality of the operands are compatible with the mathematical operation represented by the node. This validation is done by calling the ReportOutputs() method on the child nodes and ensuring that the results are consistent with the requirements of the operation. If the results are consistent, local variables are

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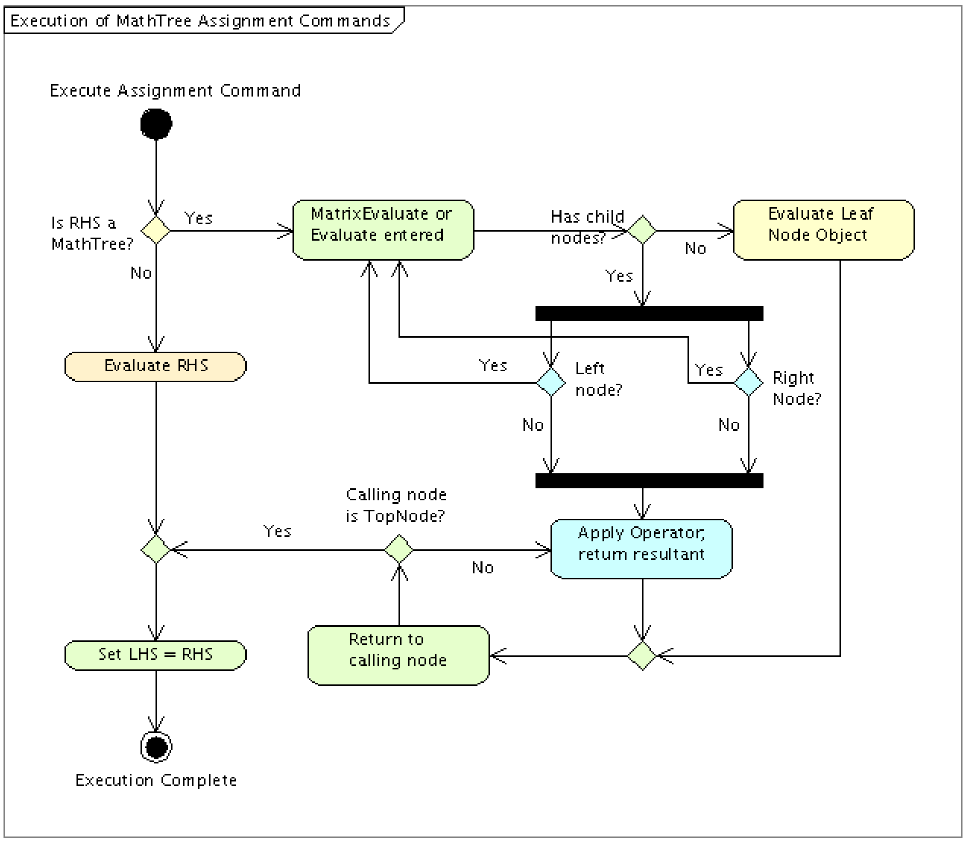

Figure 30.8: Evaluation of a MathTree Assignment

used to save data so that parent nodes to the current node can obtain consistency data without recursing through the MathTree. When the results are inconsistent with the operation, a warning message (which indicates the inconsistency of the calculation and the text of the line that generate the MathTree) is posted to the user, and an internal flag is set to false, indicating that the calculation cannot be performed. That flag is returned when the EvaluateInputs() method is called on the node. This completes the initialization of the MathFunction node, and control is returned to the node above the current node.

When the topmost node in the MathTree finishes initialization, the MathTree calls the EvaluateInputs() method for the top node. If that call returns a false value, an exception is thrown and initialization terminates for the Assignment command. When the call to EvaluateInputs() succeeds, the MathTree reports successful initialization to the Assignment command, which validates that the result of the calculation is consistent with the object that will be receiving the result, and, if so, returns a flag indicating that the calculation initialized successfully. If the resultant of the MathTree calculation is determined to be inconsistent with the receiving object, an exception is thrown that contains the text of the line that generated the Assignment command, along with information about the error encountered.

30.5.2 Execution

The task of evaluating a calculation is shown in Figure 30.8. The Assignment command determines if a MathTree calculation is being performed by determining if the right side of the assignment (denoted RHS in the figure) is a MathTree. If it is, the Assignment command checks to see if the result of the calculation

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should be a scalar value or a matrix by calling ReportOutputs() on the MathTree. If the result of this call indicates that the output is one row by one column, the output from the calculation is scalar; otherwise, it is a matrix. The corresponding Evaluate() method is called on the MathTree.

The MathTree Evaluate() methods behave identically in control flow; the difference between Evaluate() and MatrixEvaluate() is in the return value of the call. Similarly, the MathNode Evaluate() and MatrixEvaluate() methods follow identical control flow, differing only in return types. When the correct Evaluate() method is called on the MathTree, the MathTree calls the corresponding Evaluate() method on the topmost MathNode in the tree. Evaluation is then performed recursively on the nodes of the tree, as described here.

When an Evaluate() method is called on a node, the evaluation process proceeds based on the type of node that owns the method. If the node is a MathFunction node, then it calls the corresponding Evaluate() method on each of its child nodes, evaluating the left node first, then the right node. If one of those nodes is NULL that phase of the evaluation is skipped. This can occur when the mathematical operation only requires one operand – for example, for most of the trigonometric functions, or for unitary matrix operations like the transpose operation. When the child node evaluation is complete, the returned data from that evaluation are used as the operands for the mathematical operation. The operation is performed, and the resulting data are passed to the calling method.

MathElement nodes are evaluated directly when encountered, and can return either a real number or a matrix of real numbers based on which method is called – either Evaluate() for a Real, or MatrixEvaluate() for a matrix. The result of this evaluation is passed to the calling method. Since all of the leaf nodes on a MathTree are MathElement nodes, these nodes terminate the iteration through the tree.

When the calculation iteration reaches the topmost node in the MathTree, the operation for that node is performed and the resulting data are returned to the Assignment command. The Assignment command then sets the data on the GMAT object designated on the left side of the statement, designated the LHS in the figure. This completes the evaluation of the Assignment command.

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Chapter 31

GMAT and MATLAB Functions

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Scripts written for GMAT can become complicated as the needs of the mission evolve. Long missions can involve sets of commands that use the identical or nearly identical instructions in different portions of the mission. Some missions may also need to use mathematical computations that are complicated enough to be implemented more easily in MATLAB®than in GMAT's inline mathematics. These two issues – repetitive command subsequences and mathematics better implemented in MATLAB – are addressed by the function classes implemented in GMAT.

Repeated command subsequences can be stored in a separate file from the main Mission Control Sequence, and executed through either a CallFunction command or inline in mathematical expressions (see Chapter 30). The actual function code is encapsulated in an instance of the GmatFunction class. GmatFunctions provide local resources created inside of the function, proxies used for objects and parameters passed into the function, and access to objects identified as available for use by all of the objects in the Sandbox, referred to as "global" objects for the purposes of GMAT[1].

MATLAB functions are also called using either a CallFunction command or through inline mathematics[2]. The function code is contained in a MATLAB compatible m-file. The file identifier and related data structures needed for the function call are encapsulated in an instance of the MatlabFunction class. GMAT can pass variables, arrays, and objects into MATLAB for use in these functions, and can receive Variables and Arrays back as return parameters.

Scripting for the GmatFunction and MatlabFunction resources, and for the CallFunction and inline math commands that use these resources, is identical in GMAT's scripting language. Listing 31.1 shows the syntax used in the Mission Control Sequence for both types of functions. Section 31.2.1.2 shows a more complete example of a GMAT function used in a script.

```
% Sample script for Functions in GMAT

Create Spacecraft DefaultSC;
Create Array outputArray[6,1];

%----------------------------------------
%---------- Functions
```

[1]Note that these objects are not truly global in scope. Access is restricted for most of these objects to the resources in the Sandbox. Subscribers also provide some restricted access outside of the Sandbox through the Publisher. This slightly larger scoping rule for Subscribers will be defined more completely when multiple Sandbox capabilities are added to GMAT.

[2]The inline math application of MATLAB functions is part of the design presented in this document. The current code has not yet been updated to support this usage.

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```
%-----------------------------------------
Create MatlabFunction MLFunction;
GMAT MLFunction.FunctionPath = ./matlab/;

%-----------------------------------------
%---------- Mission Sequence
%-----------------------------------------

% First call a MATLAB function
[outputArray] = MLFunction(DefaultSC.A1ModJulian);

% Now a GMAT Function.  GMAT Functions are not declared using
% a "Create" line; all undeclared functions are assumed to be
% GMAT functions.
[outputArray] = GMFunction(DefaultSC.A1ModJulian);

% Finally, here is an internal function.  Internal functions
% resemble Parameters, but include argument lists so that
% data not generally available to a Parameter can be accessed
% for the encoded computations.
This example is TBD.
```

Listing 31.1: Function Usage in a GMAT Script

31.1 General Design Principles

Figure 31.1 shows the classes most directly used for the function implementation. Other classes in GMAT also play a role in the function implementation, but these other classes act inside of functions in the same way that they behave in the rest of the system. The classes shown in the figure have behaviors driven by the design of the Function subsystem.

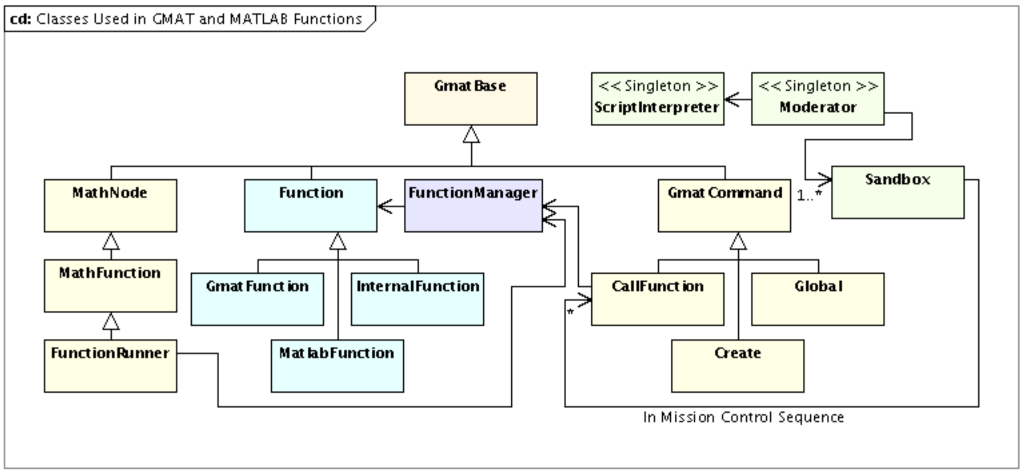

Figure 31.1: Classes Used in the Function Implementations

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This figure brings out several high level features of GMAT's function design. GMAT uses a set of classes derived from a Function base class to manage the function subsystem. This base class defines a set of interfaces that are accessed using a class called the FunctionManager. That class, shown in lavender in the figure, is the interface used by the CallFunction command to execute a function. It is also used when evaluating inline mathematics, through a specialized MathFunction called a FunctionRunner designed specifically to evaluate members of the Function subsystem. Since all MathFunctions are MathNodes, the FunctionRunner is a MathNode in a MathTree.

GMAT includes three commands, and enhancements to a fourth, that were added to the system specifically to support functions. The CallFunction command is used to execute a function on a single line; it is the entry point to function calls in GMAT's Control Sequences. Functions can be called on a single script line or GUI node using this command. Sometimes a function will need some local resources that are not used anywhere else in the mission. These resources can be constructed using the Create command. Objects built with this command only exist during a mission run – they are never registered in GMAT's configuration. Some resources need to be shared between different portions of the GMAT control sequences. These resources are identified using the third function specific command, the Global command. The Global command is used to manage resources between different Control Sequences in a Sandbox. This command lets a user set the scope for local resources so that they can be accessed in a separate Mission Control or Function Control Sequence.

The Assignment command can be used to perform mathematical calculations inline, as described in Chapter 30. These calculations are performed using a recursive descent algorithm, breaking the inline mathematics into separate nodes of a tree structure called a MathTree. Functions can be included in the MathTree through a node in the tree that instantiates a FunctionRunner object. The FunctionRunner class is a specialized node in the MathTree, derived from the MathFunction base class, that executes a function and retrieves the resulting data. It is designed to work with functions that return a single resultant – either a Real number or an Rmatrix. It throws an exception for any other function that a user attempts to use inside of inline mathematics. The Assignment command is enhanced to allow the identification and execution of functions as part of the inline mathematics capabilities, by making calls to FunctionRunner nodes.

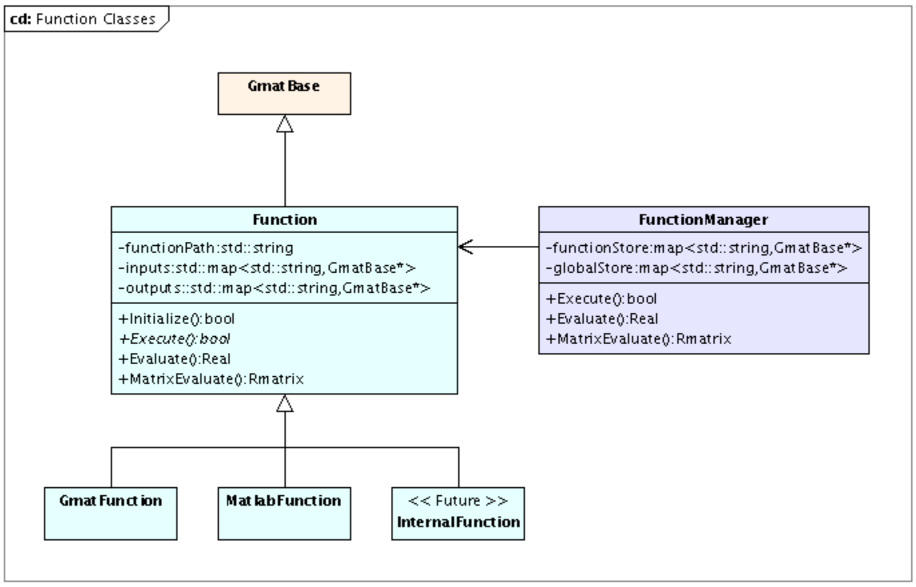
cd: Function Classes
GmatBase
Function
-functionPath:std::string
-inputs:std::map<std::string,GmatBase*>
-outputs::std::map<std::string,GmatBase*>
+Initialize():bool
+Execute():bool
+Evaluate():Real
+MatrixEvaluate():Rmatrix
FunctionManager
-functionStore:map<std::string,GmatBase*>
-globalStore:map<std::string,GmatBase*>
+Execute():bool
+Evaluate():Real
+MatrixEvaluate():Rmatrix
GmatFunction
MatlabFunction
<< Future >>
InternalFunction

Figure 31.2: Class diagram for the Function Classes

Figure 31.2 shows some of the details of the classes used to connect the function subsystem into the rest

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of GMAT. The two classes shown in detail here – Function and FunctionManager – define the interfaces used for function calls through either a CallFunction command or a FunctionRunner MathFunction. These classes are described in the following paragraphs.

31.1.1 The Function class

The base class for the MATLAB, GMAT, and internal functions is the Function class. This class defines the interfaces used by the function manager to execute the function. The class includes the following attributes and methods:

Function Class Attributes The class attributes provide storage for the input and output parameters, and the path to the function file if applicable.

- **std::string functionPath**: Identifies the location of the function file for MATLAB or GMAT functions.
- **std::map<std::string, GmatBase*> inputs**: A mapping between input names and wrappers for the associated objects used in the function. (For a discussion of GMAT's wrapper classes, see Section 26.4.3.)
- **std::map<std::string, GmatBase*> outputs**: A mapping between output names and wrappers for the associated objects used to return data from the function.

Function Class Methods The FunctionManager uses a standard set of methods, defined here, to interface with the function classes. These methods enable the setup and execution of the functions, and provide access to the results if needed for inline mathematics.

- **bool Initialize()**: Initializes the function.
- **bool Execute()**: Runs the function.
- **Real Evaluate()**: For functions that return a single Real value, this method retrieves that value. The method throws an exception for all other functions.
- **Rmatrix MatrixEvaluate()**: For functions that return a single Rmatrix value, this method retrieves that Rmatrix. The method throws an exception for all other functions.

These methods are overridden as needed for the derived Function classes. In addition to the methods listed here, the Function base class provides access methods used to set the object stores and other object references needed to run the function.

31.1.2 The FunctionManager

The CallFunction and inline math routines in GMAT use a common interface, the FunctionManager, to use GMAT's function subsystem. The FunctionManager is used to complete initialization of the function, run it, and when needed return the results of that run. This functionality is provided through the following attributes and methods:

FunctionManager Attributes The function manager passes the Function Object Store and Global Object Store to the function if needed. These stores are set during initialization on the FunctionManager, using the following attributes:

- **std::map<std::string, GmatBase*> functionStore**: The Function Object Store.
- **std::map<std::string, GmatBase*> *globalStore**: The Global Object Store, set from the Sandbox.

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FunctionManager Methods The interfaces accessed by the CallFunction and FunctionRunner classes are implemented using the following methods:

- **bool Execute()**: Initializes and runs the function.
- **Real Evaluate()**: For functions that return a single Real value, this method retrieves that value. The method throws an exception for all other functions.
- **Rmatrix MatrixEvaluate()**: For functions that return a single Rmatrix value, this method retrieves that Rmatrix. The method throws an exception for all other functions.

31.2 GMAT Functions

The preceding sections of this chapter describe features of GMAT's function model that apply to all of the function classes in GMAT. In this section, I'll describe the specific features of GMAT functions. MATLAB Functions are described in Section 31.3, and internal functions in Section 31.4.

31.2.1 GMAT Function Design Principles

GMAT functions are small sections of script that are initialized and used as part of the Mission Control Sequence. Each function is contained in a separate file that defines the input and output parameters used in the function, the name of the function, and the sequence of steps executed when running the function. The function file name is the name of the contained function, modified to add the extension ".gmf" to complete the file name.

Objects and other variables used inside of GMAT functions are limited in scope to the function itself, except when the user explicitly modifies the scope of the underlying object by declaring it "Global." Objects created outside of the function can be accessed in the function if they are used as parameters in the function call or if they are set as global objects. Propagators, GmatFunctions, and Coordinate Systems are automatically defined as global objects, so all objects of these types can be used in the Mission Control Sequence and in all included GMAT Functions.

GMAT finds GMAT function files by searching in the folders identified by the GmatFunctionPath. That path is initialized in the startup file, and can be modified from the graphical user interface or from a script file to meet specific mission needs. The system searches in the most recently added folders first, proceeding through the folders identified by the function path until the specified function has been located.

31.2.1.1 Anatomy of a Function File

GMAT functions provide users with the ability to break out sections of a mission – usually portions of the Mission Control Sequence, though functions can be used to build objects used elsewhere as well – into smaller chunks, and thus unclutter the main Mission Control Sequence. GMAT functions are defined in separate files. The function file has the same, case-sensitive, name as the function. Function files follow the same basic syntax as GMAT script files. The first uncommented line of each GMAT function defines the function using a function declaration in the form

```
function [resultants] = MyFunction(inputs)
```

The file name is identical to the function name, and has the extension ".gmf"; thus for this example, the file containing the function would be named "MyFunction.gmf" and would be located in a folder on GMAT's GmatFunction path.

The remainder of the function file defines the Function Control Sequence (FCS). The FCS defines local and global resources used in the function, and specifies the ordered sequence of actions executed when the function is called.

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A typical script showing GMAT function calls is shown in Listing 31.2. This script calls a function named SatSep on lines 28 and 36. That function is used to calculate the physical separation between two spacecraft as they are propagated.

```
 1  % This script shows how to call a GMAT function
 2  % named SatSep
 3
 4  Create Spacecraft Sat1 Sat2;
 5  Sat1.RAAN = 45;
 6  Sat1.TA   = 0.5;
 7  Sat2.RAAN = 44.5;
 8  Sat2.TA   = 0.0;
 9
10  Create ForceModel fm;
11  fm.PrimaryBodies = {Earth};
12
13  Create Propagator prop;
14  prop.FM = fm;
15
16  Create ReportFile sepData
17  sepData.Filename = Sat1_Sat2_Sep.txt;
18
19  Create ImpulsiveBurn mnvr;
20  mnvr.Axes = VNB;
21  mnvr.Element2 = 0.05;
22
23  Create Variable dx dy dz dr;
24  Global dx dy dz;
25
26  While Sat1.ElapsedDays < 0.1
27     Propagate prop(Sat1, Sat2);
28     [dr] = SatSep(Sat1, Sat2);     % 1st function call
29     Report sepData Sat1.A1ModJulian dx dy dz dr;
30  EndWhile;
31
32  Maneuver mnvr(Sat1);
33
34  While Sat1.ElapsedDays < 0.2
35     Propagate prop(Sat1, Sat2);
36     [dr] = SatSep(Sat1, Sat2);     % 2nd function call
37     Report sepData Sat1.A1ModJulian dx dy dz dr;
38  EndWhile;
```

Listing 31.2: A script that uses a Function

The function calls shown here are made using a CallFunction command. When a function is called with a CallFunction, the line of script making the call is responsible for running the function, and copying the output data returned from the function into the output parameters listed in the script line – for these cases, that means setting the value of `dr` to the value returned from the function.

Another interesting feature of this script is seen on line 24. That line,

```
Global dx dy dz;
```

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identifies three variables created earlier in the script as variables that can be accessed anywhere in the run. These variables are used in the SatSep function, shown in Listing 31.3.

```
1  % Function that calculated the separation
2  % between two spacecraft
3  function [delta] = SatSep(Sat1, Sat2);
4
5  Global dz dy dx;
6  Create Variable delta;
7  Create Array dr[3,1];
8
9  dx = Sat2.X - Sat1.X;
10 dy = Sat2.X - Sat1.X;
11 dz = Sat2.X - Sat1.X;
12
13 dr(1,1) = dx;
14 dr(2,1) = dy;
15 dr(3,1) = dz;
16
17 delta = sqrt(dot(dr, dr));
```

Listing 31.3: A Function that computes Satellite Separations

The first executable line in this function file identifies the contained function, and specifies its return (output) data, the function name, and the function inputs:

```
function [delta] = SatSep(Sat1, Sat2);
```

Note that the argument names used in the definition of the function, and later in the Function Control Sequence, do not necessarily match the names used in the function call made in the main script. For example, the output variable in this function is named "delta," but the function call uses the name "dr" in the script that calls this function.

Line 5 in the function identifies the global variables that are expected to execute the function. This line,

```
Global dz dy dx;
```

matches the list globals defined in the calling script. As can be seen here, the order of these global variables is not important. The critical feature is that each variable identified as a global needs to be defined somewhere prior to its use in the script or function.

This function builds two local objects that are used to execute the function. These local objects are constructed through calls to the Create command on lines 6 and 7:

```
Create Variable delta;
Create Array dr(3,1);
```

The objects created this way are limited in scope to this function unless they are later identified as global objects in the function.

The global objects identified on line 5 are used on lines 9–11. These objects can be used just as if they had been created locally, as is shown here. Similarly, the local array, "dr," is used on lines 13 through 15 to fill the array with data for a function call made from inside of this function.

Line 17 makes a call to another function from inside of the SatSep function. That call,

```
delta = sqrt(dot(dr, dr));
```

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is calling a function named dot, shown later in this chapter (see Listing 31.6). This script line shows the use of a GMAT function inside of inline mathematics. The function called this way is executed using a FunctionRunner MathNode object. Functions that are called this way must return exactly one value, either a Real number or an Rmatrix. This feature of the GMAT's function subsystem makes the use of user defined and internal functions natural for users of the system, because GMAT functions that return a single value can be used inline in the control sequences. Users do not need to call the functions separately before using the results in equations written in GMAT's scripting language.

This concludes the basic sample of a GMAT function. A more complete discussion and example of GMAT functions, along with a discussion of how the components of the function subsystem interact, can be found in Section 31.2.1.2. Before we can tackle that description, we'll examine the components that work together to build this functionality.

31.2.1.2 An End-to-end Example

The GMAT releases at SourceForge include a script file named "ExCart2KepMathTest.script" that demonstrates inline mathematics in GMAT's scripting language. The script includes a number of dot and cross product calculations, along with computations of vector magnitudes and manipulations of vector components. This section contains a script and several function files built based on that sample mission, where the inline vector mathematics have been replaced by function calls.

There are four GMAT function calls that will be used in this section. These functions are described and listed here:

- *LoadCartState* A utility function that retrieves the Cartesian state from a Spacecraft and returns the position and velocity vectors along with their magnitudes.

