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JSC Engineering Orbital Dynamics (JEOD) Top Level Document

Simulation and Graphics Branch (ER7)
Software, Robotics, and Simulation Division
Engineering Directorate

Package Release JEOD v5.0

Document Revision 1.3
July 2022

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

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Abstract

The JSC Engineering Orbital Dynamics (JEOD) Software Package contains a set of numerical mathematical models that provide vehicle or vehicles trajectory generation by the solution of a set of numerical dynamical models. These models are comprised of an Environment model representing the gravitational and non-gravitational forces and torques acting on the vehicle or vehicles, Dynamics models for processing and numerically integrating the equations of motion, Interaction models representing interaction with the environment and a set of mathematical and orbital dynamics Utilities. This document presents three topics:

1. An introduction to the JEOD package and its component models.
2. An overview of the design of the JEOD package and how the models are used together.
3. A top level description of verification and validation of JEOD with measured data.

Contents

Chapter 1

Introduction

1.1 Purpose and Objectives of the (JEOD) Top Level Document

The JEOD Top Level Document is designed to introduce the entire JSC Engineering Orbital Dynamics (JEOD) Software Package to users. The JEOD Software Package is a simulation tool that provides vehicle trajectory generation by the solution of a set of numerical dynamical models. These models are subdivided into four categories. There are Environment models representing the conditions surrounding the vehicle, Dynamics models for integrating the equations of motion, Interaction models representing vehicle interactions with the environment, and a set of mathematical and orbital dynamics Utility models.

JEOD is designed to simulate spacecraft trajectories in flight regimes ranging from low Earth orbit to lunar operations, interplanetary trajectories, and other deep space missions. JEOD can be used to simulate a stand-alone spacecraft trajectory and attitude state, or it can be interfaced with a larger simulation space, such as coupling with spacecraft effectors and guidance, navigation and control systems. More than one spacecraft can be simulated about one central body or separate spacecraft about separate central bodies. Many of these capabilites are demostrated in example simulations provided in a JEOD release. This includes both in the model verification simulations, top level tutorial simulations, and JEOD package verification simulations which are compared against data from real spacecraft trajectories.

JEOD had its beginnings in the early 1990s along with the advent of the Trick Simulation system. Early JEOD development efforts were performed by McDonnell Douglas, and JEOD has been managed by various Engineering groups at JSC since then. JEOD gained its own identity as an “orbital dynamics software package” as of the “dyn_v1.3” version of Trick. From that point forward, the two software systems began their own separate development and release cycles. Although the JEOD Software Package has been developed for use in the Trick Simulation Environment, it can be used independently from Trick.

JEOD has been used for years by the Space Shuttle Program and the International Space Station and now is planned for use by other programs including TS21, COTS, Orion, and SEV.

1.2 Context within JEOD

The JEOD Top Level Document document is parent document of JSC Engineering Orbital Dynamics. It is located at in the docs directory of the JEOD release.

1.3 Document History

Author	Date	Revision	Description
Christopher Thebeau	January 2012	1.3	Revised Version
A. A. Jackson and Christopher Thebeau	July 2010	1.2	Revised Version
A. A. Jackson and Christopher Thebeau	March 2010	1.1	Revised Version
A. A. Jackson and Christopher Thebeau	December 2009	1.0	Initial Version

1.4 Document Organization

This document is formatted in accordance with the NASA Software Engineering Requirements Standard [23].

The document comprises chapters organized as follows:

Chapter 1: Introduction -This introduction describes the objective and purpose of the (JEOD) Top Level Document.

Product Requirements -The requirements chapter describes the requirements on the (JEOD) Top Level Document.

Chapter 3: Product Specification -The specification chapter describes the architecture and design of the (JEOD) Top Level Document.

Chapter 4: User Guide -The user guide chapter describes how to use the (JEOD) Top Level Document.

Chapter 5: Inspections, Tests, and Metrics -The inspections, tests, and metrics describes the procedures and results that demonstrate the satisfaction of the requirements for the (JEOD) Top Level Document.

Chapter 2

Requirements

Requirement JEOD_1: Documentation

Requirement:

The documentation for JEOD and each model shall include:

1.1 Software requirements specification.

1.2 Software, interface, and software version descriptions.

1.3 User Guide.

1.4 Software test procedures and results.

Rationale:

The listed items are needed to comply with NASA NPR 7150.2A as a Class C product.

Verification:

Inspection

Requirement JEOD_2: JEOD Coding Standards

Requirement:

All source code written for JEOD shall shall follow the Coding Standards [10]. All exceptions must be waved and documented.

Rationale:

All model source code will be written, commented, and documented using the same standard so the code is easy to maintain and understand, which complies with NASA NPR 7150.2A.

Verification:

Inspection, Test

Requirement JEOD_3: Main Function

Requirement:
The JEOD Software Package shall provide the ability to model spacecraft trajectories, capable of supporting the orbital six degree of freedom propagation of multiple vehicles around multiple planets.

Rationale:
This is the main functional requirement of JEOD.

Verification:
Inspection, Test, Analysis.

Requirement JEOD_4: Relative States

Requirement:
JEOD shall provide the capability to represent and extract relative states for any simulated vehicle in relation to other vehicles and/or planets.

Rationale:
The capability to represent and extract relative states is necessary to support multi-vehicle, multi-planet simulation. It is also required by simulation users for many end applications such as rendezvous and proximity operations.

Verification:
Inspection, Test.

Requirement JEOD_5: Simulation Interface

Requirement:
JEOD shall provide a generic interface for a simulation engine which will support:

5.1 Simulations made with the Trick simulation package

5.2 Simulations independent of the Trick simulation package

Rationale:
Compatibility with Trick is required to support a large body of existing simulation code. Trick independence promotes reuse in other environments.

Verification:
Inspection, Test.

Chapter 3

Product Specification

3.1 Conceptual Design

3.1.1 Features and Linage of JEOD

JSC Engineering Orbital Dynamics (JEOD) is a collection of computational mathematical models that provide vehicle or vehicles trajectory generation by the solution of a set of dynamics models represented as differential equations. The orbital dynamics models that now comprise JEOD were part of the Trick Simulation Development Environment since its inception in the early 1990s. These models have found wide use in many simulations across NASA's Johnson Space Center. Some of these simulations have been used for Space Shuttle and International Space Station mission support. In that capacity, they have a significant lineage and have developed a level of credibility in the space operations environment that is essential to these space flight programs and more broadly valued by the agency.

It is important to note that these space flight programs are restricted to an orbital regime referred to as Low Earth Orbit (LEO - between 160 - 2,000 km (100 - 1,240 miles) above the Earth's surface). As a result, the Trick orbital dynamics package was originally designed for use and tested in that orbital regime. However, NASA has a history and now a renewed vision to explore beyond LEO and JEOD has expanded to be an orbital dynamics package that supports those regimes.

Three fundamental areas are essential to the design of JEOD and they are:

- Coordinate systems and reference frames,
- Time standards and time scales, and
- Multi-vehicle dynamics.

Of these three fundamental focus areas, the multi-vehicle dynamics area is fundamentally dependent on the time and coordinate frames areas. However, even time and coordinate frames are interdependent to some level, depending on the underlying assumptions of the dynamics. In the following few paragraphs, we discuss JEOD design and capabilities of each of these areas.

Since a key objective for JEOD is to provide support for exploration missions, it needs to allow for multiple planetary and interplanetary reference frames. In addition, the requirement for multi-vehicles about multiple planets meant no single reference frame choice was possible. Even though the solar system barycenter frame might be one potential candidate for a central reference frame, it is numerically undesirable to propagate the state of a vehicle orbiting Neptune in this frame. Therefore, JEOD is implemented to use a reference frame tree concept. This provides a framework for associating dynamical reference frames consistently and efficiently. For more detailed information on the coordinate systems modeling in JEOD, see the *Reference Frame Model* [32] and JEOD Coordinate Frames[14] documentation.

The JEOD time model supports the concept of a dynamic time that is linearly tied to simulation executive step time, but is not required to step forward in a 1 second to 1 second dependancy. This increases the accuracy (some would argue correctness) of the time model, and allows for JEOD dynamic time move backward if needed. The JEOD time model is an extensible object oriented model, which supports the concepts of time standards that can be extended by the user. These time standards can have varying rates of propagation with respect to the base dynamic time. For more detailed information on the time model, see the *Time Model* [40] documentation.

The final foundation area is multi-vehicle dynamics and JEOD is designed to efficiently and accurately propagate multiple vehicles about multiple planets. while allowing for interactions between said vehicles. This dynamic infrastructure depends on both the reference frames model and the time model discussed above. For more information on the multi-vehicle dynamics model, see the *Dynamic Body Model* [8] , *Derived State Model* [41] , *Dynamics Manager Model* [9] , *Mass Body Model* [36] documentation.

While other areas are also important to the successful implementation of an orbital dynamics package, these three form the foundation upon which the others are built. In addition to the purely technical issues associated with modeling physical orbital dynamical systems in a digital computational environment, there are also the software architecture or design challenges associated with the practical constraints of computer languages, operating systems and platforms. So, in addition to supporting the technical base of JEOD, the JEOD team focuses on what are sometimes referred to as software “ilities”. The definition of “ilities” varies from reference to reference but often includes concepts like the following: reliability, security, scalability, extensibility, manageability, maintainability, interoperability, composability, evolvability, survivability, affordability, understandability, and agility.