```
function [rv, vv, r, v] = LoadCartState(Sat);
% This function fills some arrays and variables with
% Cartesian state data
Create Variable r v
Create Array rv[3,1] vv[3,1]

rv(1,1) = Sat.X;
rv(1,2) = Sat.Y;
rv(1,3) = Sat.Z;
vv(1,1) = Sat.VX;
vv(1,2) = Sat.VY;
vv(1,3) = Sat.VZ;

[r] = magnitude(rv);

[v] = magnitude(vv);
```

Listing 31.4: The LoadCartState Function

- *magnitude* A function used to find the magnitude of a three-vector, stored in a 3 by one GMAT array.

```
function [val] = magnitude(vec1)

% This function takes a 3-vector in a GMAT array and
% calculates its magnitude
Create Variable val
val = sqrt(dot(vec1, vec1));
```

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Listing 31.5: The magnitude Function

- *dot* A function used to find the dot product of two three-vectors.

```
function [val] = dot(vec1, vec2)

% This function takes two 3-vectors in a GMAT array and
% constructs their dot product
Create Variable val
val = vec1(1,1) * vec2(1,1) + vec1(2,1) * vec2(2,1) +...
         vec1(3,1) * vec2(3,1);
```

Listing 31.6: The dot Function

- *cross* A function used to find the cross product of two three-vectors.

```
function [vec3] = cross(vec1, vec2)

% This function takes two 3-vectors in a GMAT array and
% constructs their cross product
Create Array vec3[3,1]

vec3(1,1) = vec1(2,1) * vec2(3,1) - vec1(3,1) * vec2(2,1);
vec3(2,1) = vec1(3,1) * vec2(1,1) - vec1(1,1) * vec2(3,1);
vec3(3,1) = vec1(1,1) * vec2(2,1) - vec1(2,1) * vec2(1,1);
```

Listing 31.7: The cross Function

These function files are pretty simple, but contain several interesting features worth mentioning before we see how they are used in the sample script. The first line in each of these files follows the pattern described previously; they declare that the file contains a function, specify the output argument list, and then the function name and input argument list.

The LoadCartState function in listing 31.4 shows a function call inside of the defined function (see lines 14 and 16). This function uses the magnitude function to find the lengths of the position and velocity vectors. Each of these nested function calls follows the usual CallFunction syntax, specifying the output parameter in square brackets on the left side of the equation, with the function call on the right including its input argument list in parentheses.

The magnitude function, listing 31.5, shows an alternative for functions that return exactly one parameter on line 6. Functions with that form can be used inline with other mathematics – in this case, the interesting line is

```
val = sqrt(dot(vec1, vec1));
```

The function is calling a second GMAT function, dot() – defined in listing 31.6 – to build the dot product of the input vector with itself. The returned value is a Variable, and is used directly in the equation, making a call through a FunctionRunner MathNode in the MathTree defined by this line of script.

The nesting alluded to earlier allows further nesting with this design. This feature is seen in these same functions: the LoadCartState function calls the magnitude function, which in turn calls the dot function. GMAT functions can be nested as deeply as needed by mission analysts.

These four functions are used in a script that is used to compare GMAT's internally calculated Keplerian element Parameters with calculations performed inline. This script, shown in listing 31.8, performs the element computations and reports GMAT's internal calculation, the inline calculation, and their difference to a file for review by the analyst.

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```
%  Create a s/c
Create Spacecraft Sat;

Create ForceModel Propagator1_ForceModel;
GMAT Propagator1_ForceModel.PrimaryBodies = {Earth};

Create Propagator Prop;
GMAT Prop.FM = Propagator1_ForceModel;

% Variables and arrays needed in calculations
Create Variable SMA ECC RAAN;
Create Variable r v pi2 mu d2r Energy;
Create Variable SMAError ECCError RAANError;
Create Variable x y z vx vy vz
Create Array rv[3,1] vv[3,1] ev[3,1] nv[3,1];

%  Create a report to output error data
Create ReportFile Cart2KepConvert;
GMAT Cart2KepConvert.Filename = FunctDiffs.report;
GMAT Cart2KepConvert.ZeroFill = On;

mu = 398600.4415;
pi2 = 6.283185307179586232;
d2r = 0.01745329251994329509

While Sat.ElapsedDays < 1

   Propagate Prop(Sat)
   x = Sat.X
   y = Sat.Y
   z = Sat.Z
   vx = Sat.VX
   vy = Sat.VY
   vz = Sat.VZ

   % Put the state data into some data structures
   [rv, vv, r, v] = LoadCartState(Sat);

   % Calculate the Energy and SMA
   Energy = v^2/2 - mu/r;
   SMA = -mu/2/Energy;

   % Eccentricity built from the eccentricity vector
   ev = cross(vv, cross(rv, vv)) / mu - rv / r;
   [ECC] = magnitude(ev);

   % Next the ascending node, using the node vector
   nv(1,1)  =  x*vz-z*vx;
   nv(2,1)  =  y*vz-z*vy;
   nv(3,1)  =  0;
```

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```
   [n] = magnitude(nv);
   RAAN = acos( nv(1,1)/n );
   If nv(2,1) < 0;
      RAAN = (pi2 - RAAN) / d2r;
   EndIf;

   SMAError  = Sat.SMA  - SMA;
   ECCError  = Sat.ECC  - ECC;
   RAANError = Sat.RAAN - RAAN;

   Report Cart2KepConvert Sat.SMA SMA SMAError ...
      Sat.ECC ECC ECCError Sat.RAAN RAAN RAANError;
EndWhile
```

Listing 31.8: A Script that Uses GMAT Functions

The example functions and script shown here will be used in the following discussions to help clarify how the components of the Function subsystem design interact to build and run the functions.

31.2.2 Steps Followed for the Sample Script

In this section we will look at the script (shown in Listing 31.8) along with the four functions used by this script (listings 31.4 through 31.7), and examine the behavior of the Mission Control Sequence, Function Control Sequences, Configuration, Sandbox, Sandbox Object Map, Global Object Store, and Function Object Stores as the script is loaded, executed, and removed from memory. This discussion will be broken into four distinct processes:

1. Script Parsing – the process of reading the script in Listing 31.8 and building the resources and Mission Control Sequence.
2. Initialization – The process of passing the configuration and MCS into the Sandbox.
3. Execution – The process of running the MCS, including calls to the functions.
4. Finalization – Steps taken when the run is complete.

As we will see, each of these steps can be further subdivided to a discrete set of substeps. We'll begin by examining what happens when the script is first read into memory.

31.2.2.1 Script Parsing

The details of script parsing are described fully in Chapter 17, ("Script Reading and Writing"). That chapter discusses the modes that the interpreter goes through when reading a script file, starting with the object property mode, moving through the command mode, and finishing with the final pass through the mission resources. You should review the relevant sections of that chapter if this terminology confuses you.

Table 31.1 shows the state of the components of the engine at the start of script reading. This table does not include any elements specific to the Sandbox, because the Sandbox is in an idle state at this point. When the Sandbox elements become relevant, they will be added to the tables summarizing the state of the system.

Table 31.1: Status at Start of Script Parsing

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Configuration	**MCS**	**Interpreter Mode**	**Sandbox**
Empty	Empty	Object Property	Idle

The Script Interpreter remains in Object Property mode until the first command is encountered in the script. That means that the following lines are all parsed in Object Property mode:

```
% Create a s/c
Create Spacecraft Sat;
Create ForceModel Prop_FModel;
GMAT Prop_FModel.PrimaryBodies = {Earth};
Create Propagator Prop;
GMAT Prop.FM = Prop_FModel;

% Variables and arrays needed in calculations
Create Variable SMA ECC RAAN;
Create Variable r v pi2 mu d2r Energy;
Create Variable SMAError ECCError RAANError;
Create Array rv[3,1] vv[3,1] ev[3,1] nv[3,1];

%  Create a report to output error data
Create ReportFile Cart2KepConvert;
GMAT Cart2KepConvert.Filename = FunctDiffs.report;
GMAT Cart2KepConvert.ZeroFill = On;

mu = 398600.4415;
pi2 = 6.283185307179586232;
d2r = 0.01745329251994329509
```

After these lines have been parsed, the table of objects looks like this:

Table 31.2: Status after Parsing the Objects

Configuration		**MCS**	**Interpreter Mode**	**Sandbox**
Type	*Name*			
Spacecraft	Sat	Empty	Object Property	Idle
ForceModel	Prop_FModel			
Propagator	Prop			
Variable	SMA			
Variable	ECC			
Variable	RAAN			
Variable	r			
Variable	v			
Variable	pi2			
Variable	mu			
Variable	d2r			
Variable	Energy			
Variable	SMAError			
Variable	ECCError			
Variable	RAANError			
Array	rv			

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Table 27.2: Propagate Command . . . continued

Array	vv			
Array	ev			
Array	nv			
ReportFile	Cart2KepConvert			

At this point, the configuration is complete. The objects contained in the configuration all have valid data values; those that are not set explicitly in the script are given default values, while those that are explicitly set contain the specified values.

Note that at this point, the configuration does not contain any functions. GMAT functions are added to the configuration when they are encountered, as we'll see when we encounter a script line that includes a GMAT function. The next line of the script contains a command:

```
While Sat.ElapsedDays < 1
```

When the Script Interpreter encounters this line, it toggles into command mode. Once this line of script has been parsed, the state of the engine looks like this (note that I'm abbreviating the configuration here – it still contains all of the objects listed above):

Table 31.3: Status after Parsing the First Command

Configuration		**MCS**	**Interpreter Mode**	**Sandbox**
Type	*Name*			
Spacecraft	Sat	While	Command	Idle
ForceModel	Prop_FModel			
Propagator	Prop			
Variable	SMA			
...	...			
Array	nv			
ReportFile	Cart2KepConvert			

The Script Interpreter parses the next line (a Propagate line) as expected, giving this state:

Table 31.4: Status after Parsing the Propagate Command

Configuration		**MCS**	**Interpreter Mode**	**Sandbox**
Type	*Name*			
Spacecraft	Sat	While	Command	Idle
ForceModel	Prop_FModel	+– Propagate		
Propagator	Prop			
Variable	SMA			
...	...			
Array	nv			
ReportFile	Cart2KepConvert			

The next script line is a function call:

```
[rv, vv, r, v] = LoadCartState(Sat);
```

When the Script Interpreter encounters this function call, several things happen:

1. The line is decomposed into three sets of elements: outputs (rv, vv, r, and v), the function name (LoadCartState), and inputs (Sat)

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2. The Script Interpreter builds a CallFunction command[3].

3. The Script Interpreter sends a request to the Moderator for a function named LoadCartState. The Moderator sends the request to the Configuration Manager. Since the configuration does not contain a function with this name, the Configuration Manager returns a NULL pointer, which is returned to the ScriptInterpreter.

4. The Script Interpreter sees the NULL pointer, and calls the Moderator to construct a GmatFunction object named LoadCartState. The Moderator calls the Factory Manager requesting this object. It is constructed in a function factory, and returned through the Moderator to the Script Interpreter. The Moderator also adds the function to the Configuration.

5. The Script Interpreter passes the GmatFunction into the CallFunction command.

6. The CallFunction command sends the GmatFunction to its FunctionManager instance.

7. The Script Interpreter passes the list of input and output parameters to the CallFunction.

8. The CallFunction passes the list of input and output parameters to its FunctionManager.

This completes the parsing step for the CallFunction line. Note that (1) the Function Control Sequence is not yet built, and (2) the function file has not yet been located in the file system. These steps are performed later. At this point, the system has this state:

Table 31.5: Status after Parsing the CallFunction Command

Configuration		**MCS**	**Interpreter Mode**	**Sandbox**
Type	*Name*			
Spacecraft	Sat	While	Command	Idle
ForceModel	Prop_FModel	+– Propagate		
Propagator	Prop	+– CallFunction		
Variable	SMA			
...	...			
Array	nv			
ReportFile	Cart2KepConvert			
GmatFunction	LoadCartState			

Now that we've encountered the first function in the script, it is useful to start watching the data structures for the function. We'll do this in a separate table:

Table 31.6: Function Properties after Parsing the First CallFunction

Function	**Caller**[5]	**Function Manager**			**Function Attributes**		
		inputs, outputs	Function Object Store	Global Object Store	inputs	outputs	FCS
LoadCartState	CallFunction	Names set	Empty	NULL	Empty	Empty	Empty

One feature that it is worth noting at this point is that there are two locations used for input and output arguments. The list managed in the FunctionManager tracks the parameters as listed in the function call

[3]Note that each CallFunction – and, as we'll see later, FunctionRunner – that is created includes an instance of the FunctionManager class. This internal object is used to make all of the calls needed on the Function consistent between the two avenues used to invoke a Function. All of the Function calls needed by the command or MathTree evaluation are made through these FunctionManager instances.

[5]"Caller" in this context is the type of object – a CallFunction or a FunctionRunner – that is used to execute the function in this example. It is possible that a function could be called from both types of object in the same script.

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in the control sequence that is calling the function. These parameters are listed in the order found in the call. Thus for this CallFunction, the StringArrays containing the arguments in the FunctionManager contain these data:

```
inputNames = {"Sat"}
outputNames = {"v", "vv", "r", "v"}
```

The inputs and outputs maps in the Function object map the names used in the function to the associated objects. Since the function itself has not been built at this stage, these maps are empty, and will remain empty until the function file is parsed.

The Function Object Store itself is empty at this point. It provides a mapping between the function scope object names and the objects. Since the function has not yet been parsed, this object store remains empty.

The next two script lines do not make function calls, so they can be parsed and built using the features described in Chapter17. After these two lines are built:

```
Energy = v\^{}2/2 - mu/r;
SMA = -mu/2/Energy;
```

the state tables contain these data:

Table 31.7: Status after Parsing the next two Commands

Configuration		**MCS**	**Interpreter Mode**	**Sandbox**
Type	*Name*			
Spacecraft	Sat	While	Command	Idle
ForceModel	Prop_FModel	+− Propagate		
Propagator	Prop	+− CallFunction		
Variable	SMA	+− Assignment		
...	...	+− Assignment		
Array	nv			
ReportFile	Cart2KepConvert			
GmatFunction	LoadCartState			

and

Table 31.8: Function Properties after Parsing the First Two Assignment Lines

Function	**Caller**	**Function Manager**			**Function Attributes**		
		inputs, outputs	Function Object Store	Global Object Store	inputs	outputs	FCS
LoadCartState	CallFunction	Names set	Empty	NULL	Empty	Empty	Empty

Both of the lines listed here generate Assignment commands. The right side of these assignments are MathTree elements, built using the inline math features described in Chapter 30. As you might expect, the Mission Control Sequence contains these new commands, but nothing else has changed at this level.

The next line also generates an Assignment line:

```
ev = cross(vv, cross(rv, vv)) / mu - rv / r;
```

This line also builds a MathTree for the right side of the equation. The resulting tree contains two function calls, both made to the GMAT function named "cross." The MathTree built from this Assignment line is shown in Figure 31.3.

Once this command has been built, the state of the system can be tabulated as in Tables 31.9 and 31.10.

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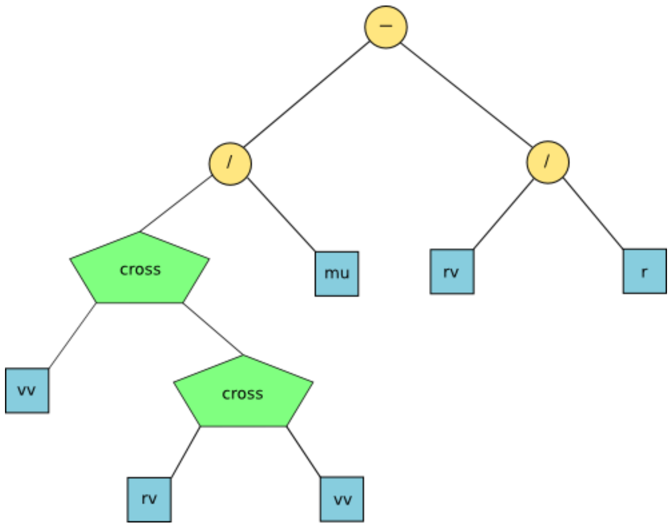

Figure 31.3: A MathTree with Two Function Calls.

Table 31.9: Status after Parsing the Assignment Line containing Two Calls to the cross Function

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Configuration *Type*	*Name*	**MCS**	**Interpreter Mode**	**Sandbox**
Spacecraft	Sat	While	Command	Idle
ForceModel	Prop_FModel	+− Propagate		
Propagator	Prop	+− CallFunction		
Variable	SMA	+− Assignment		
...	...	+− Assignment		
Array	nv	+− Assignment		
ReportFile	Cart2KepConvert			
GmatFunction	LoadCartState			
GmatFunction	cross			

and

Table 31.10: Function Properties after Parsing the cross Assignment Line

Function	**Caller**	**Function Manager**			**Function Attributes**		
		inputs, outputs	Function Object Store	Global Object Store	inputs	outputs	FCS
LoadCartState	CallFunction	Names set	Empty	NULL	Empty	Empty	Empty
cross	FunctionRunner	Names set	Empty	NULL	Empty	Empty	Empty

There are two FunctionRunner nodes in the MathTree shown in Figure 31.3. Each one has its own FunctionManager. The inputs and outputs StringArrays have the following values for these FunctionManagers:

- Inner FunctionRunner MathNode

```
inputNames = {"rv", "vv"}
outputNames = {""}
```

- Outer FunctionRunner MathNode

```
inputNames = {"vv", ""}
outputNames = {""}
```

Note that at this point in the process, the unnamed arguments are marked using empty strings in the StringArrays. This is a general feature of the argument arrays generated in a FunctionManager associated with a FunctionRunner: empty strings are used to indicate arguments that must exist, but that do not have names that can be looked up in the object stores. In general, these empty strings indicate either output data or results that come from lower calculations performed in the MathTree.

The next script line,

```
[ECC] = magnitude(ev);
```

builds another function call using a CallFunction, this time to the magnitude function. The resulting attributes are shown in Tables 31.11 and 31.12.

Table 31.11: Status after Parsing the Call to the magnitude Function

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Configuration *Type*	*Name*	**MCS**	**Interpreter Mode**	**Sandbox**
Spacecraft	Sat	While	Command	Idle
ForceModel	Prop_FModel	+− Propagate		
Propagator	Prop	+− CallFunction		
Variable	SMA	+− Assignment		
...	...	+− Assignment		
Array	nv	+− Assignment		
ReportFile	Cart2KepConvert	+− CallFunction		
GmatFunction	LoadCartState			
GmatFunction	cross			
GmatFunction	magnitude			

and

Table 31.12: Function Properties after Parsing the magnitude Line

Function	**Caller**	**Function Manager**			**Function Attributes**		
		inputs, outputs	Function Object Store	Global Object Store	inputs	outputs	FCS
LoadCartState	CallFunction	Names set	Empty	NULL	Empty	Empty	Empty
cross	FunctionRunner	Names set	Empty	NULL	Empty	Empty	Empty
magnitude	CallFunction	Names set	Empty	NULL	Empty	Empty	Empty

This process continues through the remaining lines of the script:

```
      nv(1,1)  =  x*vz-z*vx;
      nv(2,1)  =  y*vz-z*vy;
      nv(3,1)  =  0;
      [n] = magnitude(nv);
      RAAN = acos( nv(1,1)/n );
      If nv(2,1) < 0;
         RAAN = (pi2 - RAAN) / d2r;
      EndIf;

      SMAError  = Sat.SMA - SMA;
      ECCError  = Sat.ECC - ECC;
      RAANError = Sat.RAAN - RAAN;