JEOD continues to maintain as much of the pedigree and usage history of JEOD and its historical software base, but is now designed using modern and extensible computational constructs (e.g. extensibility, generalization, data encapsulation, etc.). The original Trick based dynamics packages were written in the C programming language (including JEOD 1.4 and 1.5), and the current version of JEOD is written in the C++ programming language. The principal benefits in this choice are that C is, for the most part, a subset of C++ so older models were easily converted and that C++ supports the object oriented programming constructs deemed necessary for a modern design.

Table 3.1: JEOD Features

JEOD Feature	
Reference Frame Model	A well-formulated model of reference frames and operations on them. Reference frames are organized in a tree structure, with the International Celestial Reference Frame at the root of the tree.
Multiple Integration Frames	Each independent body in a simulation has its own integration frame. This capability is essential for a multi-vehicle simulation in which one vehicle orbits one planet such as the Earth while another vehicle orbits the a different planet such as the Moon.
Time Representations Model	A flexible and extensible model of time.
Body Actions Model	A flexible and extensible mechanism for initializing and asynchronously operating on vehicle objects.
Derived States	A flexible and extensible mechanism for computing information that derives from vehicle states. The Body Action and Derived State models are designed for extensibility. Suppose you don't like the limited set provided with JEOD. Fine! Make the one that you like. It's easy.
MassBody/DynBody	Mass and OrbitalBody objects that take full advantage of inheritance allowing users to extend this inheritance even further. For example, JEOD uses the rigid body assumption, a user-defined derived class could eliminate this.
Surfaces Model	Allows the modeling of environmental effects such as aerodynamic drag, radiation pressure, contact and articulation.
JEOD Tutorial	The Tutorial takes the JEOD user from very simple simulations to the more complex, in a well-ordered progression.
C++ Language	The entire JEOD Software Package is written in the C++ language, which allows users to develop their own models by simply extending JEOD base classes.
Software Documentation	All JEOD models are documented in a concise and consistant manner.

3.1.2 Reference Documents

The following documents provide supporting reference material for understanding the orbital dynamics concepts that have been implemented in JEOD:

- Vallado,"D.A. Vallado with tech contributions by Wayne D. McClain" [42]
- Montenbruck and Gill, "Satellite Orbits" [21]
- Hughes, "Spacecraft Attitude Dynamics" [12]
- Bate, White and Mueller, "Fundamentals of Astrodynamics" [2]
- Seidelmann, "Explanatory Supplement to the Astronomical Almanac" [30]
- Heafner, "Fundamental Ephemeris Computations for use with JPL data" [11]

See the bibliography for the details associated with these references.

3.2 Detailed Design

3.2.1 JEOD Root Directory

The top level or JEOD root directory is organized into several subdirectories as follows:

- bin - Scripts to facilitate JEOD use,
- docs - Contains this document and all other JEOD-wide references or documentation,
- models - Divided into four sections (dynamics, environment, interactions, utils) which contain the functional parts of JEOD referred to as models,
- sims - Example simulations such as the JEOD Tutorial,
- verif - Verification simulations and data.

3.2.2 A JEOD Model

A JEOD model is a cohesive, related (i.e., not random) collection of C++ classes. It is also an immediate subdirectory of one of the four major model category directories; dynamics, environment, interactions, and utils. Each model is a directory and a directory is a model. This ensures that the contents of a model directory are truly related and that all components of a model are located in a single directory.

Each model directory can contain the following subdirectories.

- docs - Model documentation,
- data - Data files, suffix .d or .hh and .cc if an initialization class,
- include - Header files, suffix .hh,
- src - Implementation files, suffix .cc,
- verif - Verification files and simulations, typically organized in subdirectories, i.e.. SIM_...,

In some cases it makes sense to break a model into smaller parts, so a few JEOD models contain sub-models. These sub-models obey the same basic concepts used for models. They are reasonably self-contained (e.g., a class), separated in only one subdirectory, and consist of logically consistent parts. Each sub-model will contain an include and src subdirectory in addition to any others that are required, such as data or verif.

3.2.3 Model Categories

As a matter of basic design and organization, the models that comprise JEOD are divided into four categories. This organization was introduced in Chapter 1, and below is a table showing all the models in JEOD and the category they belong too. Each model name in the table is a hyperlink to the individual model document.

Table 3.2: JEOD Model Tree

Dynamics	Environment	Interactions	Utilities
Body Action	Atmosphere	Aerodynamics	Container
Derived State	Earth Lighting	Contact	Integration
Dynamic Body	Ephemerides	Gravity Torque	Math
Dynamics Manager	Gravity	Radiation Pressure	Memory
Mass	Planet	Thermal Rider	Message
Rel Kin	RNP		Named Item
	Time		Orbital Elements
			Orientation
			Planet Fixed
			Quaternion
			Reference Frame
			Sim Interface
			Surface

3.2.4 Dynamics

Roughly speaking the Dynamics category contains models that pertain to a vehicle. Examples of mathematical models that would be contained in Dynamics are mass properties, equations of motion, and kinematics. What follows is a list of the specific types of computations and capabilities found in the JEOD Dynamics category.

1. Initialization of vehicle states and mass properties,
2. Computation of the mass properties of a vehicle or a set of attached vehicles,
3. Force and torque collection,

4. Numerical integration of the translational and rotational equations of motion,

5. Computation of the relative translational and rotational states in various coordinate systems,

3.2.5 Environment

The Environment category contains models that describe the environment in which vehicles “live”. Examples include time, gravity, the atmosphere, and the solar system. Contained in the JEOD Environment category are models that provide the functionality in the list below.

1. A system of time,

2. Gravitational force,

3. Dynamic upper atmospheric density,

4. N-body point mass gravitational perturbation force,

5. Solid body tidal force model,

6. N-body ephemeris in the basic inertial system,

7. Modeling of on-orbit lighting and extraction the solar beta angle,

8. Computation of planetary orientation for Earth, the Moon, and Mars.

3.2.6 Interactions

The Interactions category contains models that describe interactions between a vehicle and the environment (between models in the Dynamics and Environment categories). Examples of such interaction include atmospheric drag, radiation pressure, and gravity gradient torque. This category of models provide the functionality in the following list.

1. Aerodynamic drag,

2. Gravity gradient torque,

3. Radiation pressure,

4. Thermal effects,

5. Vehicle to vehicle contact.

3.2.7 Utilities

The final category called Utilities contains models that don’t fit into the other three categories or models that contain common functionality that is shared across models in all categories.

1. Basic reference frame structure,

2. Planet fixed reference frame,
3. A system to create vehicle surface shapes and structures,
4. An orbital elements state representation,
5. Methods to track an object's orientation,
6. Integration methods and framework for creating new ones,
7. Universal models for math, memory, messages, integration, object or item naming, and the infrastructure for the creation of standard container objects such as lists and vectors in JEOD.

3.2.8 API Documentation

JEOD contains a complete set of Application Programming Interface (API) Documentation in HTML format, which can be found by opening index.html located at top level html/jeod directory. The API documentation for each model reference in the detailed design section of each model documents Product Specification chapter. The API documents are generated using the Doxygen documentation generator for C++.

3.2.9 JEOD Coding Standards

The JEOD Coding Standards [10] document is stored at the JEOD Wiki under Miscellaneous Documents.

3.3 Interactions

There are two categories of interactions that should be discussed in an overview of JEOD. The first is the JEOD interaction with simulation engines such as Trick, while the second is the interactions between the various JEOD models including the importance of phasing in initialization and execution.

3.3.1 Simulation Engine Interface

JEOD contains a *Simulation Engine Interface Model* [31] which has been implemented with a set of interfaces between JEOD and the simulation engine. These interfaces take a number of forms:

1. Making a class's protected and private data members visible to the simulation engine.
2. Making data items allocated by JEOD models visible to the simulation engine.
3. Translating addresses to and from simulation engine symbolic names.
4. Checkpointing and restarting data allocations and Container Model objects.

5. Making JEOD integration work within the context of integration as performed by the simulation engine.

6. Obtaining the rate at which the simulation engine calls the currently executing function.

3.3.2 JEOD Model Interactions and Phasing

The order in which models and the functions they contain are initialized and run is an important consideration when constructing a JEOD simulation. This order is referred to as job phasing and involves three job classifications; initialization, scheduled/environmental, and derivative. There is also an integration job, but only one exists in the JEOD model set and therefore doesn't factor into the discussion of phasing. This section is included to give an illustration of how job phasing can be implemented as specified by the Trick operating environment. For details about Job Phasing and job classification in Trick see section 4.4.6.2 of the Trick users guide [44].

The phasing diagrams presented below represent RUN_full of the SIM_dyncomp example simulation found in the root verif directory. In the diagrams below each labeled oval represents a specific function call that has been defined in a simulation object. The function calls are grouped in large boxes according to its phase. The arrows note direct relationships and indicate that a call to a function requires at least one call to the preceeding function must have occurred. A direct example is shown in the initialization phase P_Time in which the function Time Manager::initialize must be called before TimeManager::register_converter and TimeManager::register_type can be used. This style of notation is followed in each diagram.

3.3.3 Initialization sequencing

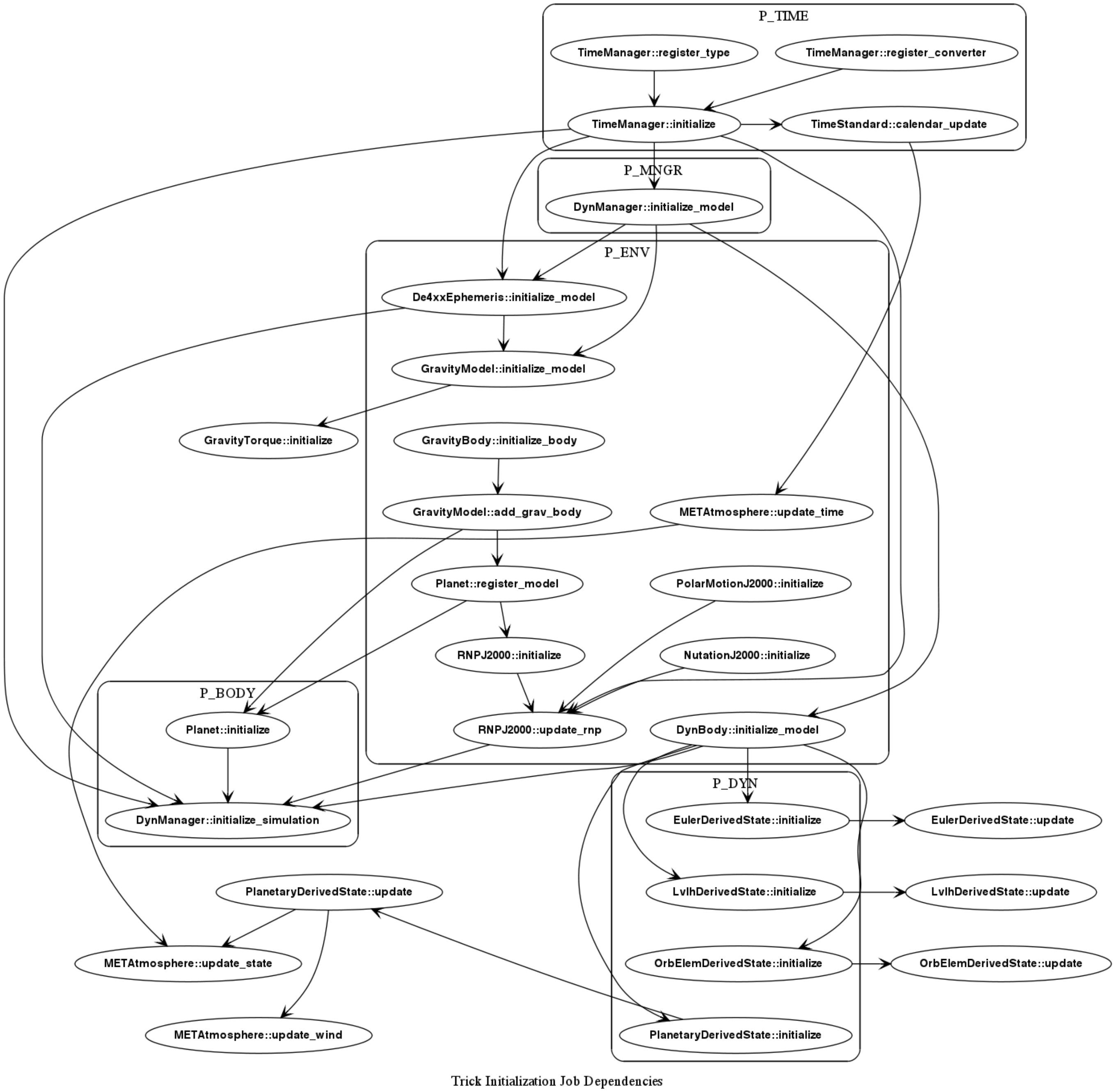

Figure 3.1: SIM_dyncomp job initialization. ERROR - the Planet::initialize method in the P_BODY box should be in a P_EPH box. This error does not affect the order in which the jobs in this diagram are called.

3.3.4 Derivative job sequencing

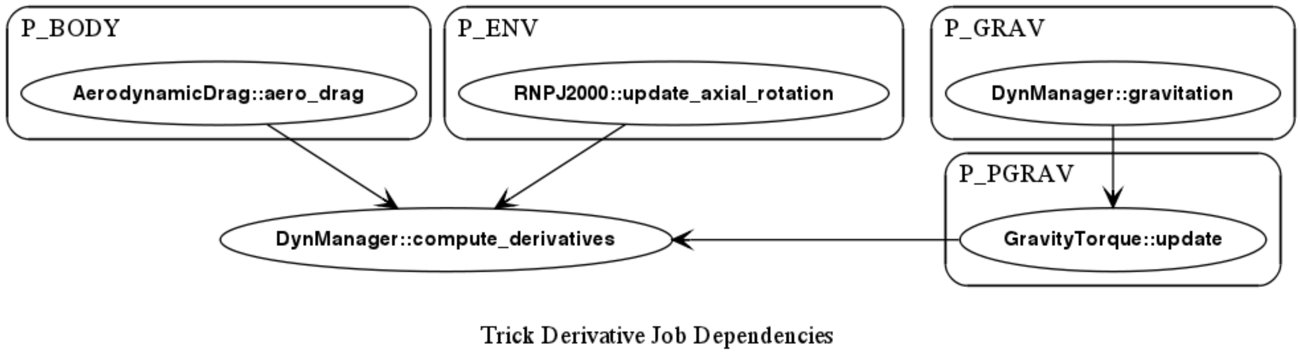

Figure 3.2: SIM_dyncomp derivative job phasing.

3.3.5 Scheduled job sequencing

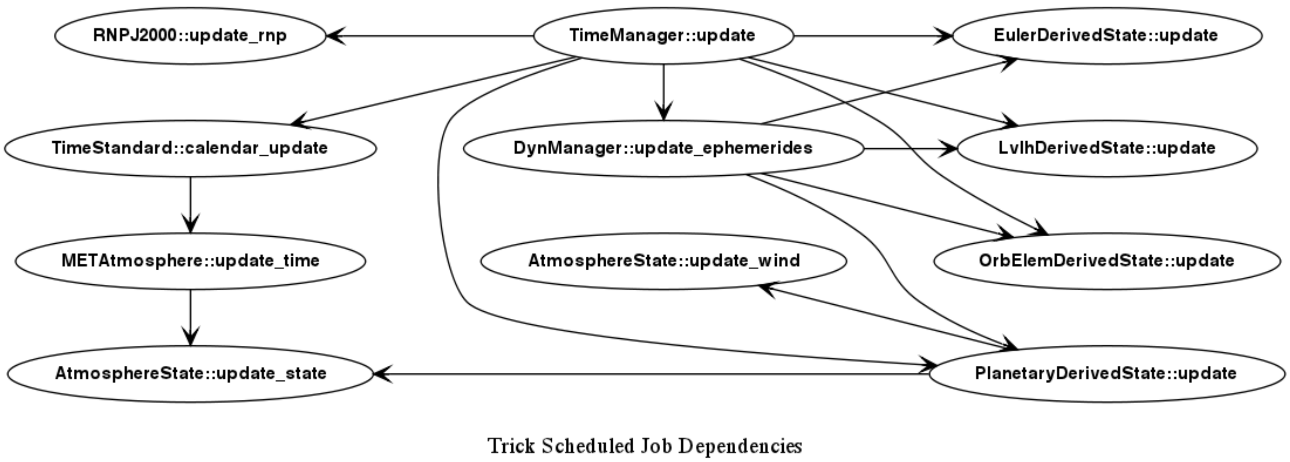

Figure 3.3: SIM_dyncomp scheduled job phasing.

Chapter 4

User Guide

4.1 Resources for JEOD Users

There are several resources for users of the JEOD Software Package.

Each JEOD model document contains its own user guide, the names and links to the individual JEOD model documents are given in Table 3.2 above.

The *JEOD Tutorial* [37] leads users from a simple simulation to incrementally more complex simulations and offers very practical guidance throughout.

Finally a user should review the documentation associated with the simulation engine in use. For the example simulations contained in the JEOD release this would include the

- *The Trick User's Guide* [44]
- *Trick Tutorial* [43]

4.2 JEOD Model User Guide Organization

This user guide is in a different format than the model documentation, because it addresses the entire JEOD package for which the user distinctions are less clear. The JEOD Model User Guides are generally divided into three sections based on the potentially different interests of users:

- Instructions for Simulation Users - commonly includes guidelines on modification of input files for a simulation containing the model,
- Instructions for Simulation Developers - will include a detailed discussion the S_define file requirements of the model,
- Instructions for Model Developers - contains instruction on the common ways that the model can be extended.

4.3 Overview of the Use of the JEOD Package

Here are some basic considerations for performing JEOD simulations. As an example consider the goal of propagating a space vehicle in low Earth orbit under the influence of the dominant environmental forces at that altitude. These forces at altitudes of 100 to 500 miles are for the Earth, mainly dominated by the geopotential, atmospheric forces, perturbations by the Sun and Moon, solid Earth tides and to a small degree by radiation forces. For this simulation it is required that there be a six degree of freedom representation of the state of the vehicle and a set of command lines for the recording of information of interest. The JEOD simulation of a single vehicle requires:

1. Initialization of the environment,
2. Initialization of the vehicle state,
3. Propagation of the environment,
4. Propagation of the state,
5. Data Recording.