      Report Cart2KepConvert Sat.SMA SMA SMAError ...
         Sat.ECC ECC ECCError Sat.RAAN RAAN RAANError;
   EndWhile
```

The only line that calls a GMAT function here is the fourth line, a CallFunction command that again calls the magnitude function. At the end of parsing, our tables of object properties look like this:

Table 31.13: Status after Parsing the Script

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Configuration *Type*	*Name*	**MCS**	**Interpreter Mode**	**Sandbox**
Spacecraft	Sat	While	Command	Idle
ForceModel	Prop_FModel	+− Propagate		
Propagator	Prop	+− CallFunction		
Variable	SMA	+− Assignment		
Variable	ECC	+− Assignment		
Variable	RAAN	+− Assignment		
Variable	r	+− CallFunction		
Variable	v	+− Assignment		
Variable	pi2	+− Assignment		
Variable	mu	+− Assignment		
Variable	d2r	+− CallFunction		
Variable	Energy	+− Assignment		
Variable	SMAError	+− If		
Variable	ECCError	+−+− Assignment		
Variable	RAANError	+− EndIf		
Array	rv	+− Assignment		
Array	vv	+− Assignment		
Array	ev	+− Assignment		
Array	nv	+− Report		
ReportFile	Cart2KepConvert	EndWhile		
GmatFunction	LoadCartState			
GmatFunction	cross			
GmatFunction	magnitude			

and

Table 31.14: Function Properties after Parsing the Script

Function	**Caller**	**Function Manager**			**Function Attributes**		
		inputs, outputs	Function Object Store	Global Object Store	inputs	outputs	FCS
LoadCartState	CallFunction	Names set	Empty	NULL	Empty	Empty	Empty
cross	FunctionRunner	Names set	Empty	NULL	Empty	Empty	Empty
magnitude	CallFunction	Names set	Empty	NULL	Empty	Empty	Empty

At this point in the process, the Configuration and Mission Control Sequence have been populated, and three GMAT functions have been identified but not yet located. The ScriptInterpreter has finished parsing the script, but has not yet made its final pass through the objects created during parsing.

During the final pass, object pointers and references are set and validated. the ScriptInterpreter uses the final pass to locate the function files for all of the GmatFunction objects built during parsing. The path to each function is set at this time. The ScriptInterpreter makes a call, through the Moderator, and locates the function file on the GmatFunctionPath. The file must be named identically to the name of the function, with a file extension of ".gmf" – so, for example, the function file for the magnitude function must be named "magnitude.gmf". These file names are case sensitive; a file named "Magnitude.gmf" will not match the "magnitude" function. If there is no matching file for the function, the ScriptInterpreter throws an exception.

Once this final pass is complete, script parsing has finished, and the ScriptInterpreter returns to an idle state. The steps followed to parse the Mission Control Sequence, described above, give GMAT enough information to fully populate the GUI so that it can present users with a view of the mission contained in

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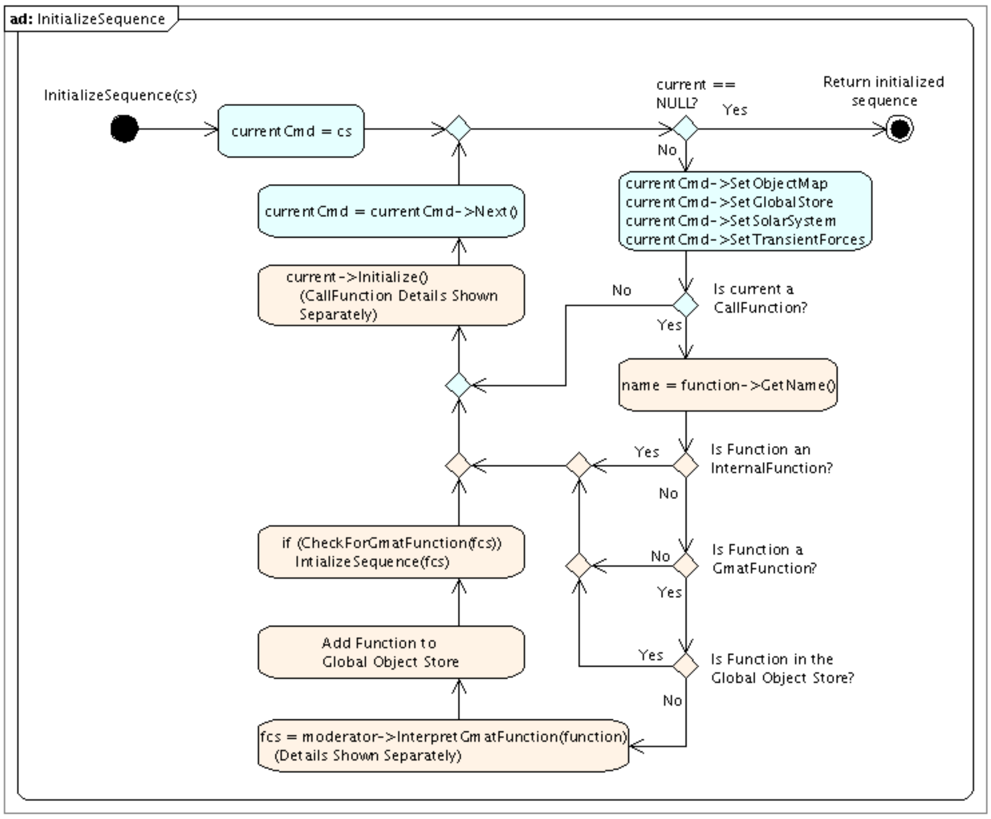
ad: InitializeSequence
InitializeSequence(cs)
currentCmd = cs
current == NULL?
Yes
Return initialized sequence
No
currentCmd = currentCmd->Next()
currentCmd->SetObjectMap
currentCmd->SetGlobalStore
currentCmd->SetSolarSystem
currentCmd->SetTransientForces
current->Initialize()
(CallFunction Details Shown Separately)
No
Is current a CallFunction?
Yes
name = function->GetName()
Yes
Is Function an InternalFunction?
No
if (CheckForGmatFunction(fcs))
IntializeSequence(fcs)
No
Is Function a GmatFunction?
Yes
Add Function to Global Object Store
Yes
Is Function in the Global Object Store?
No
fcs = moderator->InterpretGmatFunction(function)
(Details Shown Separately)

Figure 31.4: Initializing a Control Sequence

the script. The GUI includes entries for each of the functions in the main script, and displays these functions along with all of the other configured objects on the Resource tree.

31.2.2.2 Initialization in the Sandbox

At this point, GMAT knows about the functions described in the Mission Control Sequence, but has not yet constructed any of these functions. That step is performed when the mission is passed into the Sandbox and initialized. The basic initialization process is described in Chapters 3 and 5. The process followed can be described in four stages:

1. **Population**: The objects in GMAT's configuration are cloned into the Sandbox Object Map, and the Mission Control Sequence is set.
2. **Object Initialization**: The objects in the Sandbox Object Map are initialized.
3. **Global Object Management**: Objects that have their isGlobal flag set are moved into the Global Object Store.
4. **Command Initialization**: The Mission Control Sequence is initialized.

Outside of the cloning process, the GMAT function objects are not affected by the first two of these steps. Figure 31.4[6], copied from Chapter 5, shows the process followed in the fourth step to initialize the

[6]This figure needs some modification based on the text in the rest of this document.

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Mission Control Sequence.

Before going into the details of Figure 31.4, I'll describe the activities performed in the first two steps.

Initialization Step 1: Passing Objects to the Sandbox The first step in initialization is cloning the objects in the configuration into the Sandbox. At the start of this step, the system status looks like Table 31.15. The Interpreter subsystem will not play a role in this part of the initialization process – the Interpreters remain idle – so I will remove that column for the time being in subsequent tables.

One feature of GMAT's design that can be overlooked is that there is a separate Mission Control Sequence for each Sandbox, and there is a one-to-one relationship between the Mission Control Sequences and the Sandbox instances. What that means for this discussion is that the Mission Control Sequence shown in the table already belongs to the Sandbox shown there. The Mission Control Sequence is not cloned into the Sandbox[7].

Table 31.15: Status Immediately Before Initialization Starts

Configuration		**MCS**	**Interpreter Mode**	**Sandbox**
Type	*Name*			
Spacecraft	Sat	While	Idle	Idle, Sandbox Object Map is Empty
ForceModel	Prop_FModel	+– Propagate		
Propagator	Prop	+– CallFunction		
Variable	SMA	+– Assignment		
Variable	ECC	+– Assignment		
Variable	RAAN	+– Assignment		
Variable	r	+– CallFunction		
Variable	v	+– Assignment		
Variable	pi2	+– Assignment		
Variable	mu	+– Assignment		
Variable	d2r	+– CallFunction		
Variable	Energy	+– Assignment		
Variable	SMAError	+– If		
Variable	ECCError	+–+– Assignment		
Variable	RAANError	+– EndIf		
Array	rv	+– Assignment		
Array	vv	+– Assignment		
Array	ev	+– Assignment		
Array	nv	+– Report		
ReportFile	Cart2KepConvert	EndWhile		
GmatFunction	LoadCartState			
GmatFunction	cross			
GmatFunction	magnitude			

The objects in the configuration, on the other hand, are contained in GMAT's engine, outside of the Sandbox. The Moderator accesses these configured objects by type, and passes each into the Sandbox for use in the mission. The Sandbox makes copies of these objects using the object's Clone() method. These clones are stored in the Sandbox Object Map. The clones contain identical data to the objects in the configuration; making clones at this stage preserves the user's settings on the configured objects while providing working copies that are used to run the mission.

[7]This relationship between the Mission Control Sequences and the array of Sandboxes is managed in the Moderator. The behavior described here is the default behavior, and is the behavior used in current implementations of GMAT. Implementations that use multiple Sandboxes – particularly when used in a distributed manner – will implement a different relationship between the Mission Control Sequence viewed by the user and the Mission Control Sequences in the Sandboxes.

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Table31.16 shows the status of the system after the Moderator has passed the objects into the Sandbox. The Sandbox Object Map is a mapping between a text name and a pointer to the associated object. Since the map is from the name to the object, the Sandbox Object Map in the table lists the name first.

Table 31.16: Status Immediately After Cloning into the Sandbox

Configuration		**Sandbox**		
Scripted Type	*Name*	**MCS**	**Sandbox Object Map**	
			Name	*Type*
Spacecraft	Sat	While	Sat	Spacecraft*
ForceModel	Prop_FModel	+– Propagate	Prop_FModel	ForceModel*
Propagator	Prop	+– CallFunction	Prop	PropSetup*
Variable	SMA	+– Assignment	SMA	Variable*
Variable	ECC	+– Assignment	ECC	Variable*
Variable	RAAN	+– Assignment	RAAN	Variable*
Variable	r	+– CallFunction	r	Variable*
Variable	v	+– Assignment	v	Variable*
Variable	pi2	+– Assignment	pi2	Variable*
Variable	mu	+– Assignment	mu	Variable*
Variable	d2r	+– CallFunction	d2r	Variable*
Variable	Energy	+– Assignment	Energy	Variable*
Variable	SMAError	+– If	SMAError	Variable*
Variable	ECCError	+–+– Assignment	ECCError	Variable*
Variable	RAANError	+– EndIf	RAANError	Variable*
Array	rv	+– Assignment	rv	Array*
Array	vv	+– Assignment	vv	Array*
Array	ev	+– Assignment	ev	Array*
Array	nv	+– Report	nv	Array*
ReportFile	Cart2KepConvert	EndWhile	Cart2KepConvert	ReportFile*
GmatFunction	LoadCartState		LoadCartState	GmatFunction*
GmatFunction	cross		cross	GmatFunction*
GmatFunction	magnitude		magnitude	GmatFunction*
CoordinateSystem[8]	EarthMJ2000Eq		EarthMJ2000Eq	CoordinateSystem*
CoordinateSystem	EarthMJ2000Ec		EarthMJ2000Ec	CoordinateSystem*
CoordinateSystem	EarthFixed		EarthFixed	CoordinateSystem*

Once the Moderator has passed the Configuration into the Sandbox, the mission run no longer depends on the Configuration. For that reason, most of the tables shown in the rest of this document will not include a list of the contents of the configuration. If needed, the Configuration will be displayed separately.

Initialization Step 2: Object Initialization Now that the Sandbox has been populated with the configured objects and the Mission Control Sequence, the Moderator can pass control to the Sandbox to continue the initialization process. This hand off is made through a call to the Sandbox::Initialize() method. The Sandbox initializes objects in the following order:

1. CoordinateSystem
2. Spacecraft
3. All others except Parameters and Subscribers

[8]The 3 coordinate systems listed at the end of the configuration table are automatically created by the Moderator.

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4. System Parameters
5. Other Parameters
6. Subscribers

The initialization of these objects follows this basic algorithm:

- Send the Sandbox's solar system to the object
- Set pointers for all of objects referenced by this object
- Call the object's Initialize() method

The basic initialization for Function objects are part of element 3 in the list above. At that point in the initialization process, the Function objects are not yet populated, so this step does not perform any substantive action. The Sandbox checks each GmatFunction to ensure that the path to the function file is not empty as part of this initialization.

Initialization Step 3: Global Object Management Once the objects in the Sandbox Object Map are initialized, the objects flagged as global objects are moved from the Sandbox Object Map into the Global Object Store. The Sandbox does this by checking the object's isGlobal flag, a new attribute of the GmatBase class added for global object management.

Some object types are automatically marked as global objects. All instances of the PropSetup class, Function classes, and coordinate system classes fall into this category, and are built with the isGlobal flag set.

Initialization Step 4: Control Sequence Initialization The final step in Sandbox initialization is initialization of the Mission Control Sequence. This step in the initialization process includes construction of the Function Control Sequences, and does the first portion of initialization that is needed before the Function Control Sequence can be executed. At this stage in the initialization process, the Global Object Store contains clones of all of the configured objects marked as globals, the Sandbox Object Map contains clones of all other configured objects, and the GmatFunction objects know the locations of the function files. The Function Control Sequences are all empty, and the system has not identified any functions called from inside of functions that are not also called in the Mission Control Sequence. The objects in the Sandbox Object Map have the connections to referenced objects set, and are ready for use in the Mission Control Sequence.

So far, we have encountered three GmatFunctions, shown in Table 31.17 with their data structures:

Table 31.17: GmatFunction Status at the Start of Control Sequence Initialization

Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
LoadCartState	empty	NULL	empty	empty	empty	empty
cross	empty	NULL	empty	empty	empty	empty
magnitude	empty	NULL	empty	empty	empty	empty

As we will see, the call stack, implemented as the "objectStack" attribute in the GmatFunction class, remains empty throughout the initialization process.

The Sandbox initialized the Mission Control Sequence by walking through the list of commands in the sequence, and performing the following tasks on each:

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- Send the pointers to the Sandbox Object Map and the Global Object Map to the command
- Set the solar system pointer for the command
- Set the transient force vector for the command
- If the command uses a GmatFunction, build that function as described below
- Call the command's Initialize() method

In order to see how these actions work with GmatFunctions, we'll continue walking through the sample script. For clarity's sake, it is useful to have a complete picture of the contents of the Mission Control Sequence. The Mission Control Sequence, listed by node type and script line, and numbered for reference, can be written like this:

```
1   While          While Sat.ElapsedDays < 1
2   Propagate         Propagate Prop(Sat)
3   CallFunction      [rv, vv, r, v] = LoadCartState(Sat);
4   Assignment        Energy = v^2/2 - mu/r;
5   Assignment        SMA = -mu/2/Energy;
6   Assignment        ev = cross(vv,cross(rv, vv))/mu - rv/r;
7   CallFunction      [ECC] = magnitude(ev);
8   Assignment        nv(1,1) = x*vz-z*vx;
9   Assignment        nv(2,1) = y*vz-z*vy;
10  Assignment        nv(3,1) = 0;
11  CallFunction      [n] = magnitude(nv);
12  Assignment        RAAN = acos( nv(1,1)/n );
13  If                If nv(2,1) < 0;
14  Assignment           RAAN = (pi2 - RAAN) / d2r;
15  EndIf             EndIf;
16  Assignment        SMAError = Sat.SMA - SMA;
17  Assignment        ECCError = Sat.ECC - ECC;
18  Assignment        RAANError = Sat.RAAN - RAAN;
19  Report            Report Cart2KepConvert Sat.SMA SMA SMAError ...
                        Sat.ECC ECC ECCError Sat.RAAN RAAN RAANError
20  EndWhile       EndWhile
```

(The line of script associated with each node is shown on the right in this list.)

At the start of the Mission Control Sequence initialization, the Sandbox Object Map and Global Object Store contain the following items:

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Table 31.18: The Sandbox Maps

Sandbox Object Map		**Global Object Store**	
Name	*Type*	*Name*	*Type*
Sat	Spacecraft*	Prop	PropSetup*
Prop_FModel	ForceModel*	EarthMJ2000Eq	CoordinateSystem*
Prop	PropSetup*	EarthMJ2000Ec	CoordinateSystem*
SMA	Variable*	EarthFixed	CoordinateSystem*
ECC	Variable*	LoadCartState	GmatFunction*
RAAN	Variable*	cross	GmatFunction*
r	Variable*	magnitude	GmatFunction*
v	Variable*		
pi2	Variable*		
mu	Variable*		
d2r	Variable*		
Energy	Variable*		
SMAError	Variable*		
ECCError	Variable*		
RAANError	Variable*		
rv	Array*		
vv	Array*		
ev	Array*		
nv	Array*		
Cart2KepConvert	ReportFile*		
LoadCartState	GmatFunction*		
cross	GmatFunction*		
magnitude	GmatFunction*		
EarthMJ2000Eq	CoordinateSystem*		
EarthMJ2000Ec	CoordinateSystem*		
EarthFixed	CoordinateSystem*		

These maps stay the same until either a Global command is encountered or a Create command is encountered that creates an object that is automatically global.

The steps listed above for command initialization are performed for the first two commands in the list, items 1 and 2, without changing any of the object maps or function attributes. Item 3:

```
[rv, vv, r, v] = LoadCartState(Sat);
```

is a CallFunction that initializes a GmatCommand, so we need to look more closely at the initialization for this line.

The CallFunction at this point has a FunctionManager which contains the name of a GmatFunction object and StringArrays for the inputs and outputs. The StringArrays contain the following data:

```
inputNames = {"Sat"}
outputNames = {"rv", "vv", "r", "v"}
```

The Sandbox passes the pointers for the Sandbox Object Map and the Global Object Store to the CallFunction command. Once the CallFunction has received the Global Object Store, it uses that mapping to locate the function needed by the Function Manager, and passes the pointer to that function into the FunctionManager. The FunctionManager determines the type of the function – in this example, the function is a GmatFunction. The function attributes at this point are shown in Table 31.19.

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Table 31.19: GmatFunction Status after Setting the GOS and SOM

Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
LoadCartState	empty	Set	empty	empty	empty	empty
cross	empty	NULL	empty	empty	empty	empty
magnitude	empty	NULL	empty	empty	empty	empty

The Sandbox then passes in the pointers to the solar system and transient force vector, which the CallFunction passes into the FunctionManager. Since the function in the FunctionManager is a GmatFunction, these pointers will be needed later in initialization and execution, so the FunctionManager passes these pointers into the function for later use. (If the function in the FunctionManger was not a GmatFunction, the pointers would have been discarded.)

At this point, all of the items needed to build the Function Control Sequence exist. The Sandbox retrieves the pointer for the GmatFunction from the CallFunction command. It checks to see if the function's Function Control Sequence has been built. If the Function Control Sequence is NULL, the Sandbox calls the Moderator::InterpretGmatFunction() method to construct the Function Control Sequence, which in turn calls the ScriptInterpreter::InterpretGmatFunction() method. Both of these calls take the function pointer as input arguments, so that the interpreter has the local Sandbox instance of the GmatFunction that it uses to build the Function Control Sequence. The ScriptInterpreter::InterpretGmatFunction() method builds the Function Control Sequence and returns it, through the Moderator, to the Sandbox.

The LoadCartState GmatFunction that is constructed here is built from this scripting:

```
function [rv, vv, r, v] = LoadCartState(Sat);

% This function fills some arrays and variables with
% Cartesian state data

Create Variable r v
Create Array rv[3,1] vv[3,1]

rv(1,1) = Sat.X;
rv(1,2) = Sat.Y;
rv(1,3) = Sat.Z;
vv(1,1) = Sat.VX;
vv(1,2) = Sat.VY;
vv(1,3) = Sat.VZ;

[r] = magnitude(rv);
[v] = magnitude(vv);
```

The process followed in the ScriptInterpreter::InterpretGmatFunction() method will be described below. Upon return from this function call, the functions contain the attributes shown in Table 31.20.

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Table 31.20: GmatFunction Status after Building the LoadCartState FCS

Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
LoadCartState	empty	Set	'Sat'->NULL	'rv'->NULL 'vv'->NULL 'r'->NULL 'v'->NULL	Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	empty
cross	empty	NULL	empty	empty	empty	empty
magnitude	empty	NULL	empty	empty	empty	empty

The Sandbox then checks the Function Control Sequence generated in the ScriptInterpreter, and checks to see if that sequence contains a GmatFunction. If it does, then for each GmatFunction encountered, the process is repeated.

The Sandbox checks the Function Control Sequence by starting at the first node, and checking each Assignment and CallFunction command in that control sequence to see if it references a GmatFunction. Our example script does contain such a call to a GmatFunction – it calls the magnitude function twice, in the last two CallFunction commands in the Function Control Sequence. Each of the FunctionManagers associated with these CallFunction commands have StringArrays containing the names of the input and output objects that will be used during execution – more specifically, the FunctionManager associated with the first CallFunction has these StringArrays:

```
inputNames = {"rv"}
outputNames = {"r"}
```

while the second has these:

```
inputNames = {"vv"}
outputNames = {"v"}
```

When the Sandbox detects the GmatFunction in the first CallFunction command, it performs the same tasks as were performed on the CallFunction in the Mission Control Sequence – more specifically:

1. The Sandbox passes the pointer for the Global Object Store to the CallFunction command. (Note that the Sandbox does not pass in the Sandbox Object Map; the Sandbox Object Map is only used in commands in the Mission Control Sequence.)
2. Once the CallFunction has received the Global Object Store, it uses that mapping to locate the function needed by the FunctionManager.
    - If the function was found, the CallFunction passes the pointer to that function into the Function-Manager
    - If the function was not found, the pointer referenced by the Function Manager remains NULL.
3. The FunctionManager determines the type of the function. If the function is not a GmatFunction, the process ends.

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4. The Sandbox passes the pointers to the solar system and transient force vector to the CallFunction, which passes them into the FunctionManager.

5. The FunctionManager passes these pointers into the function for later use.

At this point, all of the items needed to build the nested Function Control Sequence exist. Returning to our example, the state of the function object attributes at this point is shown in Table 31.21.

Table 31.21: GmatFunction Status after Detecting the First Nested CallFunction

Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
LoadCartState	empty	Set	'Sat'->NULL	'rv'->NULL 'vv'->NULL 'r'->NULL 'v'->NULL	Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	empty
cross	empty	NULL	empty	empty	empty	empty
magnitude	empty	Set	empty	empty	empty	empty

The Sandbox then calls the Moderator::InterpretGmatFunction() method to build the Function Control Sequence for the magnitude command. The magnitude function is scripted like this:

```
function [val] = magnitude(vec1)

% This function takes a 3-vector in a GMAT array and
% calculates its magnitude
Create Variable val
val = sqrt(dot(vec1, vec1));
```

so the resulting Function Control Sequence and other attributes have the values shown in Table 31.22 when the Moderator returns control to the Sandbox.

Table 31.22: GmatFunction Status after Parsing the First Nested CallFunction

Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
LoadCartState	empty	Set	'Sat'->NULL	'rv'->NULL 'vv'->NULL 'r'->NULL 'v'->NULL	Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	empty

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Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
cross	empty	NULL	empty	empty	empty	empty
magnitude	empty	Set	'vec1'->NULL	'val'->NULL	Create Assignment	empty

The Assignment command in the newly created Function Control Sequence is particularly interesting, because it contains inline mathematics, which use a previously unencountered GmatFunction named dot. The MathTree for this Assignment command is shown in Figure 31.5.

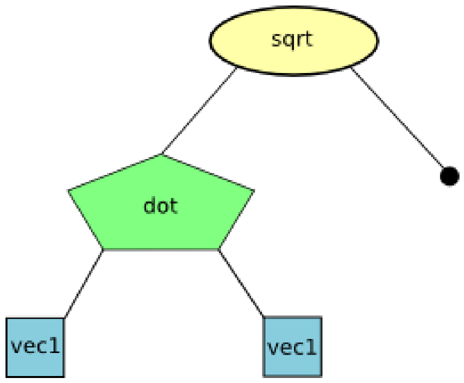

Figure 31.5: The MathTree for the Assignment command in the magnitude GmatFunction

Note that while the dot GmatFunction has been identified as a needed element for the Assignment line, there is not yet an instance of a GmatFunction object that is associated with the dot function, even though the MathTree shown in Figure 31.5 has a FunctionRunner MathNode that requires it. This issue will be resolved shortly.

The Sandbox takes this new Function Control Sequence, and checks it for the presence of a GmatFunction by walking through the list of commands in the control sequence. When it checks the Assignment command, it finds that there is a function dependency, and that the associated function does not exist in the Global Object Store. Since all function types except for GmatFunctions must be created before they can be used, the Sandbox assumes that the needed function is a GmatFunction and asks the Moderator to create an unnamed GmatFunction[9].

The Moderator calls the Factory Manager to create the function, and returns the pointer of the new function to the Sandbox. The Sandbox then sets its name to be "dot" and adds it to the Global Object Store. The Sandbox also performs the preinitialization steps described above: it sets the solar system pointer and transient force vector pointer on the function, sets any pointers referenced by the function, and calls the function's Initialize() method. Finally, the Sandbox calls the Moderator to locate the function file for the GmatFunction and sets the path to the file, completing this piece of the initialization. The Sandbox then passes the function pointer to the Assignment command, which passes it, in turn, into the FunctionRunner node. At this point, the Sandbox can continue initializing the Assignment command. The GmatFunction data is set as shown in Table 31.23.

Table 31.23: GmatFunction Status after Creating the dot Function

[9]The GmatFunction is unnamed so that it will not be passed to the configuration.

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Function	Function Object Store	Global Object Store	inputs	outputs	Function Control Sequence	Call Stack
LoadCartState	empty	Set	'Sat'->NULL	'rv'->NULL 'vv'->NULL 'r'->NULL 'v'->NULL	Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	empty
cross	empty	NULL	empty	empty	empty	empty
magnitude	empty	Set	'vec1'->NULL	'val'->NULL	Create Assignment	empty
dot	empty	NULL	empty	empty	empty	empty

Recall that we are at the point in the initialization where the Sandbox is checking the Function Control Sequence for the magnitude GmatFunction for internal function calls. The Sandbox found the dot function as an internal dependency, and built the corresponding GmatFunction. The final step performed by the Sandbox at this point is to build the Function Control Sequence for the dot command. The text of the dot file looks like this:

```
function [val] = dot(vec1, vec2)

% This function takes two 3-vectors in a GMAT array and
% constructs their dot product
Create Variable val
val = vec1(1,1) * vec2(1,1) + vec1(2,1) * vec2(2,1) +...
      vec1(3,1) * vec2(3,1);
```

The Sandbox calls the Moderator::InterpretGmatFunction() method to build the control sequence for the dot function. Upon return, the function attribute table has the contents shown in Table 31.24.

Table 31.24: GmatFunction Status after Interpreting the dot Function

Function	Function Object Store	Global Object Store	inputs	outputs	Function Control Sequence	Call Stack
LoadCartState	empty	Set	'Sat'->NULL	'rv'->NULL 'vv'->NULL 'r'->NULL 'v'->NULL	Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	empty
cross	empty	NULL	empty	empty	empty	empty

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Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
magnitude	empty	Set	'vec1'->NULL	'val'->NULL	Create Assignment	empty
dot	empty	Set	'vec1'->NULL 'vec2'->NULL	'val'->NULL	Create Assignment	empty

The Sandbox takes the Function Control Sequence built for the dot function, and checks it for internal function calls. There is an Assignment command in this control sequence that references inline mathematics, but the corresponding MathTree does not contain any functions. Therefore, the initialization for the dot function is complete, and the method that built it returns control to the calling method.

In this case, the calling method is actually the same method that called the first CallFunction – the call was a recursive call, because we were checking the Function Control Sequence for the dot function, which was called part way through the check of the Function Control Sequence for the magnitude function.

That call was made for the Assignment command in the magnitude function. The check for the magnitude Assignment command has now built all of the functions it needs, so control is returned to the method that was performing the check on the magnitude function.

Again, the calling method is the method that checks for function calls, this time for the first CallFunction in the LoadCartState function. All of the function references in that CallFunction have been resolved and initialized, so the function check method moves to the second CallFunction. That CallFunction makes a call to the magnitude function. All of the internal structures needed to execute the magnitude function have been built, following the procedures discussed above. The check for this CallFunction does detect that there is a GmatFunction in the call – a call to the magnitude function. It then checks the magnitude GmatFunction, and finds that it has been initialized, so it proceeds to the next command in the LoadCartState Function Control Sequence. Since this second CallFunction was the last command in that Function Control Sequence, the LoadCartState function control sequence is now fully initialized and ready to execute.

We have now initialized all of the system except for the cross function. The Sandbox is partway through the check on the Mission Control Sequence for function calls – all of the preceding GmatFunction initialization was performed to fully initialize the CallFunction command in the Mission Control Sequence. The next function encountered in the main script is in the third Assignment command. That command was generated by the script line

```
ev = cross(vv, cross(rv, vv)) / mu - rv / r;
```

When the Sandbox checks that line, it finds that there are two FunctionRunner nodes in the associated MathTree. The first of these nodes requires an initialized cross function, so the Sandbox follows the process described above to build the Function Control Sequence for the cross function. Once this first node has been handled by the Sandbox, the function attribute table looks like Table 31.25.

Table 31.25: GmatFunction Status after Interpreting the cross Function

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Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
LoadCartState	empty	Set	'Sat'->NULL	'rv'->NULL 'vv'->NULL 'r'->NULL 'v'->NULL	Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	empty

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Function	**Function Object Store**	**Global Object Store**	**inputs**	**outputs**	**Function Control Sequence**	**Call Stack**
cross	empty	Set	'vec1'->NULL 'vec2'->NULL	'vec3'->NULL	Create Assignment Assignment Assignment	empty
magnitude	empty	Set	'vec1'->NULL	'val'->NULL	Create Assignment	empty
dot	empty	Set	'vec1'->NULL 'vec2'->NULL	'val'->NULL	Create Assignment	empty

The Sandbox then checks the second FunctionRunner node, and finds that it uses a function that has already been built – the cross function – so no further action is necessary for this Assignment command. It moves to the next command in the Mission Control Sequence, and finds that that command – a CallFunction that uses the magnitude GmatFunction – is also ready to execute. This process continues through all of the remaining commands in the Mission Control Sequence. All of the commands and called functions have been initialized, so the commands and functions used in the Sandbox have now been fully prepared for the mission run.

Additional Notes on Initialization

Function and FunctionManager Status Summary The scripting in our example generates seven specific places where a FunctionManager interface is built in order to implement the structure needed to run a GmatFunction. Table 31.26 shows each of these interfaces, along with the string descriptors that are set in the interface tables for each of these instances. The actual data structures that contain the input and output objects are not set during initialization; they are built the first time the function is called during execution of the Mission Control Sequence. That process is described in the execution section of this text.

Table 31.26: Summary of the Function Interfaces

Script Line	**Interface Type**	**Function Manager**		**Function**		
		inputNames	*outputNames*	*name*	*inputs*	*outputs*
[rv, vv, r, v] = LoadCartState(Sat)	Call-Function	'Sat'	'rv' 'vv' 'r' 'v'	LoadCart-State	'Sat'->NULL	'rv'->NULL 'vv'-> NULL 'r'->NULL 'v'->NULL
ev = cross(vv, cross(rv, vv)) / mu - rv / r;	Function-Runner (Two instances)	'rv' 'vv'	”	cross (inner instance)	'vec1'-> NULL 'vec2'-> NULL	'vec3'-> NULL
		'vv' ”	”	cross (outer instance)	'vec1'-> NULL 'vec2'-> NULL	'vec3'-> NULL
[ECC] = magni-tude(ev)	Call-Function	'ev'	'ECC'	magnitude	'vec1'-> NULL	'val'-> NULL
[n] = magni-tude(nv)	Call-Function	'nv'	'n'	magnitude	'vec1'-> NULL	'val'-> NULL

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Script Line	Interface Type	Function Manager		Function		
		inputNames	*outputNames*	*name*	*inputs*	*outputs*
[r] = magnitude(rv)	CallFunction	'rv'	'r'	magnitude	'vec1'-> NULL	'val'-> NULL
[v] = magnitude(vv)	CallFunction	'vv'	'v'	magnitude	'vec1'-> NULL	'val'-> NULL
val = sqrt(dot(vec1, vec1));	FunctionRunner	'vec1' 'vec1'	"	dot	'vec1'-> NULL 'vec2'-> NULL	'val'-> NULL

Before we examine execution, a few items should be mentioned about the work performed in the ScriptInterpreter when the InterpretGmatFunction() method is invoked.

Details of the ScriptInterpreter::InterpretGmatFunction() Method The Interpreter::InterpretGmatFunction()[10] method is very similar to the ScriptInterpreter::Interpret() method. The differences arise in the Interpreter state, the parsing for the function line in the function file, and the management of the commands created during the parsing of the function file.

The InterpretGmatFunction() method has this signature:

```
GmatCommand* Interpreter::InterpretGmatFunction(Function *funct)
```

The InterpretGmatFunction() method does not manage state in the same sense as the Interpret() method. At the point that the InterpretGmatFunction() method is invoked, there is no longer a sense of "object mode" and "command mode," because every executable line in a GmatFunction file has an associated command – in other words, there is no "object mode" at this point in the process. Since there is no sense in tracking state, the Interpreter treats the entire time spent reading and building the GmatFunction as if it were in Command mode.

When the InterpretGmatFunction() method is invoked, it takes the Function pointer from the function's argument list and retrieves the function file name and path from that object. It opens the referenced file, and uses the ScriptReadWriter and TextParser helper classes to parse the function file, one logical block at a time.

The first logical block in a GmatFunction file defines the function, and must start with the "function" keyword. An example of this line can be see in the first line of the cross function in Listing 5:

```
function [vec3] = cross(vec1, vec2)
```

If the keyword "function" is not encountered as the first element in the command section of the the first logical block in the file, the method throws an exception stating that the Interpreter expected a GmatFunction file, but the function definition line is missing.

The remaining elements in this logical block are used to check the function name for a match to the expected name, and to set the input and output argument lists for the function. The list contained in square brackets is sent, one element at a time, into the function as the output elements using the SetStringParameter() method. Similarly, the function arguments in parentheses following the function name generate calls to the SetStringParameter() method, setting the names for the input arguments. Thus, for example, the function definition line above for the cross function generates the following calls into the GmatFunction object that was passed into the InterpretGmatFunction() method:

[10]While this method is most naturally assigned to the ScriptInterpreter – since it is interpreting a text file describing the function – the method itself is found in the Interpreter base class.

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```
// Calls that are made to the cross function.  These are not
// intended to be actual code; they are representative calls.
// The actual code will loop through the argument lists rather
// than perform the linear process shown here.

// Given these values from the TextParser:
//    inputList = {‘‘vec1’’, ‘‘vec2’’}
//    functionName = ‘‘cross’’
//    outputList = {‘‘vec3’’}

// First check the name
if (functionName != funct->GetName())
   throw CommandException("The GmatFunction \"" +
      funct->GetName() + "\" in the file \"" +
      funct->GetStringParameter("Filename") +
      "\" does not match the function identifier in the file.");

// Next set the input argument(s)\newline
funct->SetStringParameter(INPUTPARAM_ID, inputList[0]);
funct->SetStringParameter(INPUTPARAM_ID, inputList[1]);

// And the output argument(s):
funct->SetStringParameter(OUTPUTPARAM_ID, outputList[0]);
```

(Of course, the exception message should be changed to conform to GMAT's usual message formats.) The code in the GmatFunction is built to receive these values, and populate the internal data structures accordingly. This, for example, when the line

```
funct->SetStringParameter(INPUTPARAM_ID, inputList[0]);
```

is executed, the GmatFunction checks the inputs map and, if the input value is not in the map, adds it to the map, something like this:

```
// on this call: SetStringParameter(INPUTPARAM_ID, "vec1"),
// the GmatFunction does this:

if (inputs.find("vec1") == inputs.end())
   inputs["vec1"] = NULL;
else
   throw FunctionException("Invalid operation: an attempt was"
      " made to add an input argument named \"" + "vec1" +
      "\", but an argument with that name already exists.");
```

Once the function definition line has been parsed, the process followed to build the Function Control Sequence begins. The Function Control Sequence is built using the same process as is followed for the Mission Control Sequence: the function file is read one logical block at a time, the command corresponding to that logical block is constructed, and the command is appended to the control sequence. The only difference for this phase of initialization is this: when GMAT is building a Mission Control Sequence, the sequence that receives the new commands is the Mission Control Sequence associated with the current Sandbox. For GmatFunction, the control sequence is the Function Control Sequence associated with the current function.

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31.2.2.3 GmatFunction Execution

Once the Mission Control Sequence and all referenced Function Control Sequences have been initialized, they are ready for execution in the Sandbox. The Moderator launches execution by calling the Sandbox::Execute() method. When this method is called, the Sandbox sets an internal pointer to the first command in the Mission Control Sequence, and then enters a loop that walks through the Mission Control Sequence one command at a time. For each command in the Mission Control Sequence, the Sandbox performs the following actions:

1. Check to see if a user interrupt has occurred, and if so, respond to it.
2. Call the Execute() method on the current command.
3. Set the current command pointer to the command returned by calling GetNext() on the command that just executed.
4. If the new current command pointer is not NULL, loop to step 1; otherwise, the Mission Control Sequence is finished executing and control returns to the Moderator.

In this section, we will examine the behavior of the execution of the commands that reference GmatFunctions exclusively. Readers interested in the general execution of the Mission Control Sequence are referred to Chapters 3 through 5 and Chapter 26 of the GMAT Architectural Specification.

The first command that references a GmatFunction is the command near the top of the While loop which was generated by this text:

```
[rv, vv, r, v] = LoadCartState(Sat);
```

This script line generates a CallFunction command. That CallFunction has a FunctionManager that references the LoadCartState GmatFunction. The first time Execute() is called for this CallFunction, these objects have the attributes shown in Table 31.27. (For the CallFunction, only the pointers needed in this discussion are shown in the object stores. The example used here does not use any global objects, so just the status of the Global Object Store is not indicated.)

Table 31.27: CallFunction Attributes Prior to First Execution

CallFunction		**FunctionManager**			**LoadCartState Function**			
Sandbox Object Store	*Global Object Store*	*inputNames*	*outputNames*	*Function Object Store*	*inputs*	*outputs*	*Function Object Store*	*Global Object Store*
Sat rv vv r v	set	'Sat'	'rv' 'vv' 'r' 'v'	empty	Sat->NULL	rv->NULL vv->NULL r->NULL v->NULL	NULL	NULL

The first time a CallFunction or FunctionRunner is executed, the final piece of initialization is performed so that all of the data structures used for the execution are set and the Function Control Sequence is fully initialized. Subsequent calls into the same CallFunction or FunctionRunner updates the data used in the function calls by copying the data into the Function Object Store using the object's assignment operator. Both of these processes are described below, and illustrated using our sample functions.

Steps Performed on the First Execution The first time a CallFunction or FunctionRunner executes, the following processes are performed:

1. The CallFunction tells the FunctionManager to build the Function Object Store. The FunctionManager performs the following actions in response:

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- First the input arguments are set up:
  - The FunctionManager looks first in the Local Object Store, then in teh Global Object Store, and finds each input object listed in the inputNames StringArray
  - The input object is cloned, using its Clone() method, and wrapped in an ObjectWrapper[11]
  - The Function is queried for the name of the matching input argument
  - The clone is set in the Function Object Store, using the function's argument name as the map key
  - An ElementWrapper is built for the clone
  - The ElementWrapper is passed to the Function as the input argument
- Then the output arguments are set up:
  - The FunctionManager finds each output object listed in the outputNames StringArray
  - The output object is stored in an ObjectArray for later use
- If this process fails for any input or output object, an exception is thrown and the process terminates
- The Function Object Store and Global Object Store are passed into the Function

At this point, the objects managed by this CallFunction have the attributes shown in Table 31.28.

Table 31.28: CallFunction Attributes After Building the Function Object Store

CallFunction		**FunctionManager**			**LoadCartState Function**			
Sandbox Object Store	*Global Object Store*	*input-Names*	*output-Names*	*Function Object Store*	*inputs*	*outputs*	*Function Object Store*	*Global Object Store*
Sat rv vv r v	set	'Sat'	'rv' 'vv' 'r' 'v'	'Sat'-> Sat clone	Sat-> clone wrapper	rv->NULL vv->NULL r->NULL v->NULL	set	set

2. Initialize the Function by calling Function->Initialize(). This call makes the Function complete initialization for each command in the Function Control Sequence. Each command in the Function Control Sequence (1) receives the pointer to the Function Object Store, Global Object Store, transient force vector, and Solar System, and then (2) calls the Initialize() method on the command.

3. Execute the Function Control Sequence by walking through the linked list of commands in the sequence, calling Execute() on each command in the sequence and using the command's GetNext() method to access the next command that is executed. Some details are provided below for the behavior of CallFunction commands and FunctionRunner MathNodes encountered during this process.

   Create commands encountered during this execution sequence add their objects to the Function Object Store. Global commands add the identified objects to the Global Object Store as well. At the end of the execution step, the attributes for the CallFunction example are listed in Table 31.29. Note that the pointers in the outputs attribute have not been set yet.

Table 31.29: CallFunction Attributes After Executing the Create commands

[11]For the examples shown here, the function arguuments are all objects, so they use ObjectWrappers. Other data types – real numbers, for example – use wrappers compatible with their type.

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CallFunction		**FunctionManager**			**LoadCartState Function**			
Sandbox Object Store	*Global Object Store*	*input-Names*	*output-Names*	*Function Object Store*	*inputs*	*outputs*	*Function Object Store*	*Global Object Store*
Sat rv vv r v	set	'Sat'	'rv' 'vv' 'r' 'v'	'Sat'-> Sat clone 'rv'->rv 'vv'->vv 'r'->r 'v'->v	Sat-> clone wrapper	rv->NULL vv->NULL r->NULL v->NULL	set	set

4. Retrieve the output data generated from the execution, and use it to set data in the output arguments that were stored in step 1. The output arguments are retrieved through a call to

```
ElementWrapper* Function::GetOutputArgument(Integer argNumber)
```

   which finds the output argument at the indicated location and returns it

5. Reset the Function Control Sequence so it is ready for subsequent calls to this function. The final state of the function attributes is shown in Table 31.30.

Table 31.30: CallFunction Attributes After Execution

CallFunction		**FunctionManager**			**LoadCartState Function**			
Sandbox Object Store	*Global Object Store*	*input-Names*	*output-Names*	*Function Object Store*	*inputs*	*outputs*	*Function Object Store*	*Global Object Store*
Sat rv vv r v	set	'Sat'	'rv' 'vv' 'r' 'v'	'Sat'-> Sat clone 'rv'->rv 'vv'->vv 'r'->r 'v'->v	Sat-> clone wrapper	rv->rv vv->vv r->r v->v	NULL	set

Steps Performed on the Subsequent Executions Subsequent calls into a CallFunction or FunctionRunner that has executed once have a simplified first step, because the structures in the FunctionManager are initialized in the first call. Subsequent calls follow the following procedure:

1. The CallFunction tells the FunctionManager to refresh the Function Object Store. The FunctionManager performs the following actions in response:

   - The input arguments are updated using the assignment operator to set the clones equal to the original objects.
   - The Function Object Store is passed into the Function.

   At this point, the objects managed by this CallFunction have the attributes shown in Table 31.31.

Table 31.31: CallFunction Attributes After Execution

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CallFunction		**FunctionManager**			**LoadCartState Function**			
Sandbox Object Store	*Global Object Store*	*input-Names*	*output-Names*	*Function Object Store*	*inputs*	*outputs*	*Function Object Store*	*Global Object Store*
Sat rv vv r v	set	'Sat'	'rv' 'vv' 'r' 'v'	'Sat'-> Sat clone	Sat-> clone wrapper	rv->NULL vv->NULL r->NULL v->NULL	set	set

2. Initialize the Function by calling Function->Initialize(). This call makes the Function complete initialization for each command in the Function Control Sequence. Each command in the Function Control Sequence (1) receives the pointer to the Function Object Store, Global Object Store, transient force vector, and Solar System, and then (2) calls the Initialize() method on the command. (This repetition of step 2 is required because the same function can be called from multiple locations, with different input objects, so the object pointers in the Function Control Sequence have to be refreshed each time a function is entered.)

3. Execute the Function Control Sequence by walking through the linked list of commands in the sequence, calling Execute() on each command in the sequence and using the command's GetNext() method to access the next command that is executed.

4. Retrieve the output data generated from the execution, and use it to set data in the output arguments.

5. Reset the Function Control Sequence so it is ready for subsequent calls to this function.

Functions within Functions GmatFunctions can call other GmatFunctions, either in a nested manner, or by calling recursively into the same function. When a GmatFunction detects that it is about to call into a GmatFunction in this manner, it needs to preserve the current state of the function data so that, upon return from the nested call, the function can resume execution. This preservation of function data is accomplished using a call stack, implemented as the GmatFunction::objectStack data member.

An example of the use of the call stack can be seen in the example script that we've been working through. The first function call, made to the LoadCartState function, uses a CallFunction in the Mission Control Sequence. When the Sandbox calls this function, the steps outlined in the previous section are performed, initializing and setting the Function Object Store and Function Control Sequence, and then calling the Execute method on each command in the Function Control Sequence to run the function. The use of the call stack can be seen when we examine the details of this process, as we will do in the following paragraphs.

When the Sandbox receives a message to execute the Mission Control Sequence, it sets its state to "RUNNING" and sets the current command pointer to the first command in the Mission Control Sequence. For our example, that means the current pointer start out pointing to the While command generated by this line of script:

```
While Sat.ElapsedDays {\textless} 1
```

The command is executed, and control returned to the Sandbox. The Sandbox then calls the GetNext() method to determine the next command to execute. The command pointer returned from that call points back to the While command again, because the While command is a branch command. The Sandbox polls for a user interrupt, and then calls the Execute() method on the While command again. The While command begins the execution of the commands inside of the While loop by calling its ExecuteBranch() method. That call executes the first command in the while loop,

```
Propagate Prop(Sat)
```

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which advances the spacecraft one step and returns control to the While command. The While command then calls GetNext() on the Propagate command that just executed, and sets its loop command pointer to the returned value – in this case, a pointer to the CallFunction command generated by this line:

```
[rv, vv, r, v] = LoadCartState(Sat);
```

The While command then returns control to the Sandbox. The Sandbox calls GetNext() on the While command, and receives, again, a pointer back to the While command, since the While command is running the commands in the while loop. The Sandbox polls for interrupts, and then calls Execute() on the While command, which calls ExecuteBranch(), which, in turn, calls Execute() on the CallFunction command. The CallFunction command and FunctionManager have completed initialization of the GmatFunction as described above, and the CallFunction has made a call into the FunctionManager::Execute() method to run the function. The following discussion picks up at that point. I'll refer to this long sequence of calls as the "Sandbox call chain" for the rest of this section – in other words, the Sandbox call chain is the sequence

```
Sandbox::Execute() --> While::Execute()
                   --> While::ExecuteBranch()
                   --> CallFunction::Execute()
                   --> FunctionManager::Execute()
```

The function that is executing at this point is the LoadCartState GmatFunction, which has the Function Control Sequence, Function Object Store, and call stack shown in Table 31.32. The functions called during execution of this function are also listed in this table, along with their attributes. The pointer in the FCS column shows the next command that will be executed; for example, the first Create command in the LoadCartState will be executed at the point where we resume discussion of the actual process in the next paragraph.

Table 31.32: Attributes of the LoadCartState GmatFunction and Subfunctions

LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
>Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	Sat clone	empty	Create Assignment	NULL	empty	Create Assignment	NULL	empty

The first call on the Sandbox call chain at this point executes the Create command

```
Create Variable r v
```

placing the variables r and v into the function object store, as is shown in Table31.33.

Table 31.33: Attributes of the LoadCartState GmatFunction After the Executing the First Create Command

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LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create >Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	Sat clone r v	empty	Create Assignment	NULL	empty	Create Assignment	NULL	empty

The next call executes the second Create command

```
Create Array rv[3,1] vv[3,1]
```

adding the rv and vv arrays to the Function Object Store. The next six calls execute the six assignment commands that are used to set the elements of the rv and vv arrays:

```
rv(1,1) = Sat.X;
rv(1,2) = Sat.Y;
rv(1,3) = Sat.Z;
vv(1,1) = Sat.VX;
vv(1,2) = Sat.VY;
vv(1,3) = Sat.VZ;
```

Once all of these commands have executed, the attributes contain the data shown in Table 31.34, the next command to be executed is the first CallFunction command, and the function is ready to call the first nested function.