The implementation of these processes requires that the following information be in place:

1. Default data, which typically initializes environmental models such as *Rotation, Nutation, and Precession Model* [33] and *Gravity Model* [39]
2. The Input file data, which typically initializes vehicle properties and state information,
3. A Data recording file or files.

To run a JEOD simulation, the JEOD models must be properly initialized and executed with the right phasing, because some models rely on the completion of others. The rough recommended initialization order is:

- Time.
- Dynamics Manager.
- Environment-related models.
- Vehicle.
- Relative frames and states.

Also events such as scheduled and derivative class jobs should be phased properly too. In general, it is recommended to study model verification simulations and/or the *JEOD Tutorial* [37] simulations for examples of job phasing. You can also refer to the diagrams in Section 3.3.2 for more information.

Chapter 5

Inspections, Tests, and Metrics

5.1 Inspections

Inspection JEOD_1: Documentation

This document combined with the *JEOD Tutorial* [37] and the JEOD model documentation set listed in table 3.2 satisfies the requirement JEOD_1. Each document has been reviewed by a technical editor and a JEOD team member other than the author for consistency and clarity.

Inspection JEOD_2: JEOD Coding Standards

The JEOD source code satisfies the coding standards requirement JEOD_2. This has been confirmed with internal JEOD code reviews, through the use of third party tools, such as doxygen, and with scripts which flag non-compliant code.

5.2 Tests

5.2.1 Integrated Validation Introduction

To assure the user and any clients that the JEOD simulation software is valid, verification and validation through a full empirical comparison of JEOD is required. Verification of the software involves checking the numerical output of the simulation against precision orbit ephemeris data from tracked vehicle data (orbit fitting is the method of generating a precise spacecraft orbit from measured data [42]). Integrated Validation of JEOD is a viability demonstration that the software models met the reasonable requirements of the overall project. It combines with the unit testing given in the models and should serve as assurance that the software output can be trusted and a metric for the software's accuracy.

Verification and Validation provide a quantitative measure of the numerical accuracy of the trajectory generation. Figures of merit from the comparisons for the radial, in-track and cross-track (the RSW coordinate frame positions are presented in appendix D). For this validation presentation no predetermined pass-failure criteria can be stated, only the RSW errors stated as metric of measure. The values of initial measurement orbit fit errors for position are given in the appendix list of state vectors along with the errors in velocity estimation when given (though all state vector fit errors are not always available).

The top level JEOD verif directory contains a set of integrated simulations that comprise the JEOD package validation suite. These simulations, which can be found in the directory Integrated_Validation, consist of the following suite of cases for the public release version of JEOD:

- A Lunar orbit simulation to precision orbit ephemeris comparison.
- A Earth hyperbolic orbit simulation to precision orbit ephemeris comparison.
- A Mars hyperbolic orbit simulation to precision orbit ephemeris comparison.

And with the following additional cases for the NASA internal release version:

- A low earth orbit (LEO) simulation to precision orbit ephemeris comparison,
- A high earth orbit (HEO) simulation to precision orbit ephemeris comparison,
- A geosynchronous orbit (GEO) simulation to precision orbit ephemeris comparison.
- A dual vehicle Earth orbit simulation simulation to precision orbit ephemeris comparison.

These Integrated Validation simulations produce ASCII recordings in inertial coordinates which match the measured states (see the Benchmarks E). The measured and simulated states are post processed into RSW coordinates to get the radial, in-track and cross-track errors. Microsoft Excel was used to produce the plots and format the data.

The commonly accepted definition for LEO is for orbits between 160 - 2,000 km above the Earth's surface. HEO (sometimes called Medium Earth Orbit, MEO) are satellites at altitudes at or above 2,000 kilometers and below geostationary orbit altitude of 35,786 kilometers. GEO satellites, at 35,786 kilometers could be labeled as "high" but are given the particular name of geostationary or GEO.

In the integrated simulations, orbit propagation has been performed to gain a quantitative measure of the validity of the JEOD propagation and force models. Gravitational forces of a non-spherical Earth, the Moon, Mars, n-body perturbations, solid body tide forces, radiation pressure, and aerodynamic drag are tested. Also tested is the underlying environment modeling in support of the propagation, such as rotation-precession-nutation-polar-motion, the ephemerides and the MET thermosphere models. Six sets of measured precision orbits were obtained to use as measures. Four of the measurement sets are time histories from CHAMP, ENVISAT, LAGEOS and CLEMENTINE data, and two are initial and final orbit fits for the ISS and TDRS. Because of unknown attitude profiles in the following, only the basic aerodynamics was modeled by way of a coefficient of drag or a ballistic coefficient. It should be kept in mind that for low earth orbit satellites, the atmospheric density can only be modeled to within about 15 percent accuracy due to uncertainties in modeling upper atmospheric winds when not using free molecular flow (Vallado [42]). In this release of JEOD the GRACE Gravity Model 02 (GGM02C) gravitational field is used as the geopotential model [35] and [34]. The solar activity was obtained from Goddard Space Flight Center's MSIS web site, see appendixap:atmos.

Note 1: For JEOD, the *Gravity Model*[39] uses a normalization method for a high order and degree non-spherical gravitational field of the Earth and the Moon.

Note 2: For position errors see Appendix A, and note that the errors in velocity state are not always available.

5.2.2 LEO:

Test JEOD_1: Integrated Testing CHAMP

Introduction:

The Challenging Minisatellite Payload (CHAMP) satellite was launched with a Russian Cosmos launch vehicle on July 15, 2000 into an almost circular, near polar orbit with an initial altitude of 454 km. The design lifetime of the satellite system was 5 years. CHAMP is a small German satellite with a mission for geoscientific and atmospheric research and applications, managed by the GeoForschungsZentrumPotsdam (GFZ).

Test Satellite CHAMP:

In 2003 CHAMP was at 400 km during a period of enhanced solar activity, thus this satellite was a very good choice as a benchmark to measure JEOD modeling of the geopotential and atmosphere. The measurements were taken in April 2003.

Procedure:

A set of precision fit J2000 state vectors was obtained from GFZ by Blair Thompson [38]. The CHAMP ephemeris files are for three consecutive days in 2003. Each file contains 30 hours of ephemeris (ECI J2000) in 10 second intervals. The initial state and orbit environment at that date are given in appendix table A.1. The GPS fitted orbit data has an absolute error in position of 5 centimeters or less according to the following journal paper [1]. The physical characteristics of the vehicle and the aerodynamics ballistic coefficient were obtained from the GFZ [18] in Germany - see: the CHAMP state in A.1. For aerodynamics only a simple projected area model was used.

Results:

The results of this test are shown in Figure 5.1. The RSW or radial, in-track and cross-track errors (see Appendix D), for a one day propagation are shown in Figure 5.1. The biggest errors are less than 2 meters radial, less than 2 meters cross-track. There is a secular growth in in-track to less than 6 meters when using GGM02C. Most of the in-track error comes from atmospheric modeling. It is noted here that the GGM02C is used with the full fitted model order = 200 and degree = 200. The option to use GGM02C to this maximum order and degree also tested the gravitational algorithm model that handles a high order expansion. The RSW errors are very acceptable, considering the uncertainties in atmosphere and that GGM02C was fitted with the IERS RNP model [20]. This test takes almost 20,000 sec of CPU time, and checks may be run at lower order and degree. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

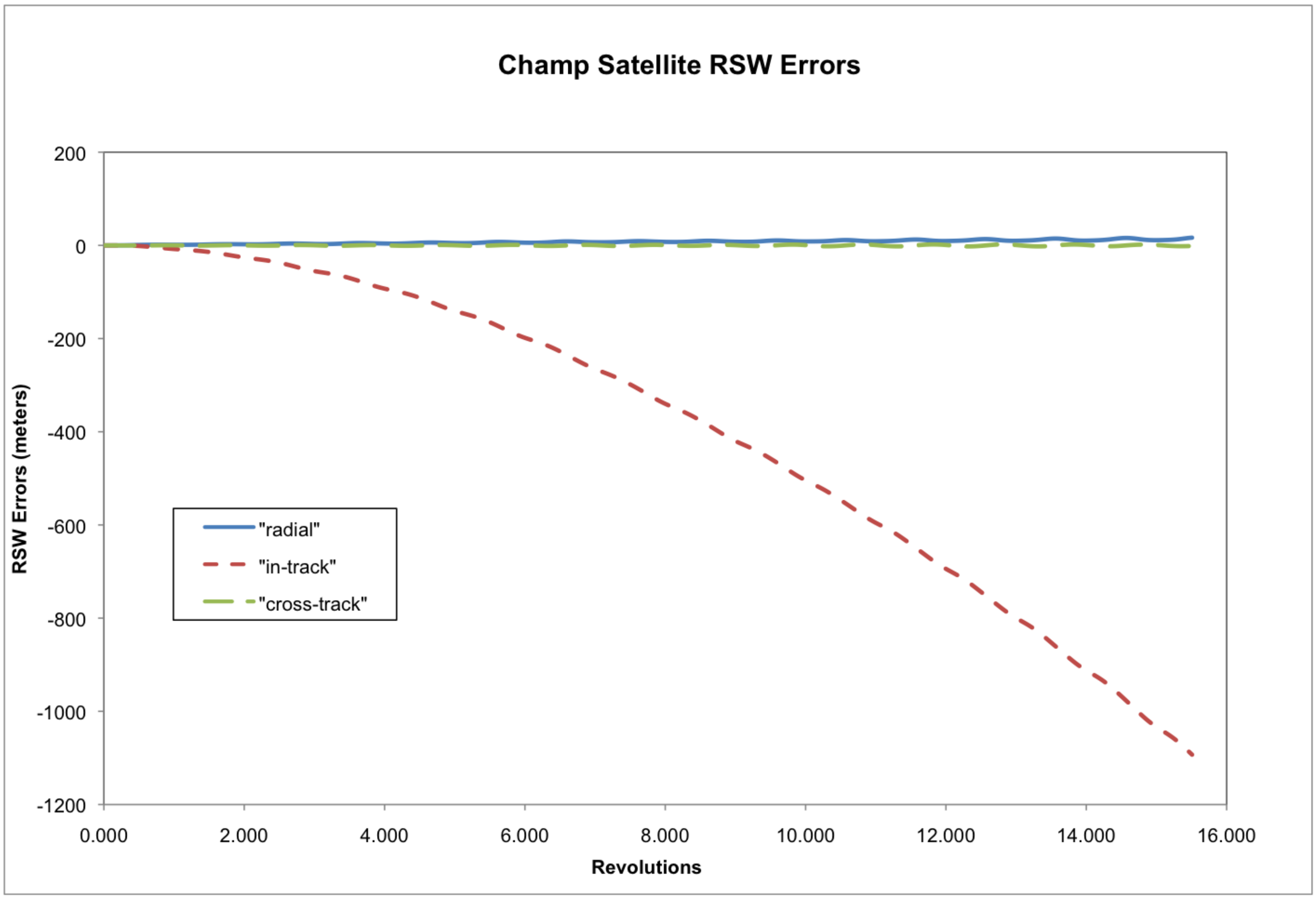

Figure 5.1: RSW errors accumulated over a day for the orbit of CHAMP .

Test JEOD_2: Integrated Testing ISS

Introduction:

The following test uses the International Space Station (ISS) as test object. The ISS is a large articulated spacecraft and hence is subject to large drag perturbations. This test uses a fixed aerodynamic configuration in the form of a projected area model. The purpose is to measure the error produced by JEOD in propagating a large orbiting object subject to drag.

Requirements:

Quantify the accuracy of JEOD with a large drag spacecraft in low Earth orbit under the influence of a dynamic atmosphere and non-spherical geopotential as the main perturbing forces. The aerodynamic configuration for the ISS is fixed throughout the run.

Procedure:

Two precision fit ISS state vectors were obtained from the Mission Operations Directorate,[4]. The aerodynamic properties are contained in a document issued by the JSC Engineering Directorate, Lumpkin [17]. The ISS is in configuration 2A in Torque Equilibrium Attitude. The initial conditions and physical conditions are shown in appendix table A.2. The solar activity was obtained at the initial ISS state vector epoch but not changed, even though the simulation duration is 1 day (this is the interval at which ISS precision states are obtained [4]). Note: Only initial and final orbit fits are available.

Results:

The initial state vector was provided in J2000 inertial coordinates and propagated for one day. Table 5.1 shows the differences in radial, in-track and cross RSW track positions. The errors in the initial orbit fit are one km in the J2000 intertial Cartesian position coordinates. The uncertainty in the ISS aerodynamics and the atmosphere density makes a considerable contribution to the propagated state in the in-track position period for a JEOD simulation. Though the solar activity did change during this period it was not large (it would be possible to change a simulation's solar activity in the input file). There is also a small contribution due to the geopotential due to very small unknown errors in using a different Earth Orientation Model than that used to fit GGM02C. The results are for a geopotential model GGM02C of degree and order 70x70 (there is only a small improvement in using the 200x200 GGM02C model). An in-track error of nearly 6 km is the accuracy of using this large vehicle with an only approximated projected area over the trajectory time line. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

Table 5.1: ISS RSW Errors for a One Day Orbit Propagation

Component	**magnitude of value**	**units**
Radial	-67.89740334	meters
In-track	6003.885756	meters
Cross-track	33.27854206	meters

5.2.3 HEO:

Test JEOD_3: Integrated Testing ENVISAT

Purpose:

The ENVISAT (Environmental Satellite) satellite is an Earth-observing satellite built by the European Space Agency. It is in high earth orbit (HEO) with a perigee of 785 km, an apogee of 791 km and has orbital inclination of 98.6. ENVISAT carries an array of nine Earth-observation instruments that gather information about the earth. The main home for data collection is the Department of Earth Observation and Space Systems (DEOS) at Technical University Delft, Delft The Netherlands.

Requirements:

This is classified as HEO because it is an orbit where the atmosphere does not dominate the translational forces. ENVISAT, near the top edge of the exosphere, the forces due to the aerodynamic drag are only noticeable during periods of high solar activity otherwise gravitational and radiation forces are dominant. It also gives a case where third body gravitational perturbations are in play.

Procedure:

The initial conditions are given in the appendix for this ENVISAT test A.3. The data was extracted from the DEOS state vector webserver. The data is generated by European Space Operations Centre (ESOC) in Darmstad. The accuracy of the orbit fit has a root mean sum square of 10 centimeters, and reference for the state error can be found on ESOC website. The physical characteristics were given by the DEOS webserver and the aerodynamics from a paper by Doornbos [7]. J2000 state vectors were extracted every 10 seconds for 1 day. The full GGM02C gravitational model of order and degree 200x200 was used in this test.

Results:

The comparison differences between the measured and numerically propagated state vectors over 24 hours are shown in Figure 5.2. The radial and cross-track differences are approximately 5 meters after 12 hours, the in-track error drifts noticeable growing to nearly 10 meters in the same period. The oscillations in all the position errors are mostly due to perturbations due to the sun and moon. The epoch of the test was during a period of low solar activity thus the atmosphere has less effect. It has been shown that under those conditions, ENVISAT is subject to about 50 percent more force due to radiation forces than aerodynamic drag forces, Doornbos [7] and Scharroo [28] and [27]. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

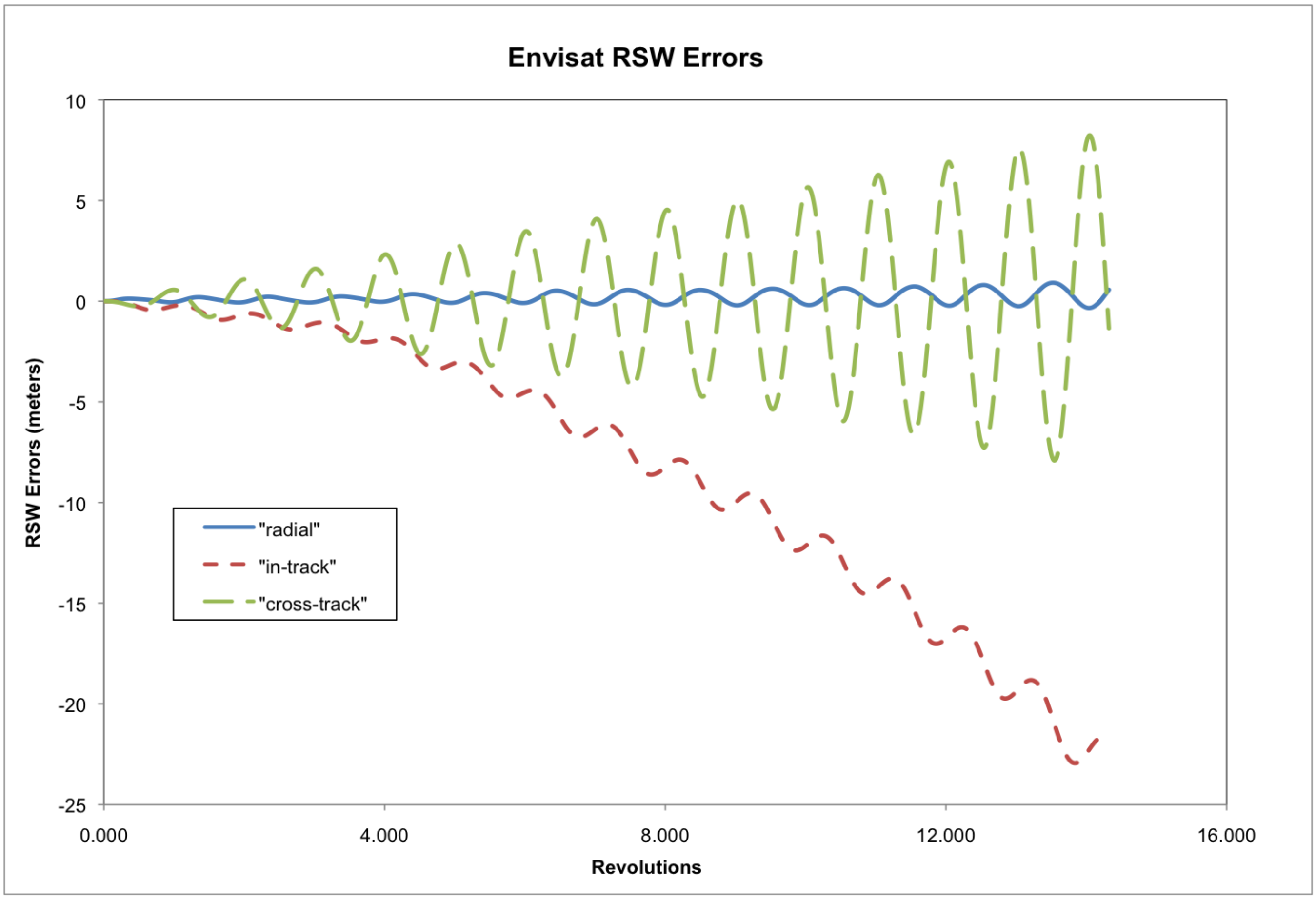

Figure 5.2: ENVISAT RSW errors between measured and simulated orbit using GGM02C.