Table 31.34: Attributes of the LoadCartState Function After the Executing the Six Assignment Commands

LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create Create Assignment Assignment Assignment Assignment Assignment Assignment >CallFunction CallFunction	Sat clone r v rv vv	empty	Create Assignment	NULL	empty	Create Assignment	NULL	empty

The CallFunction that is about to be invoked was generated from the script line

```
[r] = magnitude(rv);
```

Whenever the Sandbox call chain invokes a command, the following actions occur in the FunctionManager::Execute() method:

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1. The FunctionManager::Execute() method checks to see if the command that needs to be executed makes a function call. If it does:
   - A flag is set indicating that a nested function is being run. (This flag is used to prevent repetition of the following bullets when the FunctionManager::Execute() method is reentered after polling for a user interrupt.)
   - The Function Object Store is cloned.
   - The Function Object Store is placed on the call stack.
   - The nested function (or functions, if more than one function call is made) is initialized. The clone of the Function Object Store made in step 1 is used as the Local Object Map that supplies the arguments that are set in the new Function Object Store, which is then passed to the nested function during this initialization.
2. The Execute() method is called for the command.
3. The GetNext() method is called for the command. If the pointer returned from this call is NULL, the flag set in step 1 is cleared.
4. Control is returned to the caller so that interrupt polling can occur.

Once this process is started, calls from the Sandbox call chain into the FunctionManager::Execute() method as the result of polling for user interrupts skip the first step.

For the CallFunction command under discussion here, the attribute table shown in Table 31.35 describe the internal state of the data immediately following the initialization in step one.

Table 31.35: The LoadCartState Function after Initializing the First CallFunction

LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create Create Assignment Assignment Assignment Assignment Assignment Assignment >CallFunction CallFunction	Clones of: Sat clone r v rv vv	Original FOS: Sat clone r v rv vv	>Create Assignment	'vec1'-> clone of vv clone	empty	Create Assignment	NULL	empty

The magnitude GmatFunction is now ready to be run through the LoadCartState function. The next call through the Sandbox call chain invokes a call to the magnitude function's Create() command, which builds a variable named val. Table 31.36 shows the attributes after running this command.

Table 31.36: Attributes of the Function After Running the First magnitude Command

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LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create Create Assignment Assignment Assignment Assignment Assignment Assignment >CallFunction CallFunction	Clones of: Sat clone r v rv vv	Original FOS: Sat clone r v rv vv	Create >Assignment	'vec1'-> clone of vv clone val	empty	Create Assignment	NULL	empty

The next call through the Sandbox call chain invokes the magnitude function's Assignment command, built off of this line of script:

```
val = sqrt(dot(vec1, vec1));
```

The right side of this equation generates a MathTree. One node of that MathTree is a FunctionRunner, constructed to run the dot GmatFunction. Hence the check performed by the FunctionManager that is running the magnitude function detects that there is a nested function call in its Assignment command. Accordingly, when it is time to evaluate the MathTree, the controlling FunctionManager passes a pointer to itself, through the Assignment command, into the MathTree, which passes that pointer to each FunctionRunner node in the tree. Then when the MathTree makes the call to evaluate the FunctionRunner node, the FunctionRunner starts by calling the controlling FunctionManager::PushToStack() method, which clones its local Function Object Store, places the original on its call stack, and build the Function Object Store for the nested function. It then sets the clone as the Function Object Store for the FunctionManager inside of the FunctionRunner, and calls that FunctionManager's Evaluate() method. The Evaluate method starts by initializing the function, using the newly cloned Function Object Store as the source for the objects needed for initialization. The resulting attributes are shown in Table 31.37.

Table 31.37: LoadCartState Attributes After Running the First magnitude Command

LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create Create Assignment Assignment Assignment Assignment Assignment Assignment >CallFunction CallFunction	Clones of: Sat clone r v rv vv	Original FOS: Sat clone r v rv vv	Create >Assignment	Clones of: 'vec1'-> clone of vv clone val	Original FOS: 'vec1'-> clone of vv clone val	>Create Assignment	'vec1'-> clone of clone of vv clone 'vec2'-> clone of clone of vv clone	empty

The dot function can now be run. This execution is made by calling the Evaluate() method on the FunctionRunner. In turn, the FunctionRunner executes the function. Fortunately, this function does not call another. Upon completion of the execution of the dot function, the attributes have the values shown in Table 31.38.

Table 31.38: LoadCartState Attributes After Evaluating the dot Function in the magnitude Function

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LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create Create Assignment Assignment Assignment Assignment Assignment Assignment >CallFunction CallFunction	Clones of: Sat clone r v rv vv	Original FOS: Sat clone r v rv vv	Create >Assignment	Clones of: 'vec1'-> clone of vv clone val	Original FOS: 'vec1'-> clone of vv clone val	Create Assignment	'vec1'-> clone of clone of vv clone 'vec2'-> clone of clone of vv clone val	empty

At this point we can start unwinding the call stack. The Function Object Store for the dot function includes a Variable, val, that has the scalar product of the vv Array with itself. Once the dot function has completed execution, the FunctionManager retrieves this value, and saves it so that it can be passed to the MathTree as the result of the Evaluate() call on the FunctionRunner node. The FunctionManger then finalizes the dot function, clearing the Function Object Store pointer in the dot function. The FunctionRunner then calls the controlling FunctionManager's PopFromStack() method, which deletes the cloned call stack and restores the Function Object Store that was on the call stack. The MathTree completes its evaluation, retrieving the values obtained from the dot function, and using that value to build the resultant needed by the Assignment command that contains the MathTree. The attributes at this point are shown in Table 31.39.

Table 31.39: LoadCartState Attributes After Evaluating the magnitude Assignment Command

LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create Create Assignment Assignment Assignment Assignment Assignment Assignment >CallFunction CallFunction	Clones of: Sat clone r v rv vv	Original FOS: Sat clone r v rv vv	Create Assignment	'vec1'-> clone of vv clone val	empty	Create Assignment	NULL	empty

The Assignment command that called into the dot function used the results of that function to set the value of the val Variable in the magnitude function's Function Object Store. That Assignment command was the last command in the magnitude function's Function Control Sequence, so the call to the magnitude function made from the LoadCartState function has completed execution. The FunctionManager for the LoadCartState function retrieves the output argument – in this case, the val Variable – from the magnitude function. It then deletes the cloned function object store, pops the Function Object Store off of the call stack, locates the object set to contain the output – that is, the r Variable – in this Function Object Store, and calls the assignment operator to set these two objects equal. That process is followed for all of the output arguments in the function call, and then the FunctionManager clears the magnitude function, completing the execution of the CallFunction command. These steps result in the attributes tabulated in Table 31.40.

Table 31.40: LoadCartState Attributes After Clearing the magnitude Function

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LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction >CallFunction	Sat clone r v rv vv	empty	Create Assignment	NULL	empty	Create Assignment	NULL	empty

This process is repeated for the last CallFunction in the LoadCartState Function Control Sequence, resulting in calls that set the value of the v Variable in the LoadCartState Function Object Store. Once this final CallFunction has been evaluated, the FunctionManager in the Mission Control Sequence CallFunction command that started this process – that is, the FunctionManager that is running the LoadCartState function – retrieves the output objects, one at a time, and sets the objects in the Sandbox Object Map referenced by the CallFunction command equal to the objects found in the LoadCartState Function Object Store using the corresponding assignment operators. This completes the LoadCartState function execution, so the CallFunction FunctionManager finalizess the LoadCartState function, resulting in the attributes shown in Table 31.41. The LoadCartState function is now ready for a new call, should one be encountered later in the mission.

Table 31.41: Attributes after running the LoadCartState Function

LoadCartState			**magnitude**			**dot**		
FCS	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*	*FCS*	*FOS*	*Call Stack*
Create Create Assignment Assignment Assignment Assignment Assignment Assignment CallFunction CallFunction	NULL	empty	Create Assignment	NULL	empty	Create Assignment	NULL	empty

31.2.2.4 Finalization

The final step in running scripts that use GMAT functions is the cleanup after the function has been run. The normal procedure followed in the Sandbox is to call RunComplete() on the Mission Control Sequence, which gives each command the opportunity to reset itself for a subsequent run. The CallFunction and Assignment commands that access GmatFunctions use this call to execute the RunComplete() method in the Function Control Sequences contained in those functions.

The Sandbox Object Map and Global Object Store are left intact when GMAT finishes a run. Subsequent runs in GMAT start by clearing and reloading these object stores. The preservation of the final states of the objects in the Sandbox makes it possible to query these objects for final state data after a run completes execution.

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31.2.3 Global Data Handling: Another Short Example

In this section, we will examine another short sample to show how global data is managed in GMAT when functions are present. The main script that drives this example is shown here:

```
Create ImpulsiveBurn globalBurn;
Create Spacecraft globalSat;
Create Variable index;

Create ForceModel fm
fm.PrimaryBodies = {Earth}
Create Propagator prop
prop.FM = fm

Create OpenGLPlot OGLPlot1;
GMAT OGLPlot1.Add = {globalSat, Earth};

Global globalBurn globalSat
Propagate prop(globalSat) {globalSat.Earth.Periapsis}
For index = 1 : 4
  RaiseApogee(index);
  Propagate prop(globalSat) {globalSat.Earth.Periapsis}
EndFor
```

The function called here, RaiseApogee, applies a maneuver to the spacecraft so that subsequent propagation moves the spacecraft on different trajectory. The function is defined like this:

```
function [] = RaiseApogee(burnSize)

Global globalBurn globalSat
globalBurn.Element1 = burnSize / 10.0;
Maneuver globalBurn(globalSat);
```

This function uses two objects that are not defined in the function, and that are also not passed in using arguments to the function. These objects are placed in the Sandbox's Global Object Store. In the next few pages we will examine this object repository during initialization, execution, and finalization.

31.2.3.1 Globals During Initialization

At the start of initialization in the Sandbox, the Global Object Store is empty, the Sandbox Object Map contains the objects from the Configuration, and the Mission Control Sequence has been built from parsing of the script. The state of the objects in the Sandbox immediately before the start of Mission Control Sequence initialization is shown in Table 31.42.

Table 31.42: The Objects in the Globals Example at the Start of Initialization

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Mission Objects			RaiseApogee Function		
Sandbox Object Map	*Global Object Store*	*Mission Control Sequence*	*Function Object Store*	*Global Object Map*	*Function Control Sequence*
globalBurn globalSat index fm prop EarthMJ2000Eq EarthMJ2000Ec EarthFixed OGLPlot1 RaiseApogee	empty	Global Propagate For CallFunction Propagate EndFor	NULL	NULL	empty

The first thing the Sandbox does after initializing the objects in the Sandbox Object Map is to collect all objects in the Sandbox Object Store that are marked as globals via the isGlobal flag, and moves those objects into the Global Object Store. This includes the objects that are automatically set as global in scope. Other objects are set as globals using a check box on the GUI, or using the "MakeGlobal" object property in the script file. For this example, neither case is met, so the only global objects are the automatic globals – the Propagator and the Function found in the script, along with the three coordinate systems that GMAT automatically creates. Table 31.43 shows the resulting rearrangement of objects. Note that the objects marked by the Global command in the script are not put into the Global Object Store at this point. They are moved when the Global command is executed.

Table 31.43: The Objects in the Globals Example after moving the Globals

Mission Objects			RaiseApogee Function		
Sandbox Object Map	*Global Object Store*	*Mission Control Sequence*	*Function Object Store*	*Global Object Map*	*Function Control Sequence*
globalBurn globalSat index fm OGLPlot1	prop EarthMJ2000Eq EarthMJ2000Ec EarthFixed RaiseApogee	Global Propagate For CallFunction Propagate EndFor	NULL	NULL	empty

Note that the global objects have been moved from the Sandbox Object Map into the Global Object Store. This feature – glossed over in the earlier discussion – makes memory management for the objects at the Sandbox level simple. When the Sandbox is cleared, all of the objects in the Sandbox Object Map and the Global Object Store are deleted.

This feature has implications for global objects created inside of functions as well. If an object created inside of a function is declared global, either explicitly using a Global command or implicitly by virtue of its type, the Create or Global command checks the Global Object Store to see if an object of that name is already stored in it. If the object already exists in the Global Object Store, the types of the objects are compared, and if they do not match, an exception is thrown. Additional discussion of the interplay between the Create command and the Global command are provided in the design specifications for those commands.

Once the automatic globals have been moved into the Global Object Store, the Sandbox proceeds with initialization of the commands in the Mission Control Sequence. This process follows the procedure described in the preceding sections, so the results are summarized here, with details related to global objects discussed more completely.

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The first command of interest in this discussion is the Global command. At construction, this command was given the names of the global objects identified for the command. These names are stored in the command for use at execution time. No action is applied for this command during initialization.

The next command of interest is the CallFunction command. When the CallFunction command initializes, the Global Object Store pointer is passed into the function contained in the CallFunction – in this case, the RaiseApogee function. Then the solar system and transient force vector pointers are set in the function. The function is then retrieved by the Sandbox, and passed to the ScriptInterpreter::InterpretGmatFunction() method, which builds the Function Control Sequence. Upon return, the attributes are set as shown in Table 31.44.

Table 31.44: The Objects in the Globals Example on return from InterpretGmatFunction

Mission Objects			**RaiseApogee Function**		
Sandbox Object Map	*Global Object Store*	*Mission Control Sequence*	*Function Object Store*	*Global Object Map*	*Function Control Sequence*
globalBurn globalSat index fm OGLPlot1	prop EarthMJ2000Eq EarthMJ2000Ec EarthFixed RaiseApogee	Global Propagate For CallFunction Propagate EndFor	NULL	set	Global Assignment Maneuver

Like the Mission Control Sequence, the Function Control Sequence contains a Global command. The names of the global objects identified for this command are set in the InterpretGmatFunction() method when the GmatFunction is parsed. Nothing else happens for the Global command during the initialization that builds the Function Control Sequence.

The Sandbox continues initializing the commands in the Mission Control Sequence until they are all initialized, completing the process.

31.2.3.2 Globals During Execution

Next we will examine the behavior of the Global commands during execution of the Mission Control Sequence. The first command that is executed in the Mission Control Sequence is the Global command defined by the line

```
Global globalBurn globalSat
```

in the Function Control Sequence. This command contains a list of the global objects, specified as objects named “globalBurn” and “globalSat”. When the Global::Execute() method is called, it takes this list and, for each element in the list, performs these actions:

1. Check the command’s object map (in this case the Sandbox Object Store) for the named object.
2. If the object was found:
    (a) Check the Global Object Store for an object with the same name.
    (b) If no such object was found, remove the object from the object map and set it in the Global Object Store. Continue at step 4.
    (c) If the object was found in the Global Object Store, throw an exception stating that an object was found in the Global Object Store with the same name as one that was being added, and terminate the run.

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3. The object is not in the object map, so the Global command needs to verify that it was set by another process in the Global Object store. Looks for the object, and verify that it in the Global Object Store and that its pointer is not NULL. If the pointer is NULL, throw an exception and terminate the run.

4. Get the next name from the list of global objects. If the list is finished, exit, otherwise, return to step 1 to process the next global object.

The Global command in the Mission Control Sequence follows the process shown in step 2b, moving the declared objects into the Global Object store, as shown in Table 31.45.

Table 31.45: The Objects in the Globals Example after Executing the Global Command in the Mission Control Sequence

Mission Objects			**RaiseApogee Function**		
Sandbox Object Map	*Global Object Store*	*Mission Control Sequence*	*Function Object Store*	*Global Object Map*	*Function Control Sequence*
index fm OGLPlot1	prop EarthMJ2000Eq EarthMJ2000Ec EarthFixed RaiseApogee globalBurn globalSat	Global Propagate For CallFunction Propagate EndFor	NULL	set	Global Assignment Maneuver

Execution of the Global command in the Mission Control Sequence simply verifies that the global objects are set as specified.

31.2.4 Additional Notes and Comments

This section contains a few items that may need additional notes to fully explain the function design.

31.2.4.1 Search Order for Reference Objects

Previous builds of GMAT contain a single mapping for reference object names, the Sandbox Object Map. The function subsystem design requires the addition of two new mappings between names and object pointer: the Global Object Store and the Function Object Store.

In context, a command only has access to two of these three possible mappings. The Global Object Store is visible to all commands. Commands that are part of the Mission Control Sequence also access the Sandbox Object Map, while commands in a Function Control Sequence access the function's Function Object Store. I'll refer to this second mapping – either the Sandbox Object Map or the Function Object Store, depending on context – as the Local Object Store.

It is possible that objects in the Local Object Store have identical names to objects in the Global Object Store. As an example, both the dot and cross functions described in the function example in this document use local objects named vec1 and vec2. If one of these functions declared vec1 as a global object, a call to execute that function would move the local vec1 object into the Global Object Store. A subsequent call to the other function would result in a case where both the Local Object Store and the Global Object Store contain an object named vec1, and the commands that use this object would need a rule that specifies how to resolve the referenced object between these two object mappings.

The general rule for resolving reference objects for this type of scenario is that local objects have precedence over global objects. When reference object pointers are located prior to executing a command, the Local Object Store is searched first for the named object. If the Local Object Store does not contain the

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reference object, then the Global Object Store is used to resolve the reference. If the object is not found there either, an exception is thrown stating that a referenced object – with a specified name that is states in the exception message – was not available for use by the command.

31.2.4.2 Identifying Global Objects using the isGlobal Flag

The GmatBase base class gains a new attribute as part of the function design. This attribute is a boolean data member named isGlobal, which defaults to false in the base class. The isGlobal attribute can be accessed using the Get/SetBooleanParameter methods through the script identifier "MakeGlobal". Thus, in parameter mode, the following scripting:

```
Create Spacecraft Satellite
Satellite.MakeGlobal = true
```

specifies that the Spacecraft named Satellite is a global object, and should be placed in the Global Object Store when that mapping is populated – for example, as part of the global object mapping described in Initialization Step 3 (see section 31.2.2.2).

The isGlobal flag is used by GMAT's GUI to determine the state of the Global checkbox on resource panels – if the isGlobal flag is true, then a call to the GetBooleanParameter("MakeGlobal") method returns true, and the box is checked. When a user changes the state of the checkbox, that change is passed to the object using a call to the SetBooleanParameter("MakeGlobal", newValue) method.

In the Sandbox, the Global command moves local objects into the Global Object Store. When the command moves an object, it also toggles the isGlobal flag so that queries made to the object can identify that the object is globally acessible. This state data can be used by the Create command to determine if an object that it manages has been added to the Global Object Store, and therefore does not need to be resent to an object map.

31.2.4.3 Function Object Management

Each GMAT function can define input parameters and output parameters. Neither set is required. Functions that omit a set of parameters also omit the brackets for the parameter, as is shown here:

```
function MyFunctionWithoutResultants(inputs)
```

here:

```
function [resultants] = MyFunctionWithoutInputs
```

and here:

```
function MyFunctionWithoutParameters
```

The input and output parameters, marked in the sample above with the names "inputs" and "resultants," respectively, consist of labels for data that is passed between the calling object and the function. Each of the fields indicated that way in the examples above consist of one or more actual parameters. When GMAT's Script Interpreter encounters a function call, it creates either a CallFunction command or a FunctionRunner object that encapsulates the function call. This object analyzes the parameters for the function and stores them for use at runtime. During execution of the Mission Control Sequence, the CallFunction or FunctionRunner passes an object associated with each parameter into a member FunctionManager object, which in turn places the associated objects into the Function Object Store and them passes this store into the GmatFunction object that manages the call.

Objects used inside of the GMAT function can be obtained from three sources, shown in Table 31.46. The first source is the set of parameters defined in the function call – that is, the input and output variables. These clones are made by locating the objects named in the parameter lists (either the Sandbox Object Map

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Table 31.46: Object Maps used to Set References in Control Sequences

Object Map	Contents	Manager	Source
Sandbox Object Map	Clones of Configured Objects	Sandbox	Objects built from the Create keyword, in object mode
Global Object Store	Pointers to Global Objects	Sandbox	Objects identified as Globals
Function Object Store	Input and Output parameters, and locally created objects	CallFunction or FunctionRunner	Clones of the parameters, or created using the Create command

or the Global Object Store), making copies, and placing these copies in the Function Object Store. GMAT provides a command, the Create command, that can be used to create local variables in a control sequence. Variables created this way are also stored in the Function Object Store of the function, providing a second supply of objects used in the function.

The final source is the Global Object Store, managed by the Sandbox and supplied at initialization to the function. The Global Object Store contains every object that has been identified as available for use in all functions and sequences in the Sandbox. Objects are identified as members of the Global Object Store using the GMAT keyword "Global" in a script, or by checking the "global" checkbox on the object's configuration panel on the GUI. Coordinate Systems, Propagators, and Functions are automatically included in the Global Object Store.

GmatFunctions can call other GmatFunctions, and can call themselves iteratively. This feature of the class is implemented through a call stack incorporated into the GmatFunction class. When a GmatFunction is executing, calls to a CallFunction or FunctionRunner in the Function Control Sequence are preceded by a push of the Function Object Store onto the call stack. Once the called object completes execution, the call stack pops the Function Object Store off of the call stack and continues execution of the Function Control Sequence.

31.2.4.4 The Function Control Sequence

Each GmatFunction object manages a list of commands called the Function Control Sequence. The Function Control Sequence acts similarly to the Mission Control Sequence. It is a linked list of commands that defines a sequential set of actions taken by GMAT to perform a user designed task. The FCS differs from the Mission Control Sequence in several key ways: (1) it does not have direct access to the configuration or to the Sandbox's Object Map, (2) every object created for local use in the FCS is created at run time rather than when the Mission Control Sequence is opened, and (3) the corresponding object linkages and validation occur at build and run time.

GMAT parses the FCS for each function used in a script when the CallFunction command or FunctionRunner MathNode that calls the function is initialized in the Sandbox prior to a run. This function parsing is idempotent – in other words, if a given function is parsed in a CallFunction command or in a FunctionRunner, subsequent CallFunctions and FunctionRunners that access the same function do not force a reparsing of the function file.

The FCS is initialized when the CallFunction or FunctionRunner that calls the function is executed. At that point, the Function Object Store for the FCS is constructed, passed to the commands in the FCS, and used to initialize the commands in the FCS[12].

Functions are executed through a call to the Execute() method on the FunctionManager that runs the function for the calling control sequence. This process mimics the execution of the Mission Control Sequence,

[12]This late binding may prove to be prohibitively expensive for performance. If that turns out to be the case, we'll need to move the command initialization from run time to build time.

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as run by either the Sandbox or (for nested calls) an enclosing CallFunction or FunctionRunner. The sequence controlled by this caller is:

1. The CallFunction or FunctionRunner is prepared for execution:
    - The current command pointer is set to the first command in the FCS.
    - The FCS Function Object Store is built and passed into the FCS.
    - The FCS is initialized.
    - The commandExecuting flag for the CallFunction or Assignment command containning the function call is set to true.
    - The commandComplete flag is set to false.
2. The caller calls the Execute() method on the CallFunction or Assignment command.
3. The CallFunction or FunctionRunner calls the Execute() method on the FunctionManager, which in turn calls the Execute() method on the FCS command pointed to by the current command pointer.
4. Upon return, the FunctionManager advances the current command pointer by calling Next() on the command that was just executed.
5. The FunctionManager returns control to the caller so that interrupt polling can occur.
6. The caller calls the CallFunction::Next() or Assignment::Next() method.
    - If the current command pointer is NULL, the function has completed execution, and the next pointer in the control sequence is returned.
    - If the current command pointer is not NULL, the pointer to this command is returned.
7. The caller calls the Execute() method on the pointer returned from the call to Next().
    - If that pointer is the pointer for this command, and execution through the function loop resumes at step 3.
    - If that pointer is neither the current command nor a NULL pointer, the command has completed its work, and the calling control sequence proceeds to the next command in its list.
    - If that pointer is NULL, the script has completed execution and control is returned to the user.

The interactions between the CallFunction and Assignment command and the GmatFunction object, as enumerated here, are the focus of the design features presented in the following sections. Section 31.2.5 presents the class design for the GmatFunction class.

The CallFunction command is described in Section 31.5.1.

Details of the interplay between these component and the rest of GMAT are presented in Section 31.2.6. Global object management is presented in the discussion of the Create and Global commands, in Sections 31.5.2 and 31.5.3, respectively.