Test JEOD_4: Integrated Testing Lageos

Purpose:

The Lageos satellites are passive vehicles covered with retroreflectors designed to reflect laser beams transmitted from ground stations. By measuring the time between transmission of the beam and reception of the reflected signal from the satellite, stations can precisely measure the distance between themselves and the satellite. These distances can be used to calculate station positions to within 1-3 cm.

Requirements:

This is a definitive test of a HEO, being at an altitude of 6000 km, because on the Lageos the forces due to the aerodynamic drag are dominated by radiation pressure. This also gives a case where third body gravitational perturbations are significant.

Procedure:

The initial conditions are given in the appendix for this Lageos test A.4. The full GGM02C gravitational model of order and degree 200x200 was used in this test. The data was provided by Goddard Space Flight Center (private communication Erricos C. Pavlis [24]). The measurement data by laser tracking is accurate to less than one tenth of a meter, per NASA TM 104549 [6].

Results:

The comparison differences between the measured and numerically propagated state vectors over 24 hours are shown in Figure 5.3. After 6 revolutions there was a .5 meter error and 1.7 meter cross-track differences. The in-track error of 10.6 meters is attributable to the Lageos ultra precision orbit fit and some radiation pressure modeling. In addition, there are error contributions due to the RK4 numerical integrator and other possible non-gravitational effects such as the albedo of the Earth. Earth shadowing was modeled by a simple cylinder. Studies have shown that Lageos undergoes many complex non-gravitational forces which JEOD does not model [26]. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

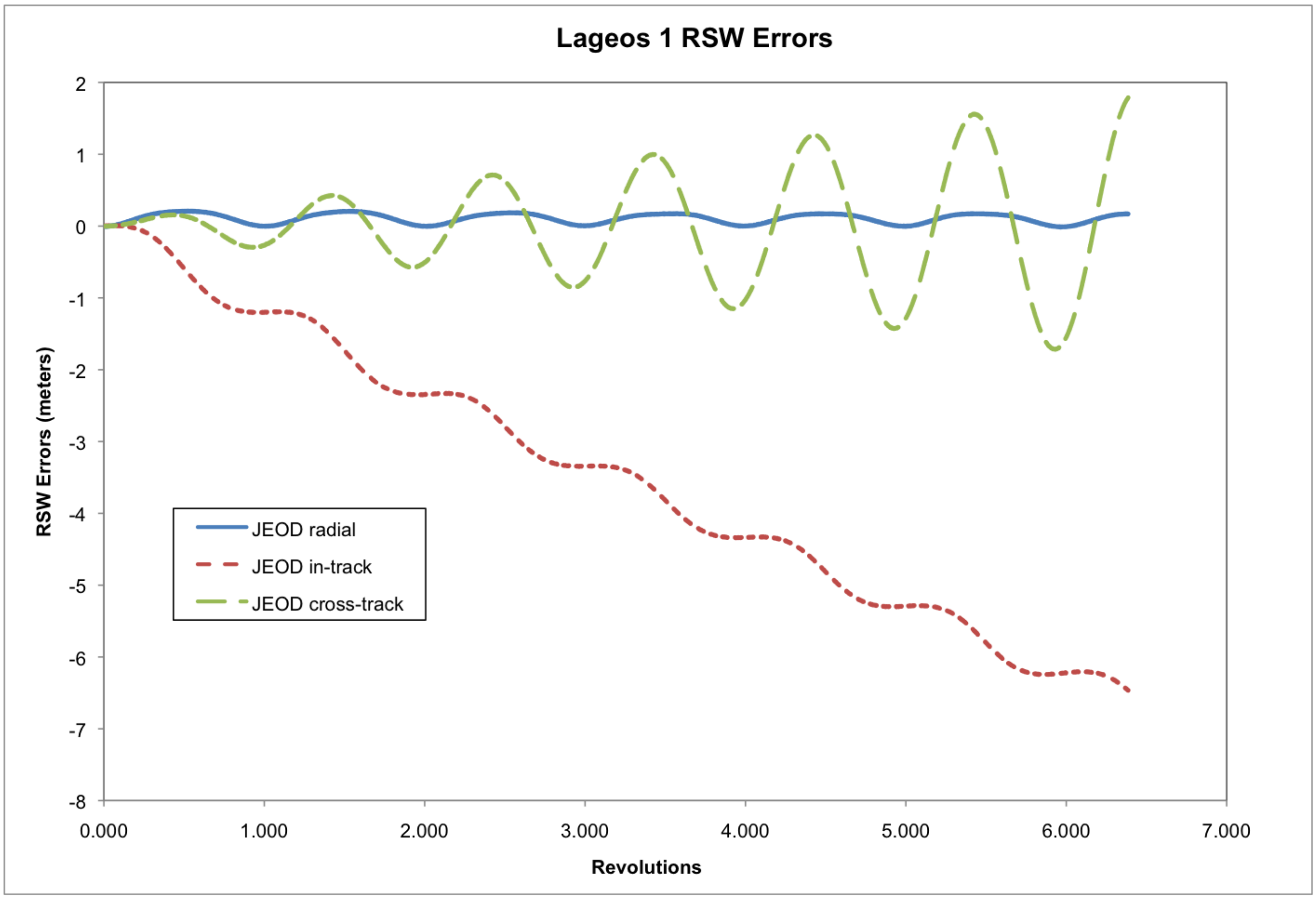

Figure 5.3: Lageos RSW errors between measured and simulated orbit using GGM02C.

5.2.4 GEO:

Test JEOD_5: Integrated Testing TDRS

Introduction:

At geosynchronous orbital altitudes the atmospheric drag forces are non-existent, and the main perturbation forces are the low order geopotential terms, third body gravitational forces (mainly due to the Moon and Sun) and radiation forces. The Tracking and Data Relay Satellite (TDRS) is one of a network of communications satellites used by NASA and other United States government agencies for communication to satellites or the International Space Station. (For this satellite one finds also, the name Tracking and Data Relay Satellite System (TDRSS)).

Requirements:

This test is a characterization of the accuracy of a geosynchronous orbit propagation by comparison to a precision orbit fit. This test mainly measures the influence of third body perturbations which are dependent on the generation of the JPL ephemerides and radiation pressure forces.

Procedure:

A precision fit state vector was obtained from JSC's Mission Operations Directorate, [4] see the appendix table A.5. These vectors are separated in time by a day. The accuracy of the TDRS initial state vectors is approximately 1 km in position [5].

Results:

The results are shown as plots in Figure 5.4. The in-track error reflects a long propagation of the orbital state by numerical integration. The step size for the Runge Kutta (order 4) method has a quadratic accumulation of error. GGM02C was used setting order and degree to 8x8. It is known that radiation pressure makes a contribution to perturbations at geosynchronous distances, and these are modeled in JEOD. In this case TDRS is a complex object, thus radiation pressure modeling can only be approximated. The in-track error generated by JEOD is about 250 m for a one day propagation, and this may be due to radiation pressure. For long propagations, JEOD will be sensitive to initial position errors of a given state which are of the order of 1km for this TDRS case. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