31.2.5 Design

Figure 31.6 shows the Function class hierarchy, with the details relevant to the GmatFunction class explicitly displayed. GmatFunction is derived from the Function base class, which, in turn, is a child of the GmatBase root class. Using GmatBase as the root class for the function classes provides GMAT with all of the infrastructure needed to configure and manipulate the function classes, including type identifiers, names, and standardized interfaces. More details about the GmatBase class can be found in Section 9.3.

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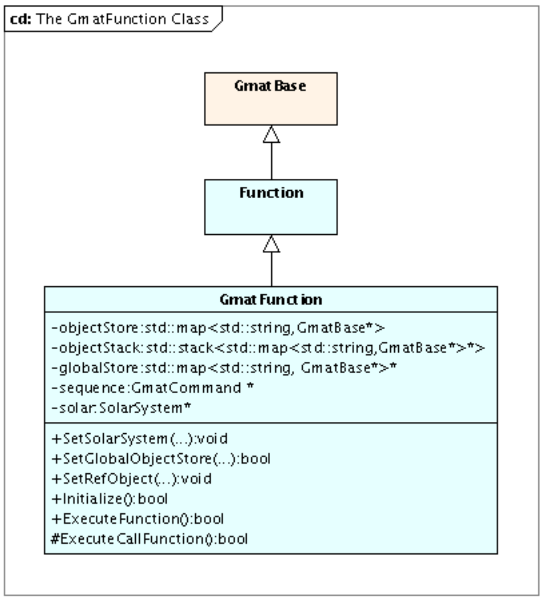
cd: The GmatFunction Class
GmatBase
Function
GmatFunction
-objectStore:std::map<std::string,GmatBase*>
-objectStack:std::stack<std::map<std::string,GmatBase*>*>
-globalStore:std::map<std::string, GmatBase*>*
-sequence:GmatCommand *
-solar:SolarSystem*
+SetSolarSystem(...):void
+SetGlobalObjectStore(...):bool
+SetRefObject(...):void
+Initialize():bool
+ExecuteFunction():bool
#ExecuteCallFunction():bool

Figure 31.6: Class diagram for the GmatFunction Class

31.2.5.1 GmatFunction Attributes

The GmatFunction class is the most complicated of the function classes. It provides mechanisms to manage objects used in the function, provide storage for nested calls (including iteration), receive input and output parameters and global objects, and manage the Function Control Sequence. The data attributes used for these functions are itemized here:

- **std::map<std::string, GmatBase*> objectStore**: The GmatFunction's local object store.
- **std::stack<std::map<std::string, GmatBase*» objectStack**: The function stack used to support recursion and function nesting.
- **std::map<std::string, GmatBase*> *globalStore**: The global object store.
- **GmatCommand *sequence**: The Function Control Sequence (FCS).
- **SolarSystem *solar**: The SolarSystem instance used in the Sandbox, passed to the GmatFunction for use in the FCS.

31.2.5.2 GmatFunction Methods

GmatFunctions include methods specific to the needs of the GmatFunctions, listed here:

- **void SetSolarSystem(SolarSystem *ss)**: Sets the solar system used in the FCS.
- **void SetGlobalObjectStore(std::map<std::string, GmatBase*> gos)**: Sets the global object store pointer.
- **bool SetRefObject(GmatBase *obj, const Gmat::ObjectType type, const std::string &name = "")**: Virtual method overridden from GmatBase. The Sandbox and CallFunction use this method to set up the GmatFunction, passing in the input and output parameters and Function Control Sequence.

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- **bool Initialize()**: Method used to set up all of the inter-object connections and verify that all required objects are available to run the FCS.
- **bool ExecuteFunction()**: Executes the FCS. This method is called to run the Function Control Sequence.
- **bool ExecuteCallFunction()**: This method is called when a CallFunction is found in the FCS to run the nested function.

The following paragraphs describe how these attributes and methods interact with the rest of GMAT to provide the function implementation.

31.2.6 GmatFunction Details: Construction, Initialization, and Execution

Before a GmatFunction can be used, it must be constructed through interactions between the FunctionManager, GmatFunction instance, and Sandbox. Figure 31.7 shows the Sandbox's role in these interactions. The figure shows the process for a CallFunction; FunctionRunner initialization is similar.

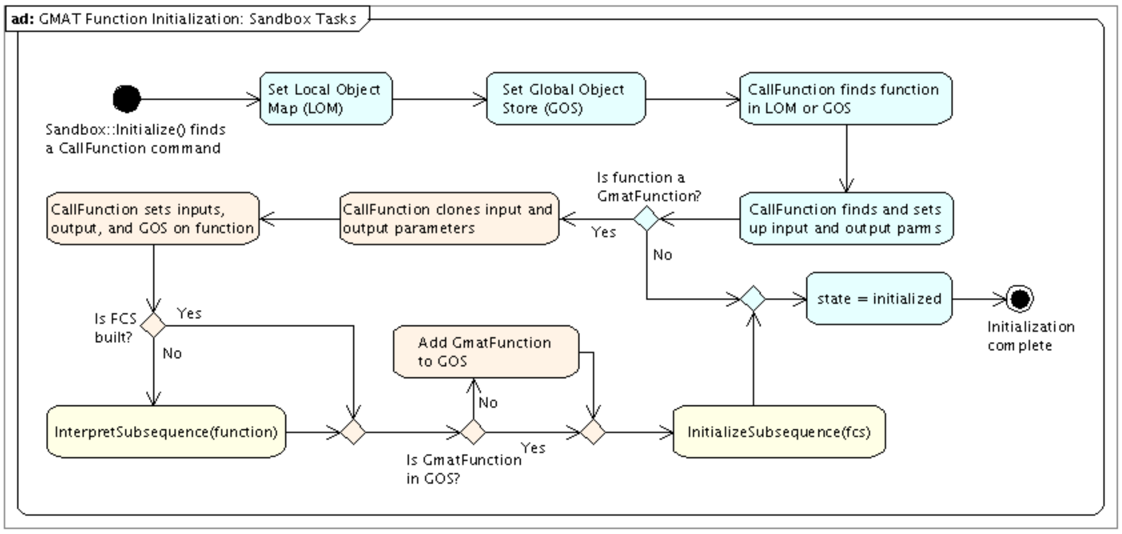
ad: GMAT Function Initialization: Sandbox Tasks
Sandbox::Initialize() finds a CallFunction command
Set Local Object Map (LOM)
Set Global Object Store (GOS)
CallFunction finds function in LOM or GOS
CallFunction finds and sets up input and output parms
Is function a GmatFunction?
Yes
No
CallFunction clones input and output parameters
CallFunction sets inputs, output, and GOS on function
Is FCS built?
Yes
No
InterpretSubsequence(function)
Add GmatFunction to GOS
No
Yes
Is GmatFunction in GOS?
InitializeSubsequence(fcs)
state = initialized
Initialization complete

Figure 31.7: CallFunction Initialization Details. The blue boxes show the path followed for all function types. The orange and yellow blocks are specific to GmatFunctions. The yellow blocks are have additional diagrams explaining how they work.

An overview of Sandbox initialization and execution is provided in Section 3.2.5, with additional details in the chapter describing the Sandbox (Chapter 5). The steps shown in Figure 31.7 illustrate the steps taken to initialize a CallFunction command. This command is used to execute any of the function types supported in GMAT – GMAT functions, MATLAB functions, and internal functions – on a single line. Functions can also be run using the FunctionRunner MathNode when they are called to generate input for inline mathematics. Of the three Function types described here, GMAT functions alone require extensive interactions with the other components of the GMAT engine and Interpreter subsystems. The figure shows an overview of these interactions in the orange and yellow boxes of the activity diagram.

The basic flow through CallFunction and FunctionRunner initialization can be described in the following 5 steps:

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1. The Sandbox passes the Sandbox Object Map and the Global Object Store to the CallFunction or FunctionRunner.
2. The CallFunction or FunctionRunner passes the Global Object Store to the Function Manager.
3. The Sandbox calls the Initialize() method on the CallFunction or FunctionRunner. It locates the Function and the input and output parameters in the Sandbox Object Map or the Global Object Store, and uses these objects to populate the Function Object Store in the FunctionManager.
4. The Sandbox checks to see if the function is a GmatFunction. If so, additional actions, described below, are taken.
5. The CallFunction or FunctionRunner sets its initialized flag to true, completing initialization.

The initialization procedure for GMAT functions includes the construction of the Function Control Sequence for the GmatCommand. Each FunctionManager begins the initialization process by checking to see if the contained function is a GmatFunction. If it is, the FunctionMagnager reports this information to the Sandbox through the containing CallFunction or FunctionRunner, which then retrieves the GmatFunction pointer from the FunctionManager and performs the following actions:

1. The input and output parameter objects are cloned into the FunctionManager.
2. The FunctionManager passes the input and output parameters to the GmatFunction object.
3. The FunctionManager passes the Global Object Store to the GmatFunction object.
4. The Sandbox checks to see if the Function Control Sequence for the GmatFunction has been interpreted. If not, it builds the Function Control Sequence using the Sandbox::InterpretSubsequence() method. The steps taken to build the Function Control Sequence are shown in Figure 31.8 and explained below.
5. If the GmatFunction is not in the Global Object Store, it is added to it.
6. The FunctionManager initializes the Function Control Sequence, following the process shown in Figure 31.10 and described below.

31.2.6.1 Interpreting the Function Control Sequence

GMAT's Interpreter subsystem, described in Chapter 17, is responsible for reading the text files containing GMAT scripting. This responsibility includes the pieces necessary to interpret GMAT function files. The Interpreter base class has a public method,

GmatCommand *InterpretGmatFunction(GmatFunction *function);[13]

designed to access the GmatFunction file and build the associated Function Control Sequence. Each time the Sandbox encounters a CallFunction command during initialization that references a GmatFunction, the Sandbox checks to see if the Function Control Sequence has been built. If the Function Control Sequence needs to be built, the Initialize method calls the Sandbox's InterpretSubsequence() method to build it.

The Sandbox::InterpretSubsequence() method is shown in Figure 31.8. The method starts by building the list of commands comprising the Function Control Sequence. This construnction is done by passing control to the Moderator, which, in turn, passes the build request to an interpreter for processing. The interpreter locates the function file and parses its contents, setting global objects in the Global Object Store as needed and building up the Function Control Sequence. Once the function file has been parsed, the interpreter sets

[13]The current code has a function, GmatCommand* InterpretGmatFunction(const std::string &pathAndName), which is mostly commented out but can be used as a starting point for the function described here. The method described here replaces that method. See Chapter 17 for more details.

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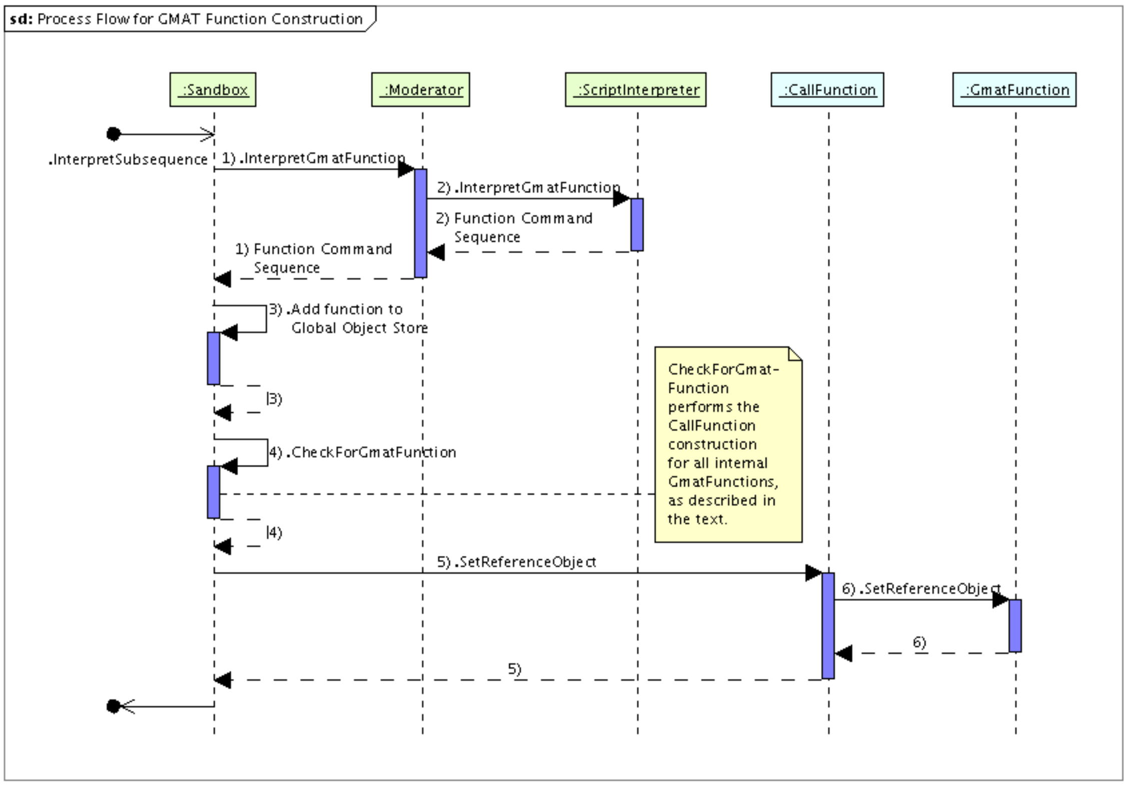
sd: Process Flow for GMAT Function Construction
:Sandbox
:Moderator
:ScriptInterpreter
:CallFunction
:GmatFunction
.InterpretSubsequence
1) .InterpretGmatFunction
2) .InterpretGmatFunction
2) Function Command Sequence
1) Function Command Sequence
3) .Add function to Global Object Store
3)
4) .CheckForGmatFunction
4)
CheckForGmat-Function performs the CallFunction construction for all internal GmatFunctions, as described in the text.
5) .SetReferenceObject
6) .SetReferenceObject
6)
5)

Figure 31.8: Message Flow for Interpreting the Function Control Sequence

the Function Control Sequence pointer on the GmatFunction and returns the head of the sequence, through the Moderator, to the Sandbox.

Once the Function Control Sequence has been built, the InterpretSubsequence() method checks the returned sequence for CallFunction commands and FUnctionRunner nodes. For each CallFunction or FunctionRunner encountered, it checks to see if the object uses a GmatFunction, and if so, if the Function Control Sequence for that GmatFunction has been built. If not, the method sets the needed data structures on the nested object and GmatFunction, and then calls InterpretSubsequence() for the nested function. This process continues until all of the GmatFunctions references in the Function Control Sequence have been built.

These steps are performed to prepare the GmatFunctions for initialization. The initialization steps are described in the next few paragraphs.

31.2.6.2 Initializing the FunctionManager

Figure 31.9, discussed in detail in Section 5.2.2.1, shows the process followed by the Sandbox to initialize a control sequence. This method, Sandbox::InitializeSequence(), provides the core work performed when initializing any control sequence – either a Mission Control Sequence or a Function Control Sequence. As part of the initialization process, the Sandbox method checks each command as it initializes it and performs additional processing on the CallFunction commands and FunctionRunner nodes in the sequence. Each of these objects acts as a container for a FunctionManager object, which performs the actual Function initialization. These details are described here.

FunctionManager objects are used to run the code contained in the classes derived from the Function

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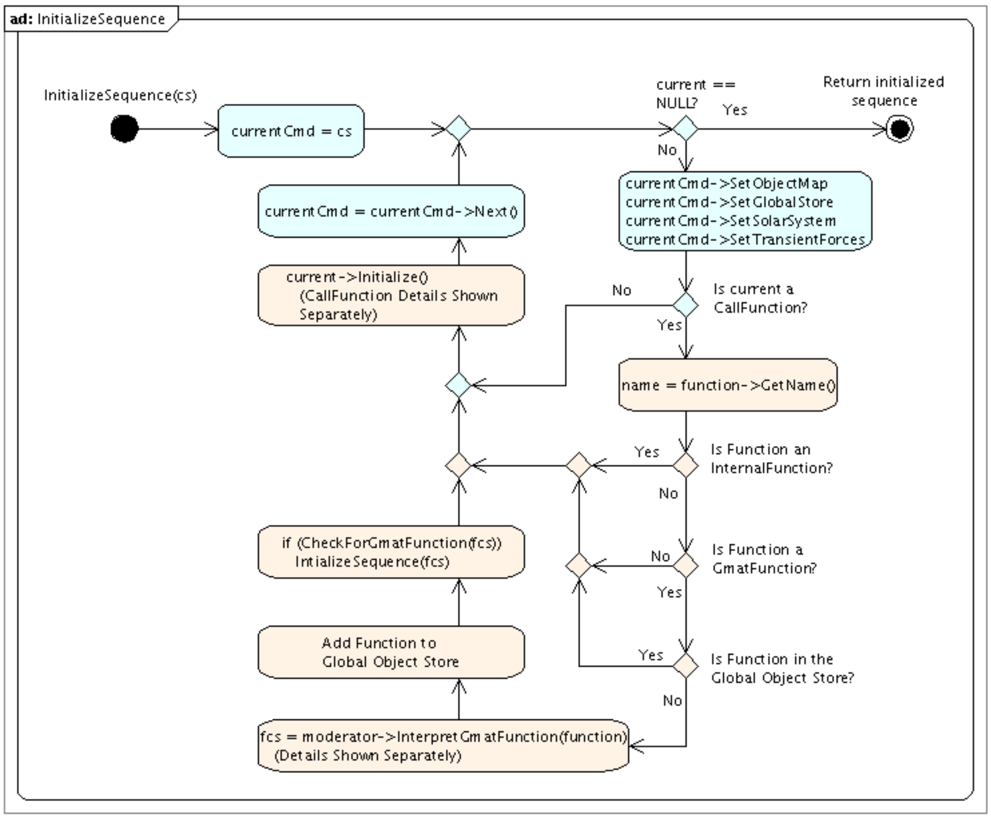
ad: InitializeSequence
InitializeSequence(cs)
currentCmd = cs
current == NULL?
Yes
Return initialized sequence
No
currentCmd->SetObjectMap
currentCmd->SetGlobalStore
currentCmd->SetSolarSystem
currentCmd->SetTransientForces
currentCmd = currentCmd->Next()
current->Initialize() (CallFunction Details Shown Separately)
No
Is current a CallFunction?
Yes
name = function->GetName()
Yes
Is Function an InternalFunction?
No
if (CheckForGmatFunction(fcs)) IntializeSequence(fcs)
No
Is Function a GmatFunction?
Yes
Add Function to Global Object Store
Yes
Is Function in the Global Object Store?
No
fcs = moderator->InterpretGmatFunction(function) (Details Shown Separately)

Figure 31.9: Initialization of a Control Sequence in the Sandbox (Copied from Figure 5.1)

base class. There are three categories of Functions that the FunctionManager manages: internal functions, GMAT functions that run a Function Control Sequence, and functions executed using an external system like MATLAB. The initialization procedure for the FunctionManager object, shown in Figure 31.10, contains branches specific to each of these function types.

The first branch tests to see if the FunctionManager references an internal function. Internal functions are function objects instantiating classes derived from the InternalFunction class. GMAT's internal functions take one or more input and output parameters. The FunctionManager completes initialization of the InternalFunction objects by querying the function object for the name or names of these parameters and setting the references to the associated objects for the InternalFunction instance.

Every function that is not an internal function is either a GMAT function or an external function. The current build of GMAT has only one type of external function, the MatlabFunction. Future builds may extend the external function hierarchy; when that happens, the same considerations as described here for MATLAB functions will apply to the other external function classes. When the Sandbox determines that the function referenced by the FunctionManager is an external function, it immediately moves to the next command in the control sequence because external functions do not require any additional initialization.

The final function type is the most complex of the three categories: the GMAT function. The FunctionManagers that exercise GMAT functions need to build the local object stores for these functions, pass these stores into the functions, and then initialize the function objects, including the contained Function Control Sequences. This process is discussed in the following paragraphs.

Before a GMAT function can be executed, it must set all of the internal object pointers to access existing

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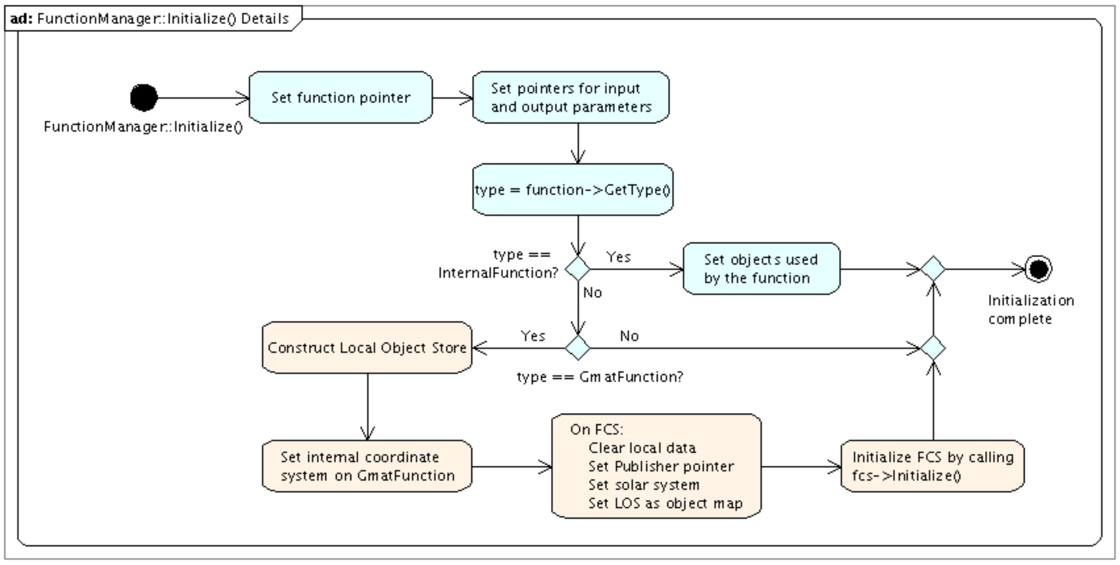
ad: FunctionManager::Initialize() Details
FunctionManager::Initialize()
Set function pointer
Set pointers for input and output parameters
type = function->GetType()
type == InternalFunction?
Yes
No
Set objects used by the function
Initialization complete
Construct Local Object Store
Yes
No
type == GmatFunction?
Set internal coordinate system on GmatFunction
On FCS: Clear local data Set Publisher pointer Set solar system Set LOS as object map
Initialize FCS by calling fcs->Initialize()

Figure 31.10: Message Flow for Initializing in the FunctionManager

objects in the Global Object Store, as parameters in the function call, or locally created. Some of this initialization cannot be performed until the Mission Control Sequence is executing. For that reason, the object pointers used when running the mission are set in the FunctionManager::Execute() method during the run.

During initialization, a preliminary pass is made through each Function Control Sequence to check that all of the objects referenced in the Function Control Sequence have been defined. This ensures that the scripted functions can access objects that they need in order to execute their control sequences. In other words, it checks the necessary condition that the objects must exist, but it does not guarantee that everything needed is of the correct type for successful execution. In particular, objects created using the Create command have their names registered for use, but the objects themselves are not available for validation and use until the Create command is executed during the run. Since these objects are not available, they cannot be validated during initialization. However, since the names are available, GMAT can ensure that an object of the specified name is expected. Initialization capitalizes on this state of the object lists to ensure that all of the needed objects are expected to exist, validating the Function Control Sequences based on these conditions.