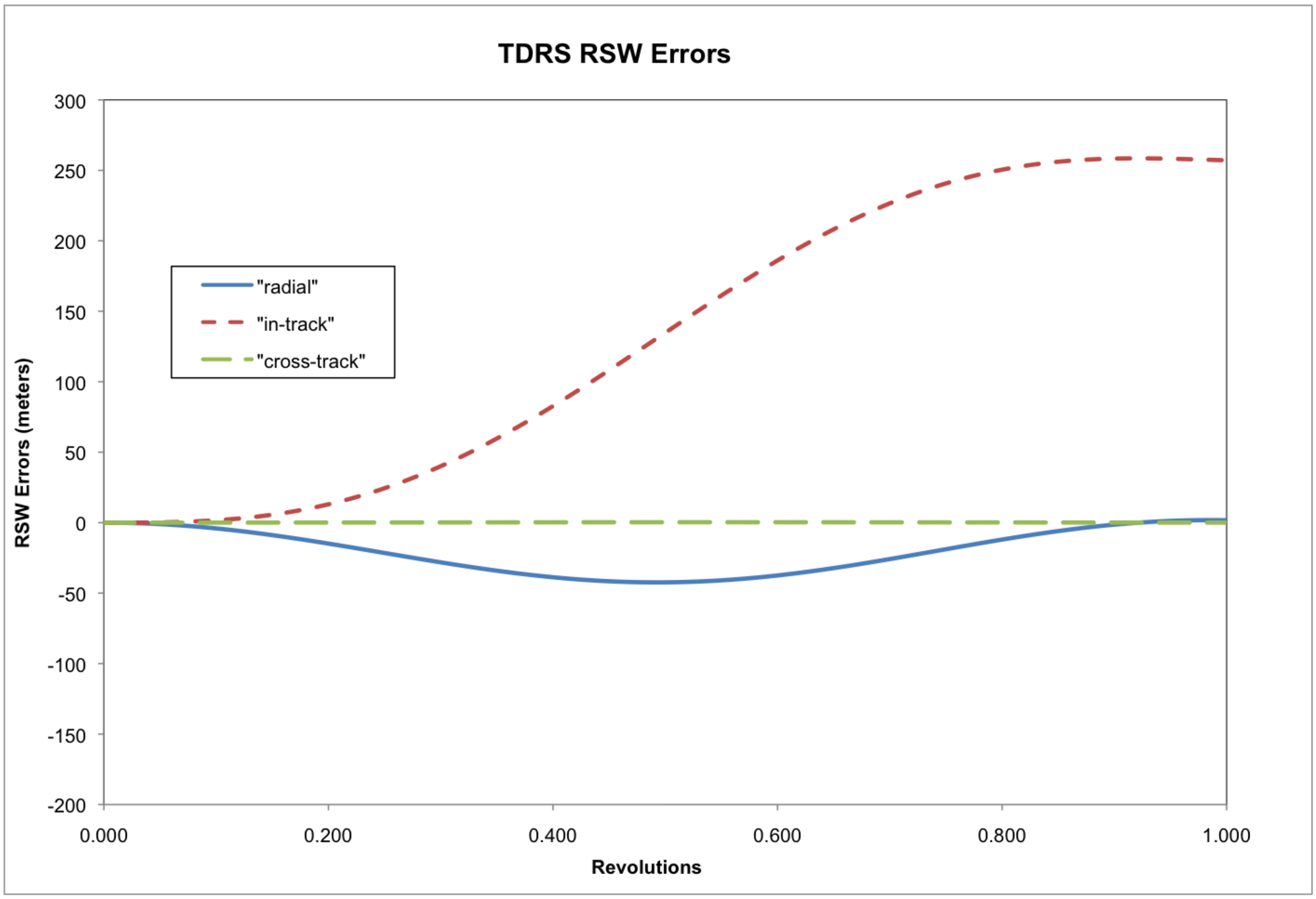

Figure 5.4: TDRS RSW errors between measured and simulated orbit using GGM02C.

5.2.5 Lunar Orbit:

Test JEOD_6: Integrated Testing Clementine

Introduction:

The Clementine spacecraft was built at the US Naval Research Laboratory in Washington, DC, and carried sensors, attitude control systems, and software designed and built by the Lawrence Livermore National Laboratory (LLNL). The US Air Force supplied advanced lightweight composite structures and the launch vehicle, a Titan IIB refurbished ICBM. Several other organizations were involved, especially NASA, with communications support, through the Jet Propulsion Laboratory's (JPL) Deep Space network, and orbit determination and operations support came from both the Goddard Space Flight Center and JPL. The spacecraft consists of an octagonal prism about 2 meters high. A thruster for delta-V maneuvers is on one end of the prism and a high-gain fixed dish antenna is on the other end. Clementine was launched on January 25, 1994 from Vandenberg Air Force Base aboard a Titan IIB rocket. After two Earth flybys, lunar insertion was achieved on February 19th. Lunar mapping took place over approximately 2 months in two systematic mapping passes over the Moon, semi major axis 5,116.0 km, eccentricity 0.36 and inclination of 90 degrees.

Procedure:

An initial and final precision fit state vectors were obtained from JPL's SPICE data sets for Clementine [13]. The gravitational field is LP150 [15], and the field is truncated to 60x60. Radiation pressure is modeled using a simple constant area. See the appendix table A.6.

Results:

The radial error after 4.8 revolutions of Clementine is 60.6 meters, the in-track error is 416.0 meters and the cross-track error is 5.3 meters see figure 5.5. There are several contributing factors to the in-track error: (1) The orbit fit of the measured data has a large error in the in-track component of 30 meters, (2) The lunar gravitational field is very complicated and gravitational models are still being refined [15] (increasing the degree and order of the model to 150x150 did not change to error results). The spacecraft is modeled as a cannonball not as a complex spacecraft for radiation pressure purposes which contributes some error. Figure 5.5 exhibits the fact that there is shadowing by the Moon, most noticeable in the in-track component. Solar and earth third body perturbations dominate the high eccentricity of Clementine orbit. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

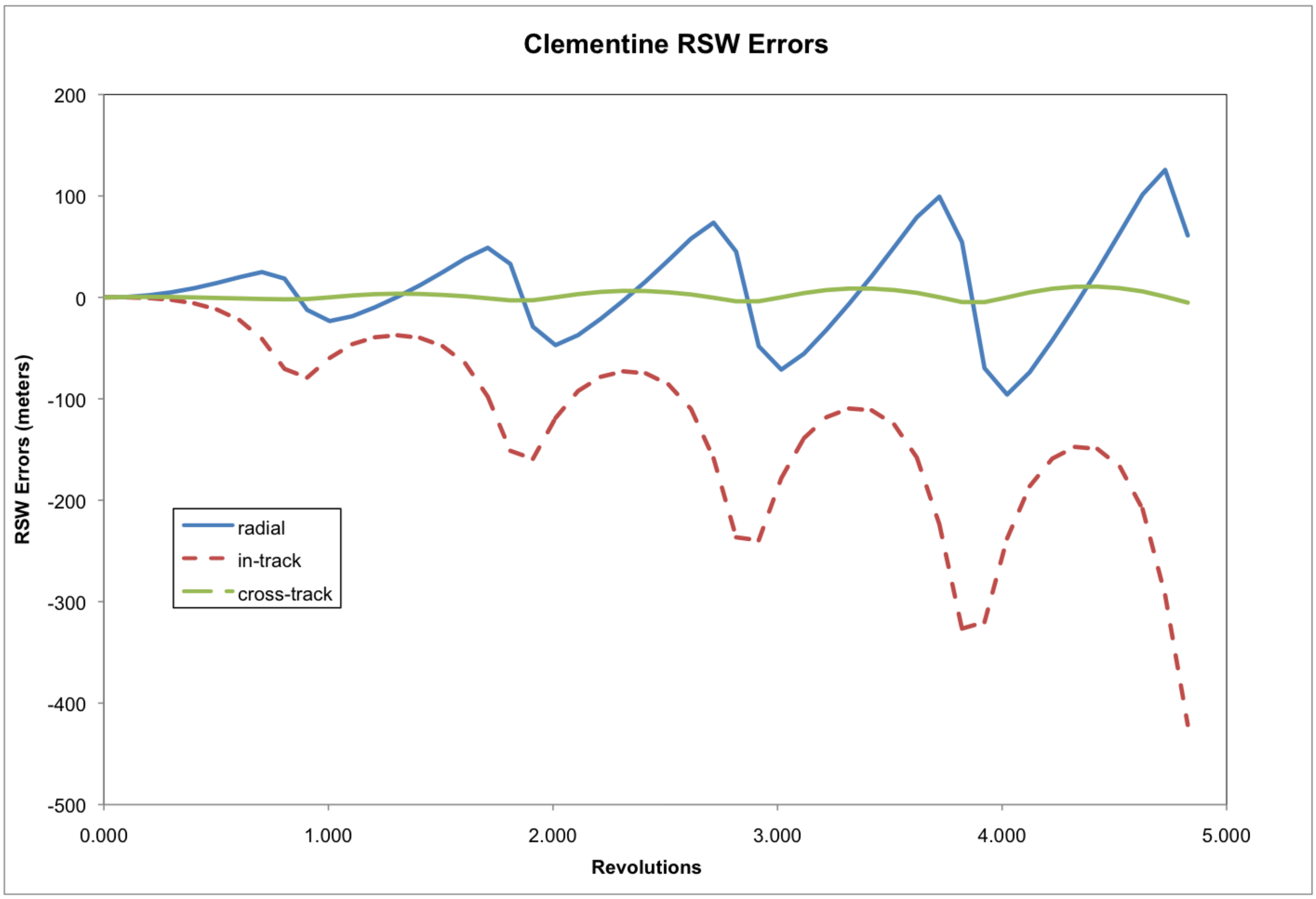

Figure 5.5: RSW errors accumulated over 4.8 revolutions (5 hr period) .

5.2.6 Earth Orbit:

Test JEOD_7: Integrated Testing Grace

Introduction:

The Gravity Recovery and Climate Experiment (GRACE) is a dedicated spaceborne mission to map the Earth's gravity field with unprecedented accuracy. The GRACE mission was launched in March 2002, for a lifetime of approximately 5 years. It consists of two satellites, co-orbiting in nearly polar orbit, at approximately 300-500 km altitude, separated by 100-500 km along track. Primary measurements are the range change between the two satellites, which represents the gravity perturbation differences between the two locations. These range changes are measured by a high accuracy microwave raging system. To detect the non-gravitational perturbations, which also affect the range change, three axis accelerometers are used. The satellites are known as Grace A and Grace B.