The FunctionManager builds the GmatFunction's Function Object Store by populating it with clones of the objects associated with its input and output parameters. The resulting Function Object Store is a mapping between object names and the associated object clones, stored in the FunctionManager member

```
std::map<std::string, GmatBase*> functionStore
```

The Function Object Store mapping is built during initialization and populated with the parameter names and NULL pointers. Once the input and output parameters have filled the Local Object Store, the Sandbox Object Map and Global Object Store are checked for the associated objects, using the following procedure for each input and output parameter:

- The GmatCommand looks for the object in the Function Object Store. If found, then:

    1. The object is cloned.

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2. The pointer to the clone is set as the object reference in the Function Object Store.

- If a parameter is not found in the Function Object Store, the GmatCommand looks for the object in the Global Object Store. If it is found there[14]:

  1. If the Global Object Store reference is not NULL, the object is cloned and the pointer to the clone is set as the object reference in the Function Object Store.

  2. If the Global Object Store pointer is NULL, the Function Object Store pointer is left pointing to NULL as well. The object clone will be made in the FunctionManager during execution.

- If the object is not in either the Function Object Store or the Global Object Store, the object has not been defined, and an exception is thrown identifying the missing object.

Once the Function Object Store is built, the FunctionManager sends all of the necessary object pointers to the GmatFunction. This process starts by passing the internal coordinate system pointer to the function. This is followed by pointers to the Publisher, Solar System, and Function Object Store. The GmatFunction clears the object references in the Function Control Sequence, and then passes these object pointers to the control sequence. Finally, the FunctionManager initializes the Function Control Sequence, completing the initialization process.

One final note on initialization is needed. The process performed here is iterative in nature. That means that FunctionManager objects contained inside of a Function Control Sequence are initialized using these same steps, and Function calls inside of GmatFunctions in those calls also follow this process, and so on until all of the GmatFunctions used in the Mission Control Sequence have been initialized. After a GmatFunction has been initialized once, it is not reinitialized by another FunctionManager. The function initialization operates on the assumption that if the function has been initialized once, then it is ready for use during a mission run. This initialization termination is necessary to prevent iterative calls of a function on itself from recursing forever.

[14]The treatment of global objects when used as input or output parameters to GmatFunction objects may need to be modified once we have a working implementation. The current design calls for all input and output parameters to be passed into the functions as clones. That means that the global objects, when passed into a function as an input or output parameter, is not modified inside of that function.

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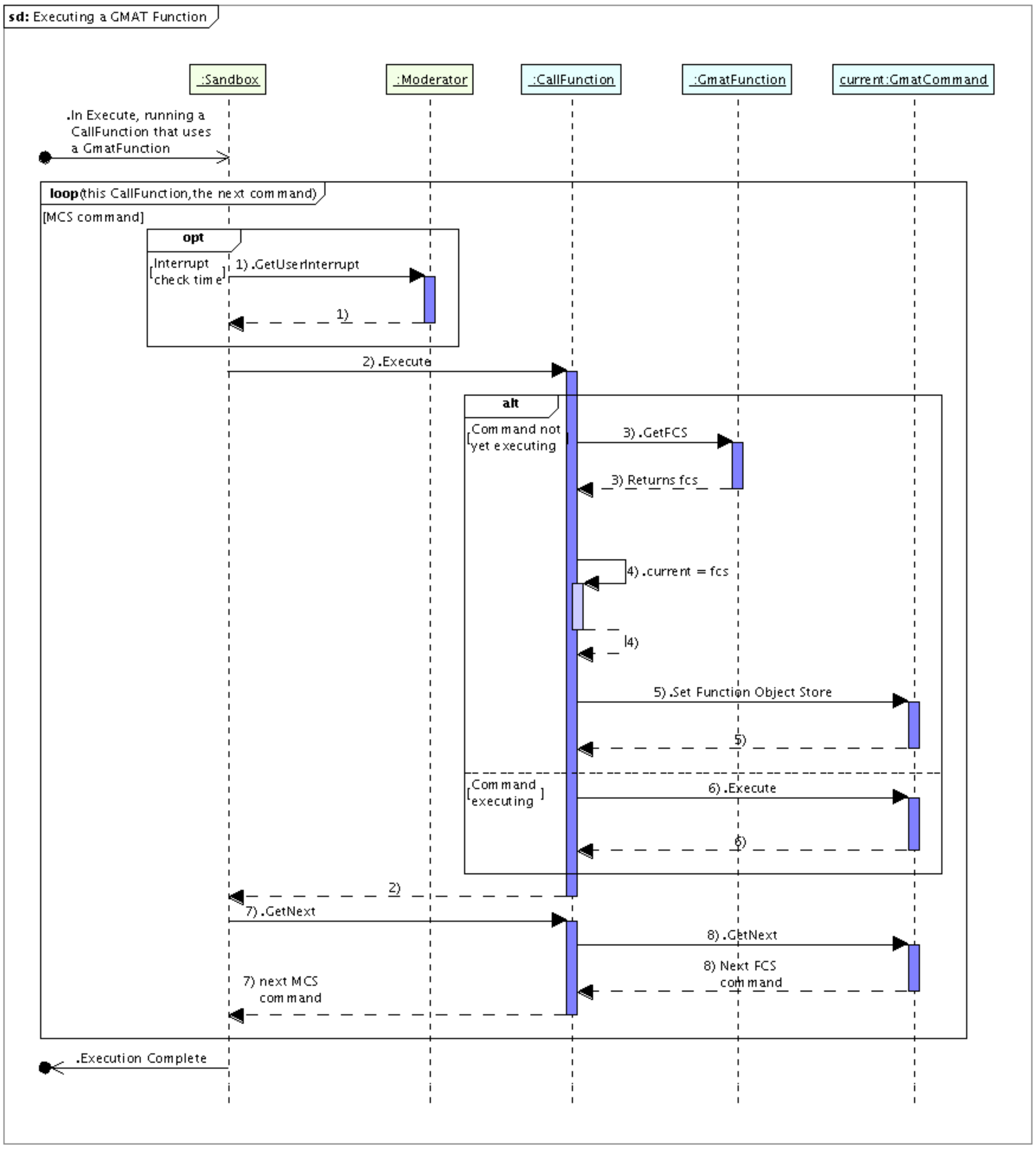

Figure 31.11: The Sequence Followed to Run a GmatFunction Command

31.2.6.3 Executing a GMAT Function

At the end of initialization, all of the objects used in the function that can be preset are set and ready for use. Pointers to objects that are obtained from the Global Object Store might not be set yet, depending on their status at initialization time. Locally created objects are not yet set; they are set when the corresponding Create command is executed. Details about setting these final pointers are provided in the discussions of

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the Create and Global commands, Sections 31.5.2 and 31.5.3, respectively.

Execution for the Function Control Sequence, shown in Figure 31.11 is very similar to execution of the Mission Control Sequence in the Sandbox. The process starts when the Mission Control Sequence prepares to execute a CallFunction or FunctionRunner that uses a GmatFunction. The Sandbox checks first to see if a user interrupt has occurred, following the process common to all commands as described in Section 5.2.3. Once this initial check has been performed, GMAT is ready to prepare and execute the function.

Execution of a Function Control Sequence can be broken into two distinct pieces: the final piece of initialization and the actual execution of the Function Control Sequence. These processes are managed in the Sandbox through repeated calls to the CallFunction's Execute() method, or the the Assignment command's Execute() method for FunctionRunner nodes. The process for the CallFunction calls differs in detail from that for a FunctionRunner, and will be described first here. FunctionRunner details are similar, and will be summarized following this discussion.

CallFunction Details For a CallFunction, each call to Execute() causes the CallFunction to run a portion of the process needed to execute the function, as is described below, and then returns control to the Sandbox so that it can perform interrupt processing. The Sandbox then calls the CallFunction's GetNext() method to determine the next command that needs to execute. The CallFunction returns its pointer as long as the Function Control Sequence is initializing or executing. Once the function has completed its task, the CallCunction clears its commandExecuting flag and returns the pointer to the next command in its control sequence, completing the function execution.

When Execute() is called for a CallFunction that is not already running a Function Control Sequence, the CallFunction accesses the GmatFunction that contains the Function Control Sequence and retrieves the head of that control sequence. That node is stored in the CallFunction's FunctionManager's internal data and used to set the pointer to the current command for the Function Control Sequence. The CallFunction then finalizes initialization of the Function Object Store by setting the input and output parameter pointers for the current function call. This object store is then sent to the commands in the Function Control Sequence, those commands finalize their initialization, and, if everything is constructed successfully, the function is ready for execution. If an error is encountered during this process, an exception is thrown reporting the error and execution terminates. The CallFunction handles the thrown exception, adds its own information to the error message so that the user can see information about both the error thrown in the function and information about the CallFunction that encountered the error, and then throws the resulting exception in turn for handling in the GMAT engine.

Once these steps have been performed, the CallFunction is ready to run the Function Control Sequence. All of the linkages and cloning necessary for execution have been performed. Running the Function Control Sequence follows the same process as is followed when running a branch inside of a BranchCommand. The Sandbox calls the Execute() method on the CallFunction, which calls Execute on the FunctionManager. The FunctionManager calls the Execute() method on the current command in the Function Command Sequence. That command runs, and returns control to the FunctionManager, which returns control to the CallFunction in turn. The CallFunction then returns control to the Sandbox. The Sandbox then calls GetNext() on the CallFunction. The CallFunction uses the FunctionManager to call GetNext() on the current command in the Function Control Sequence. That call returns with either a pointer to the next command in the Function Control Sequence, a pointer to itself, or a NULL pointer. In either of the former two cases, the Function Control Sequence has not completed execution, so the FunctionManager reports a valid next pointer, and the CallFunction returns a pointer to itself to the Sandbox. If the current Function Control Sequence command returns NULL, the FunctionManager reports this value to the CallFunction, informing it that the Function Control Sequence has completed execution. The CallFunction has finished running the Function Control Sequence, so it clears its commandExecuting flag, and returns its next pointer to the Sandbox so that the Sandbox can run the next command in the Function Control Sequence.

The process followed to execute nested GmatFunctions proceeds identically to that described above, except that the CallFunction containing the Function Control Sequence that has the nested CallFunction plays the role of the Sandbox in the description above. The Execute() method on the outer CallFunction walks

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the inner CallFunction through the function initialization and execution following an identical procedure to that described above.

FunctionRunner Differences The key difference in this process for a FunctionRunner node is in the handling of interrupt processing. FunctionRunner nodes are part of a larger mathematical expression in a MathTree. This makes interrupt processing impractical for functions called through a FunctionRunner. Instead, the FunctionRunner runs the Function Control Sequence until it has completed execution, and then obtains the return value from the function using the Evaluate() or MatrixEvaluate() method on the FunctionManager to retrieve the results for the calculation.

31.2.7 Usage and Modification

GMAT Functions behave similarly to the Sandbox. You are not likely to need to make changes to the implementation of the GmatFunction class structure unless you are making similar changes to the Sandbox itself. Similarly, you are not likely to need to do anything special to use the GmatFunction class. All of the interfaces from the class are provided through the CallFunction command.

31.3 MATLAB Functions

31.3.1 Design

31.3.2 Usage and Modification

31.4 Internal Functions

The specifications for internal functions is TBD.

31.4.1 Design

31.4.2 Usage and Modification

31.5 Related Classes: Command Classes

31.5.1 Design for the CallFunction Command

31.5.2 Design for the Create Command

31.5.3 Design for the Global Command

31.6 Related Classes: Engine Components

The function classes interact with engine components in some very specific ways, as are described in Sections 31.2.6, 31.4.2, and 31.3.2. The Sandbox features specific to functions are described in Chapter 5. The features added to the Interpreters and the Moderator can be found in their Chapters 17 and 4, respectively.

<These chapters are yet to be filled in. I'll post their updates when they are ready.>

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Chapter 32

Adding New Objects to GMAT

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Thinking Systems, Inc.

Chapter 11 provided an introduction to the GMAT Factory subsystem. This feature of the GMAT design provides an interface that users can use to extend GMAT without impacting the core, configuration managed, code base. Any of the scriptable object types in the system can be extended using this feature; this set of objects includes hardware elements, spacecraft, commands, calculated parameters, and any other named GMAT objects. This chapter provides an introduction to that interface into the system.

32.1 Shared Libraries

32.2 Adding Classes to GMAT

32.2.1 Designing Your Class

This is a list of steps taken to construct the steepest descent solver.

- Create the class (.cpp and header, comment prologs, etc.).
- Add shells for the abstract methods.
- Fill in code for the shells.
- Add the object file to the list of objects in the (base) makefile.
- Unit test if possible.
- Build the code and debug what can be accessed at this point.

32.2.2 Creating the Factory

This is a list of steps taken to incorporate the steepest descent solver.

- Create the factory (in this case I edited SolverFactory).
- Add constructor call to the appropriate "Create..." method.
- Add the new object type name to the "creatables" lists in the factory constructors.
- Build and fix any compile issues.
- Test to see if the object can be created from a script.

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32.2.3 Bundling the Code

32.2.4 Registering with GMAT

32.3 An Extensive Example

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Part IV

Appendices

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Appendix A

Unified Modeling Language (UML) Diagram Notation

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This appendix presents an overview of the Unified Modeling Language diagrams used throughout the text, including mention of non-standard notations in the presentation. A more thorough presentation is given in [fowler].

The presentation made here uses UML to sketch out how GMAT implements specific components of the architecture. What that means is that the UML diagrams in the text do not necessarily present the full implementation details for a given system component.

All of the UML diagrams in this document were drawn using Poseidon for UML, Professional edition [poseidon]. The compressed UML files for these diagrams are configuration managed in a repository at Thinking Systems' home office.

A.1 Package Diagrams

Package diagrams are used to present an overview of a collection of objects, ranging from the top level parts of an entire system to subelements of subsystems. Figure A.1 shows an example of a package diagram. In this figure, four primary GMAT system subsystems are shown: the Executive subsystem, the Interfaces, the Factory subsystem, and the model elements.

Each box on the diagram represents a group of one or more classes that perform a task being discussed. Package diagrams may include both package boxes and class boxes. The packages are represented by a box with a tab on the upper left corner; classes are represented by boxes which may be subdivided into three regions, as described in the Class Diagram section. Packages can be further divided into constituent elements, either subpackages within a given package, or classes in the package. For example, in the figure, the interface package consists of an External Interface package and a User Interface package. The User Interface package is further broken into three classes: the Interpreter base class and the ScriptInterpreter and GuiInterpreter derived classes.

Sometimes important interactions are included in the Package diagram. When this happens, the interaction is drawn as a dashed arrow connecting two elements on the diagram, and the nature of the interaction is labeled. In the example, the relationship between the Factory package and the Model Element package is included: Factories are used to construct model elements.

In this document, package diagrams are used to communicate design structure. The packages shown in the figures do not explicitly specify namespaces used in the GMAT code, even though UML does allow

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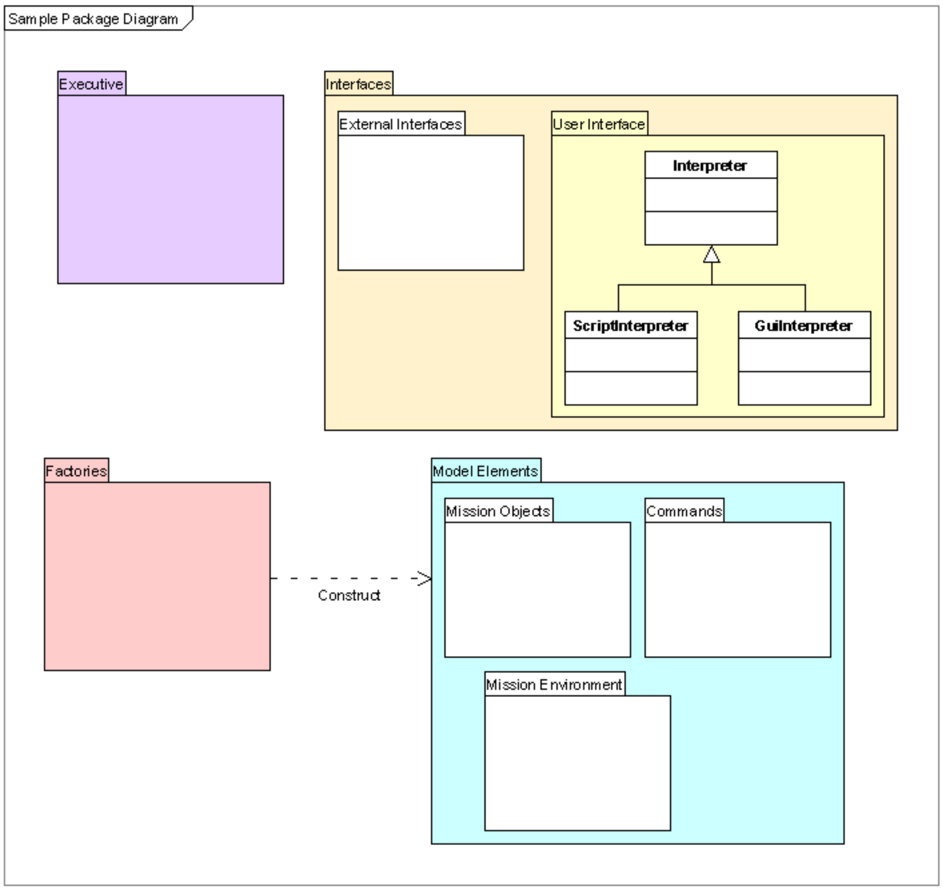

Figure A.1: GMAT Packaging, Showing Some Subpackaging

that use for package diagrams. When a package documented here has implications for a namespace used in GMAT, that implication will be explicitly presented in the accompanying text.

A.2 Class Diagrams

Figure A.2 shows a typical class diagram for this document. This figure is an early version of the class diagram for the solver subsystem. The classes directly used in that subsystem are colored differently from the related base classes – in this figure, the Solver classes have a yellow background, while the base classes are blue. Each box on the diagram denotes a separate class; in this example, the classes are GmatBase, Solver, Optimizer, SteepestDescent, SequentialQuadratic, DifferentialCorrector, Factory, and SolverFactory. Abstract classes are denoted by italicizing the class name; here the classes GmatBase, Solver, Optimizer, and Factory are all abstract because they contain pure virtual methods.

The box representing the class is broken into three pieces. The top section indicates the name of the class. The center section lists the attributes (i.e. data members) of the class, and the bottom section stores the operations (aka methods) available for the class. Attributes and operations are prefaced by a symbol indicating the accessibility of the class member; a '+' prefix indicates that the member is publicly accessible, '#' indicates protected access, and '-' indicates private access. Static members of the classes are underlined,

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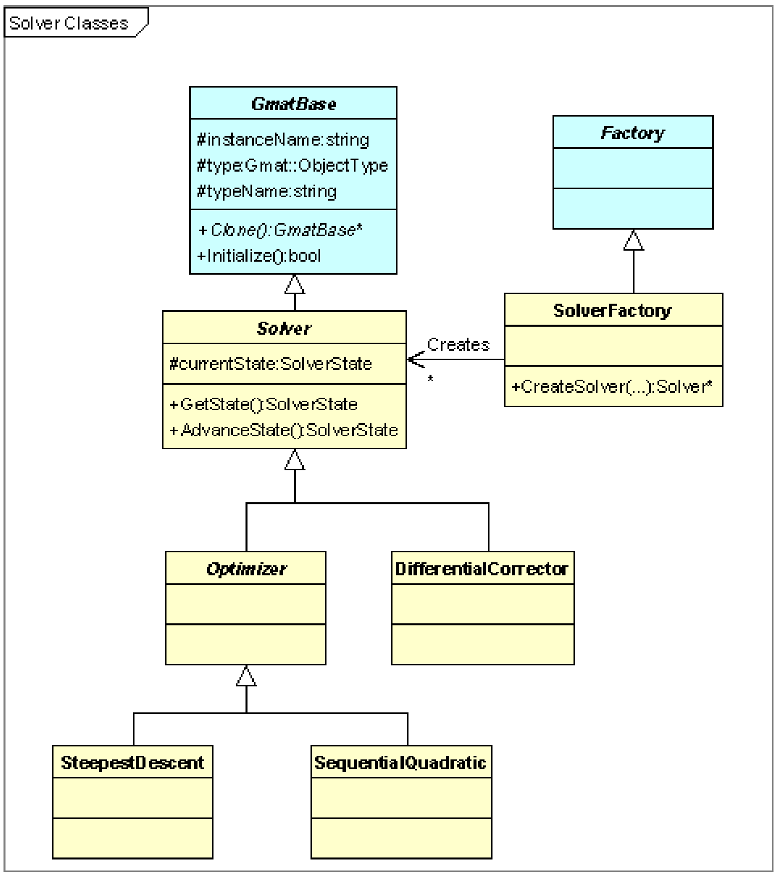

Figure A.2: Solver Classes

and singleton classes receive a <<Singleton>> designation above the class name.

The class diagrams included in this document suppress the argument list for the methods. This is done for brevity's sake; the model files include the argument lists, as does the code itself, of course. When a method requires arguments, that requirement is indicated by ellipses on the diagram.

Classes are connected to one another using lines with arrows. If the arrowhead for the line is a three-sided triangle, the line indicates inheritance, with the line pointing from the derived class to its base. For example, in the figure, SolverFactory is derived from the Factory base class. SolverFactory is not abstract, and can be instantiated, but Factory is an abstract class as represented in this figure (the class name is italicized), even though the figure does not explicitly provide a reason for the class to be abstract.

Lines terminated by an open arrowhead, like the line connecting SolverFactory to the Solver base class, indicates an association. The arrow points in the direction that the association is applied – in this case, the SolverFactory creates instances of Solvers. The decorations at the ends of these lines indicates multiplicity. An asterisk indicates 0 or more, so for this example, a SolverFactory can create 0 or more Solvers, depending on the needs of the program during execution.

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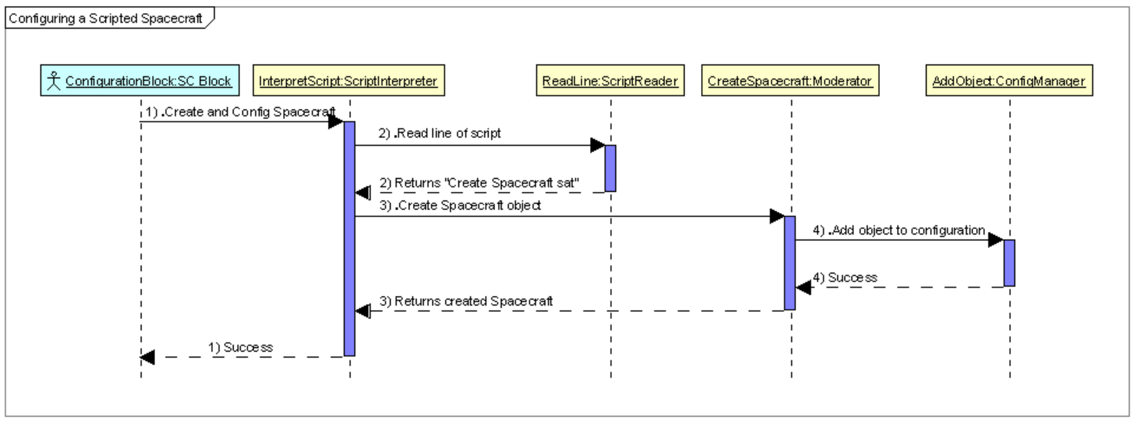
Configuring a Scripted Spacecraft
ConfigurationBlock:SC Block
InterpretScript:ScriptInterpreter
ReadLine:ScriptReader
CreateSpacecraft:Moderator
AddObject:ConfigManager
1) .Create and Config Spacecraft
2) .Read line of script
2) Returns "Create Spacecraft sat"
3) .Create Spacecraft object
4) .Add object to configuration
4) Success
3) Returns created Spacecraft
1) Success

Figure A.3: A Sequence Diagram

A.3 Sequence Diagrams

Sequence Diagrams are used to indicate the sequence of events followed when performing a task. The task shown in Figure A.3 is the creation of an instance of the Spacecraft class from the ScriptInterpreter. Sequence diagrams are used in this document to illustrate a time ordered sequence of interactions taken in the GMAT code. In this example, the interactions between the ScriptInterpreter and the other elements of GMAT are shown when a "Create Spacecraft..." line of script is parsed to create a Spacecraft object.

Each of the players in the illustrated action receive a separate timeline on the figure, referred to as a “lifeline”. Time flows from top to bottom. The player is described in the label at the top of the lifeline. In the example shown here, each player is a method call on a core GMAT object – for example, the line labeled CreateSpacecraft:Moderator represents the Moderator::CreateSpacecraft(...) method. Sequence diagrams in this document can also use lifelines to for larger entities – for instance, the sequence diagram that illustrates the interaction between the GUI, ConfigManager, Moderator, Sandbox, and mission components when a mission is run, Figure 3.16. The vertical blocks on each lifeline indicate the periods in which the lifeline is active, either because it is being executed, or because it is waiting for a called method to return.

Blocks are nested to indicate when a function is called inside of another. In the example, the ConfigManager::AddObject(...) call is nested inside of the Moderator::CreateSpacecraft(...) call because that inner call is performed before control returns from the Moderator function. Arrows from one lifeline to another are used to indicate the action that is being performed – in the example, line 4 shows when the newly created Spacecraft is handed to the Config manager. (Note that this is a bit more verbose than in the UML standard; the standard is to just list the method that is called, while I prefer to give a bit more description of the invoked operation.)

Iteration can be indicated on these diagrams by enclosing the iterated piece in a comment frame. Similarly, recursion is indicated by a control line that loops back to the calling timeline. When this type of action occurs, a note is also included on the figure to indicate how the recursion or self reference gets resolved; an example can be seen in Figure 30.6. (These notes are called "Interaction Frames" in the UML documentation.)

A.4 Activity Diagrams

Activity Diagrams are used to illustrate the work flow for a given task, particularly when the steps taken in the task can occur in parallel, and when the order of these steps is not necessarily fixed. An example of this type of diagram is shown in Figure A.4. This diagram, which is a subset of the activity diagram shown in

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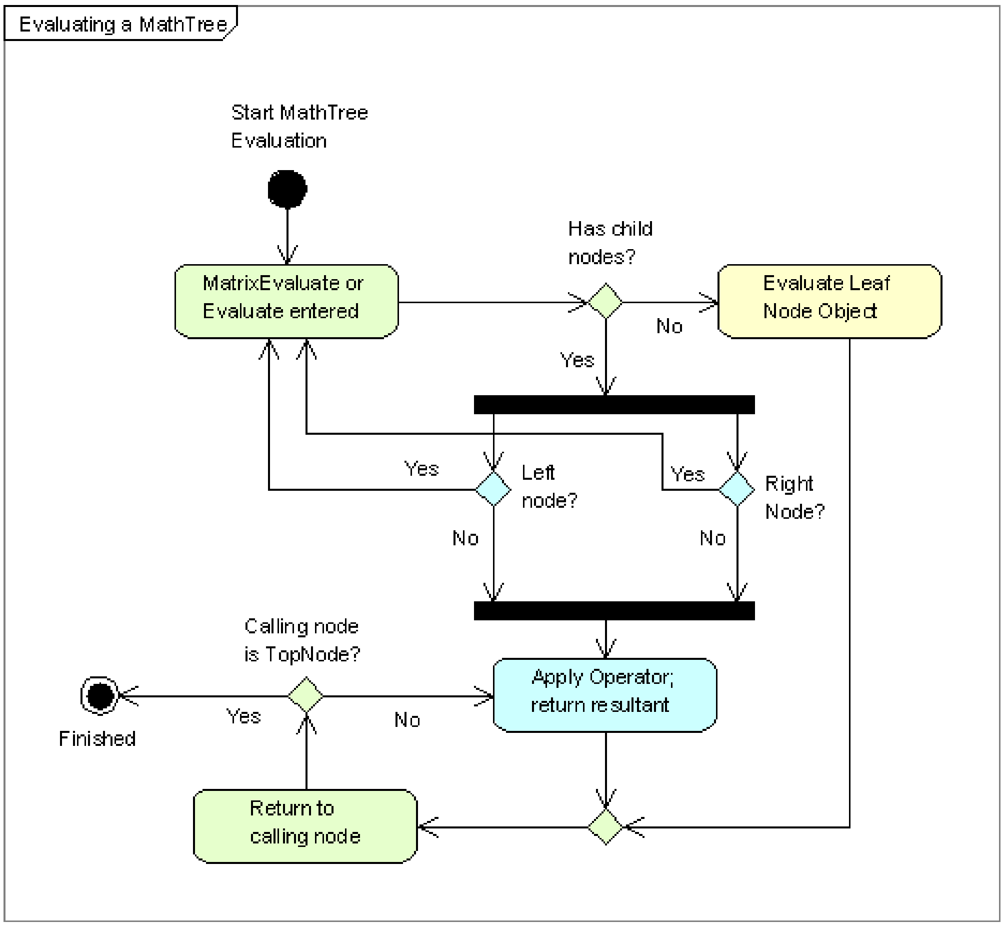

Figure A.4: An Activity Diagram

Figure 30.8, shows the actions that occur when an equation is evaluated in a MathTree object.

Action starts at the black circle, in this case in the upper left of the figure, and follows the arrows through the blocks on the figure, terminating when it reaches the other circular marker, a filled circle with a concentric circle around it. Each rounded block in the diagram represents a step in the task, referred to as an activity in the UML documentation. These blocks include text indicating the activity to be accomplished.

Diamond shaped markers are used to indicate splits in the control flow through the diagram. There are two types markers used for this purpose: branches, which have a single input with multiple exits, and merges, which bring together multiple paths to a single output. Text labels are placed on the branch markers indicating the test that is performed for the branching. Labels on each branch indicate which path is followed based on the test. For example, in the figure, the branch point labeled “Has child nodes?” proceeds downwards if the current node has child nodes, and to the right if the current node does not have child nodes.

Activity diagrams also have fork nodes, which are displayed as heavy, black horizontal line segments. Fork nodes are used to split the work flow into parallel paths that are all executed. The example in the figure shows the evaluation of the subnodes nodes of a MathNode object. Each MathNode operator can have a left subnode and a right subnode. These subnodes must be evaluated before the operator can execute, but

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it does not matter which subnode is evaluated first, as long as the results of both are available when the operator is applied. The diagram indicates this behavior by forking the process into parallel paths, and then showing the process logic for each of these paths. When both lines of execution complete, the work flow comes back together into a single execution path. This merging of the control paths is shown by a second heavy black line segment, called a Join Node in the UML specifications.

A.5 State Diagrams

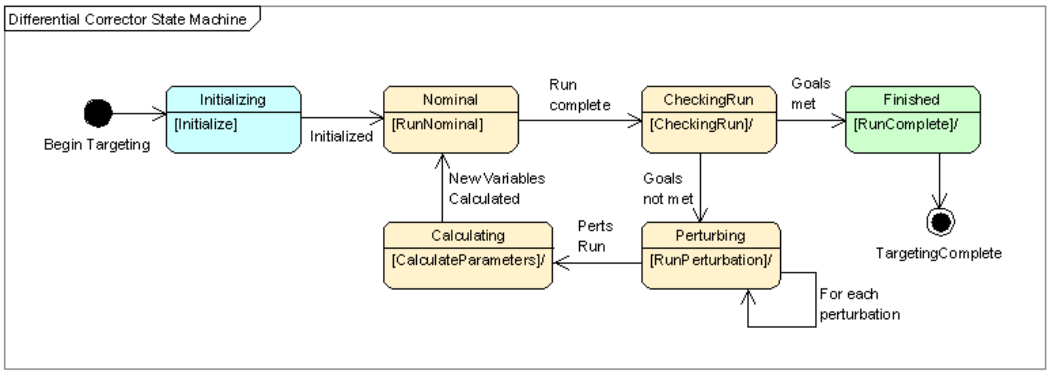

Figure A.5: A State Diagram

State diagrams are similar in format to activity diagrams. The start and end nodes are marked the same way as in an activity diagram, and the program flow is shown using similar transition arrows. The differences lie in the objects represented by the diagram, and interpretation of the figure. Activity diagrams are used to illustrate the interactions amongst various objects that collectively perform a task. State diagrams are used to model how a specific component evolves over time.

In this model of the component being described, that component is always modeled as being in a specific system state, and transitioning from that state to another state based on changes in the system. The Solvers in GMAT are implemented explicitly as finite state machines, so they provide a prime example for this type of diagram; the finite state machine for a differential corrector object is shown in Figure A.5.

Each block in a state diagram represents one of the states available for the object. These blocks are divided into two sections. The upper portion of the block provides a label for the state. The lower portion of the block provides information about the process executed within that block – in this case, the method called on the object – and may also provide information about the outcome of that process. For the differential corrector shown here, the states are Initializing, Nominal, CheckingRun, Perturbing, Calculating, and Finished. Each of these states includes the descriptor for the function called when the state machine is executed.

The arrows connecting the blocks in this figure show the allowed state transitions. Each arrow is labeled with the check that is made to ensure that it is time to make the corresponding transition.

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Appendix B

Design Patterms Used in GMAT

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The GMAT design was influenced by many different sources: prior experience with Swingby, Navigator, FreeFlyer, and Astrogator, exposure to analysis and operational systems for Indostar, Clementine, WIND, ACE, and SOHO, and design experiences on other software projects. Part of the theoretical background for the GMAT design comes from exposure to the object oriented design community, captured in the writings of Scott Meyers, Herb Sutter, Bruce Eckel, Martin Fowler, and the Gang of Four[GoF].

This latter reference provides a framework for describing recurrent patterns in software systems. Patterns that are used by reference in this document are summarized here for completeness; avid readers will also want to read the Gang of Four text or a similar book derived from it.

B.1 The Singleton Pattern

B.1.1 Motivation

Some of the components of GMAT require implementation such that one and only one instance of the component exist. Examples of these components are the Moderator, the ScriptInterpreter, the Publisher, the ConfigurationManager, and the FactoryManager. These objects are implemented using the Singleton design pattern.

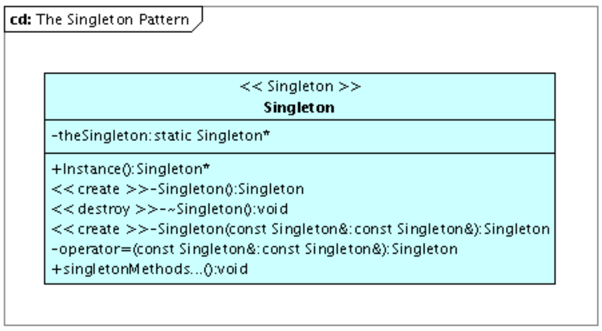
cd: The Singleton Pattern
<< Singleton >>
Singleton
-theSingleton:static Singleton*
+Instance():Singleton*
<< create >>-Singleton():Singleton
<< destroy >>-~Singleton():void
<< create >>-Singleton(const Singleton&:const Singleton&):Singleton
-operator=(const Singleton&:const Singleton&):Singleton
+singletonMethods...():void

Figure B.1: Structure of a Singleton

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B.1.2 Implementation

Figure B.1 shows the key elements of a singleton. The class is defined so that there is only one possible instance during the program's execution. This instance is embodied in a private static pointer to a class instance; in the figure, this pointer is the "theSingleton" member. This pointer is initialized to NULL, and set the first time the singleton is accessed.

The class constructor, copy constructor, assignment operator, and destructor are all private in scope. The copy constructor and assignment operator are often declared but not implemented, since they cannot be used in practice for singleton objects. All access to the Singleton is made through the Instance() method.

The first time Instance() is called, the pointer to the singleton is constructed. Subsequent calls to Instance() simply return the static pointer that was set on the first call. A sample implementation of the Instance() method is shown here:

```
Singleton* Instance()
{
   if (theSingleton == NULL)
      theSingleton = new Singleton();
   return theSingleton;
}
```

B.1.3 Notes

In GMAT, the Singletons are all terminal nodes in the class hierarchy. Some designs allow subclassing of Singletons so that the final singleton type can be selected at run time. GMAT does not subclass its singletons at this time.

B.2 The Factory Pattern

B.2.1 Motivation

The Factory design pattern – sometimes called the Factory Method, defines an interface for creating objects, and uses that interface in subclasses to create objects os specific types. GMAT uses this pattern for user created objects. The Factory base class specifies the creation interfaces into GMAT's factories. Derived factory classes override the interfaces specific to the type of factory that is being implemented.

B.2.2 Implementation

The factory classes as implemented in GMAT are discussed, with sample code, in Section 11.1. Please refer to that section for implementation details.

B.3 The Observer Pattern

B.4 The Mediator Pattern

B.4.1 Motivation

The Mediator design pattern centralizes the communications between objects into a single component. This consolidation of the communications simplifies the interfaces that the mediator's clients need to support, and helps decouple the objects from one another. Additionally, the interfaces can be made more consistent by keeping the Mediator interfaces consistent.

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B.4.2 Implementation

GMAT uses the Mediator pattern in the engine code. The Moderator is the mediator for GMAT's engine. Details of the implementation for the Moderator are in Chapter 4.

B.4.3 Notes

The colmmon terminology in the literature refers to the mediator as the core class for the Mediator pattern, and calls the classes that are mediated "Colleagues." For the GMAT engine, the Mediator is the Moderator, and the Colleagues are the Factory Manager, the Configuration Manager, and the Sandboxes.

B.5 The Adapter Pattern

GMAT uses adapters to simplify invocation of calculations on different types of objects, making the interface identical even though the underlying classes are quite different. One example of the use of adapters in GMAT is the ElementWrapper classes used by the command subsystem. Many of the commands in GMAT need a source of Real data in order to function correctly. This data can be supplied as a number, an object property, a GMAT Parameter, an Array element, or any other source of Real data in the system. ElementWrappers encapsulate the disparate interfaces to these objects so that the commands can use a single call to obtain the Real data, regardless of the underlying object.

B.6 The Model-View-Controller (MVC) Pattern

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Appendix C

Command Implementation: Sample Code

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The wrapper classes described in Chapter 26 encapsulate the data used by commands that need information at the single data element level, giving several disparate types a common interface used during operation in the GMAT Sandbox. This appendix provides sample code for the usage of these wrappers, starting with sample setup code, and proceeding through initialization, execution, and finalization. The Vary command, used by the Solvers, is used to demonstrate these steps.

C.1 Sample Usage: The Maneuver Command

Maneuver commands are used to apply impulsive velocity changes to a spacecraft. They take the form

```
Maneuver burn1(sat1)
```

where burn1 is an ImpulsiveBurn object specifying the components of the velocity change and sat1 is the spacecraft that receives the velocity change. The Maneuver command overrides InterpretAction using the following code:

```
//------------------------------------------------------------------------------
//  bool InterpretAction()
//------------------------------------------------------------------------------
/**
 * Parses the command string and builds the corresponding command structures.
 *
 * The Maneuver command has the following syntax:
 *
 *     Maneuver burn1(sat1);
 *
 * where burn1 is an ImpulsiveBurn used to perform the maneuver, and sat1 is the
 * name of the spacecraft that is maneuvered.  This method breaks the script
 * line into the corresponding pieces, and stores the name of the ImpulsiveBurn
 * and the Spacecraft so they can be set to point to the correct objects during
 * initialization.
```

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```
 */
//------------------------------------------------------------------------------
bool Maneuver::InterpretAction()
{
   StringArray chunks = InterpretPreface();

   // Find and set the burn object name ...
   StringArray currentChunks = parser.Decompose(chunks[1], "()", false);
   SetStringParameter(burnNameID, currentChunks[0]);

   // ... and the spacecraft that is maneuvered
   currentChunks = parser.SeparateBrackets(currentChunks[1], "()", ", ");
   SetStringParameter(satNameID, currentChunks[0]);

   return true;
}
```

The maneuver command works with GMAT objects – specifically ImpulsiveBurn objects and Spacecraft – but does not require the usage of the data wrapper classes. The next example, the Vary command, demonstrates usage of the data wrapper classes to set numeric values.

C.2 Sample Usage: The Vary Command

The Vary command has a much more complicated syntax than does the Maneuver command. Vary commands take the form

```
Vary myDC(Burn1.V = 0.5, {Pert = 0.0001, MaxStep = 0.05, Lower = 0.0, ...
    Upper = 3.14159, AdditiveScaleFactor = 1.5, MultiplicativeScaleFactor = 0.5);
```

The resulting InterpretAction method is a bit more complicated:

```
//------------------------------------------------------------------------------
//  void Vary::InterpretAction()
//------------------------------------------------------------------------------
/**
 * Parses the command string and builds the corresponding command structures.
 *
 * The Vary command has the following syntax:
 *
 *     Vary myDC(Burn1.V = 0.5, {Pert = 0.0001, MaxStep = 0.05, ...
 *               Lower = 0.0, Upper = 3.14159);
 *
 * where
 *
 * 1. myDC is a Solver used to Vary a set of variables to achieve the
 * corresponding goals,
 * 2. Burn1.V is the parameter that is varied, and
 * 3. The settings in the braces specify features about how the variable can
 * be changed.
 *
 * This method breaks the script line into the corresponding pieces, and stores
 * the name of the Solver so it can be set to point to the correct object
```

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```
 * during initialization.
 */
//------------------------------------------------------------------------------
bool Vary::InterpretAction()
{
   // Clean out any old data
   wrapperObjectNames.clear();
   ClearWrappers();

   StringArray chunks = InterpretPreface();

   // Find and set solver object name --the only setting in Vary not in a wrapper
   StringArray currentChunks = parser.Decompose(chunks[1], "()", false);
   SetStringParameter(SOLVER_NAME, currentChunks[0]);

   // The remaining text in the instruction is the variable definition and
   // parameters, all contained in currentChunks[1].  Deal with those next.
   currentChunks = parser.SeparateBrackets(currentChunks[1], "()", ", ");

   // First chunk is the variable and initial value
   std::string lhs, rhs;
   if (!SeparateEquals(currentChunks[0], lhs, rhs))
      // Variable takes default initial value
      rhs = "0.0";

   variableName = lhs;
   variableId = -1;

   variableValueString = rhs;
   initialValueName = rhs;

   // Now deal with the settable parameters
   currentChunks = parser.SeparateBrackets(currentChunks[1], "{}", ", ");

   for (StringArray::iterator i = currentChunks.begin();
        i != currentChunks.end(); ++i)
   {
      SeparateEquals(*i, lhs, rhs);
      if (IsSettable(lhs))
         SetStringParameter(lhs, rhs);
      else
         throw CommandException("Setting \"" + lhs +
            "\" is missing a value required for a " + typeName +
            " command.\nSee the line \"" + generatingString +"\"\n");
   }

   MessageInterface::ShowMessage("InterpretAction succeeded!\n");
   return true;
}
```

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Appendix D

GMAT Software Development Tools

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GMAT is a cross-platform mission analysis tool under development at Goddard Space Flight Center and Thinking Systems, Inc. The tool is being developed using open source principles, with initial implementations provided that run on 32-bit Windows XP, Linux, and the Macintosh (OS X). This appendix describes the build environment used by the development team on each of these platforms.

The GMAT code is written using ANSI-standard C++, with a user interface developed using the wxWindows toolkit available from http://www.wxwidgets.org. Any compiler supporting these standards should work with the GMAT code base. The purpose of this document is to describe the tools that were actually used in the development process.

Source code control is maintained using the Concurrent Versions System (CVS 1.11) running on a server at Goddard. Issues, bugs, and enhancements are tracked using Bugzilla 2.20 running on a server at Goddard.

D.1 Windows Build Environment

- Compiler: gcc version 3.4.2 (mingw special)
- IDE Tool: Eclipse 3.1.1, with CDT 3.0.1 plug-in
- wxWindows Version: wxMSW 2.6.2

On Windows, GMAT has also been built using the Dev-C++ environment.

D.2 Macintosh Build Environment

- Compiler: gcc 4.0.1, XCode v. 2.2
- IDE Tool: Eclipse 3.1.2, with CDT 3.0.1 plug-in
- wxWindows Version: wxMac 2.6.2

D.3 Linux Build Environment

GMAT is regularly built on two different Linux machines at Thinking Systems, one running Mandriva Linux, and the second running Ubuntu Linux. Both build environments are listed here.

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On Mandriva 2006

- Compiler: gcc version 4.0.1 (4.0.1-5mdk for Mandriva Linux release 2006.0)
- IDE Tool: Eclipse 3.1.1, with CDT 3.0.1 plug-in
- wxWindows Version: wxGTK 2.6.2

On Ubuntu 5.10, Breezy Badger

- Compiler: gcc version 4.0.2 20050808 (prerelease) (Ubuntu 4.0.1-4ubuntu9)
- IDE Tool: Eclipse 3.1.2, with CDT 3.0.2 plug-in
- wxWindows Version: wxGTK 2.6.2

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Appendix E

Definitions and Acronyms

E.1 Definitions

ad A UML Activity Diagram. For diagrams generated in Poseidon, this label appears in the diagram's title box, located at the top left corner of the diagram.

Application The GMAT executable program.

cd A UML Class Diagram. For diagrams generated in Poseidon, this label appears in the diagram's title box, located at the top left corner of the diagram.

Command One step in the Mission Control Sequence.

Control Sequence Either a Mission Control Sequence or a Function Control Sequence.

Engine The "guts" of GMAT, consisting of all of the classes, control structures, objects, and other elements necessary to run a mission.

Factory or Factories Components used to create pieces that users use when modeling a mission.

Function Control Sequence The time ordered steps taken in a GMAT function.

GMAT General Mission Analysis Tool.

Graphical User Interface The graphical front end for GMAT, built using the wxWidgets toolkit. GMAT can also be built as a console application, but most users work from the GUI.

GUI The Graphical User Interface.

Interface The connection between GMAT and external systems, like MATLAB.

Interpreter The connection point between users and the Application. GMAT uses a ScriptInterpreter when constructing a mission from a script file, and a GuiInterpreter when configuring from the GUI.

Mission All of the elements configured by the user to solve a specific problem. Every element of a GMAT Mission is contained in the Model, but the Model may include components that are not part of a specific Mission.

Mission Control Sequence The time ordered steps taken to run a mission.

Model All of the elements configured by a user in the GMAT Application.

Moderator The central control point in the Engine.

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Parameter A value or other property calculated outside of a GMAT object. Parameters as used in this context are all elements derived from the Parameter base class, as described in Chapter 20.

Property A data member of a Resource or Command. Properties are the internal data associated with the objects used in a GMAT model.

Resource An element of the GMAT model that represents an object used when running the Mission Control Sequence.

Sandbox The portion of GMAT used to run a mission.

Script A text file that contains all of the instructions required to configure a mission in GMAT.

sd A UML Sequence Diagram. For diagrams generated in Poseidon, this label appears in the diagram's title box, located at the top left corner of the diagram.

sm A UML State Diagram. For diagrams generated in Poseidon, this label appears in the diagram's title box, located at the top left corner of the diagram.

E.2 Acronyms

GMAT General Mission Analysis Tool

GSFC Goddard Space Flight Center

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