Procedure:

The benchmark precision orbit was obtained from Dr. John Ries [25] Center for Space Research at the University of Texas. The data was for one day (October 2 2002) starting at midnight. The state vector data was provided in 5 second intervals for both Grace A and Grace B. Earth gravity was modeled up to 36x36 terms, atmosphere was modeled using the MET atmosphere , and the Moon and Sun were third body perturbers. This simulation is a separate directory under Integrated_Validation as Sim_grace and has it's own S_define. See the appendix tables A.7, A.8

Results:

The RSW errors for both Grace A and Grace B are shown in figures 5.6 and 5.7. The two error histories are essentially the same as would be expected, since the two vehicles are in the same orbit. The in-track error is nearly 11 km after one day and fairly negligible in radial and cross-track. The benchmark measured data was in the year of the launch during a period of high solar activity. The ballistic coefficient value used in the simulation was estimated based on the mass of the vehicles, the projected area, and the coefficient of drag [25]. However it is known that there is variation in the simple projected area drag model [19]. The ballistic coefficient was varied and one can change the error; however, this is an objective of a future study. For now the user is presented with this canonical value and the errors are the metrics which, for now, characterize the JEOD modeling. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

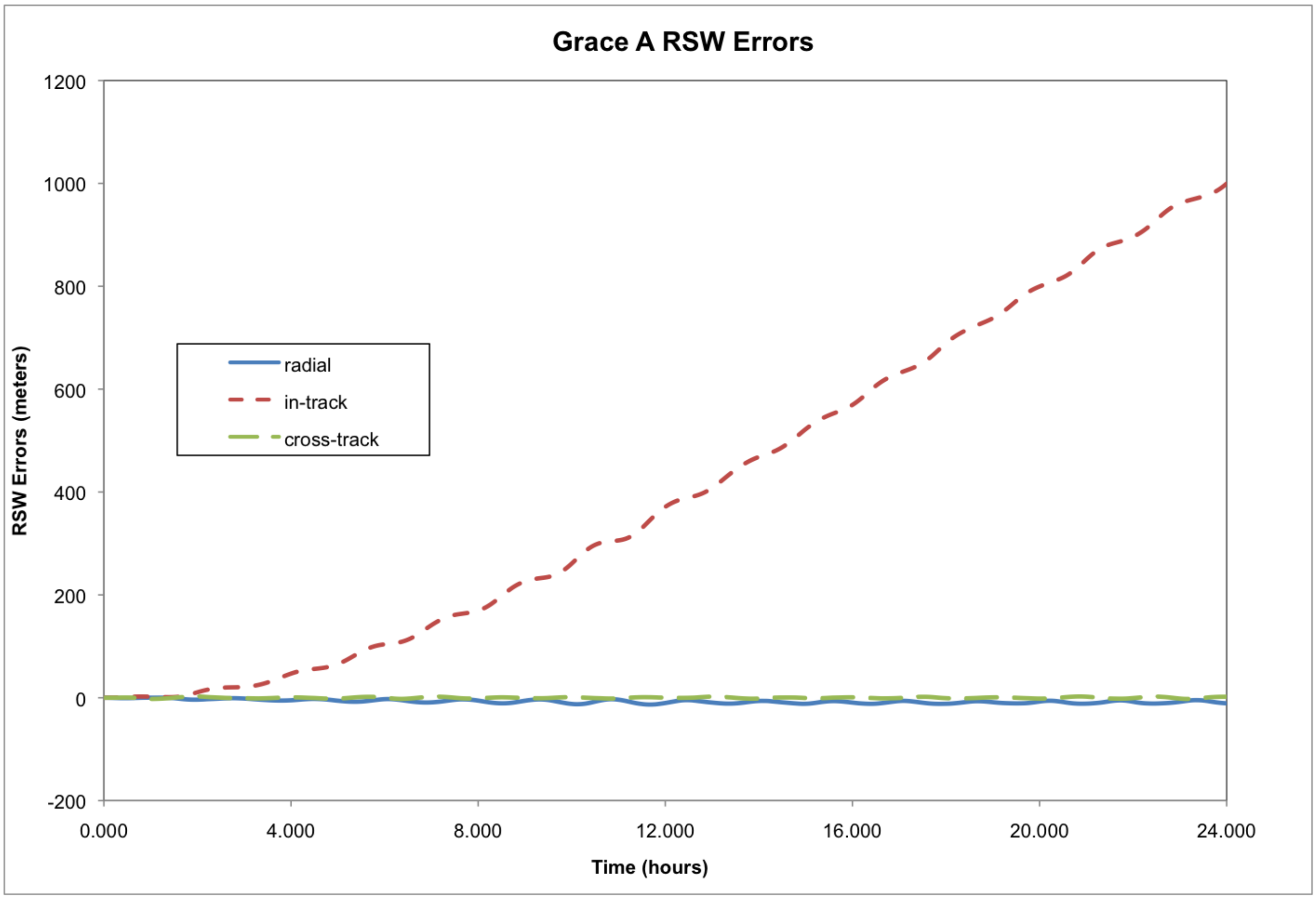

Figure 5.6: Grace A RSW errors accumulated over one day .

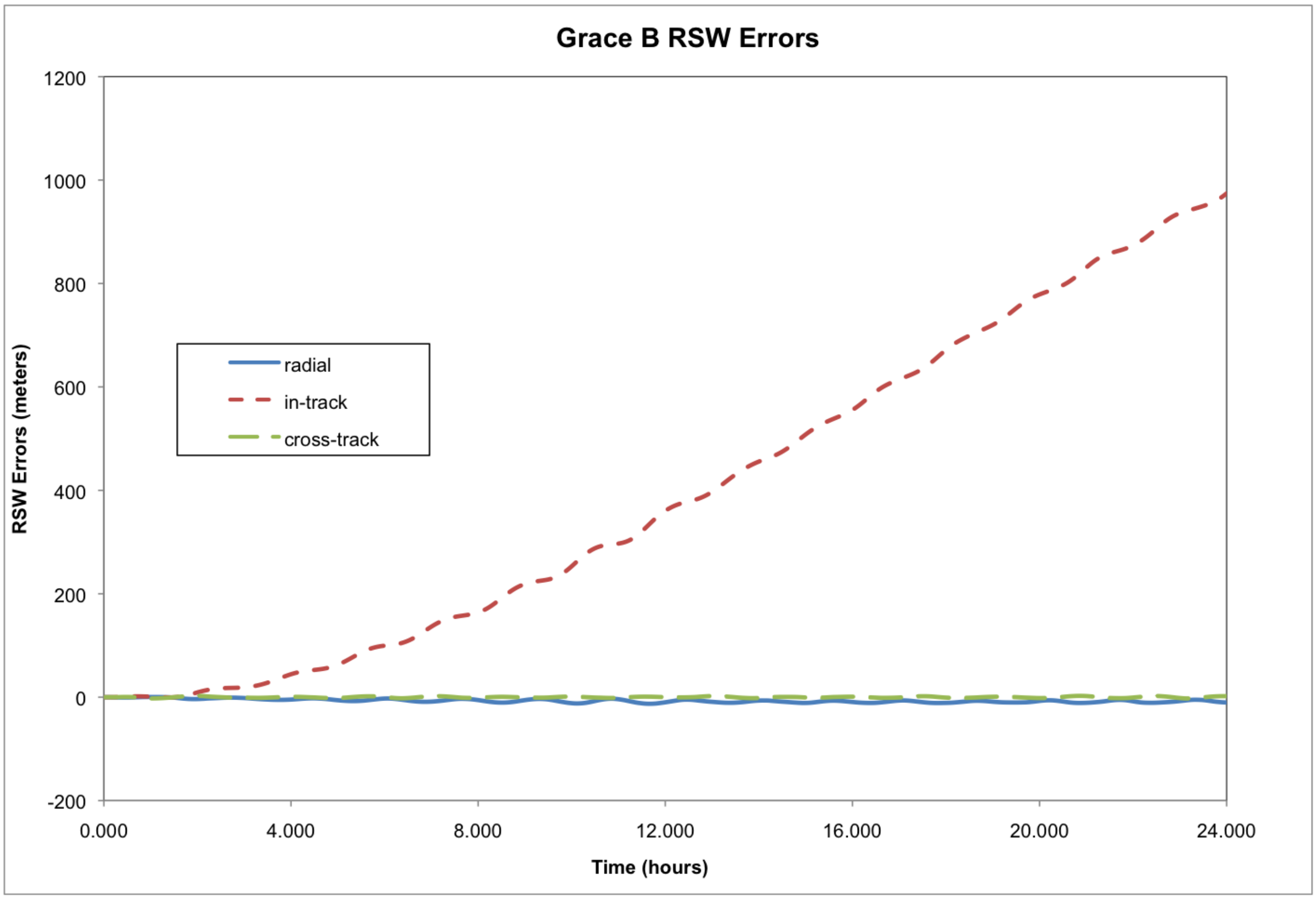

Figure 5.7: Grace B RSW errors accumulated over one day .

Test JEOD_8: Integrated Testing Rosetta

Introduction:

Rosetta is a European Space Agency-led robotic spacecraft mission launched in 2004, intended to study the comet 67P/Churyumov-Gerasimenko. Launched in March 2004 with an Ariane-5/G1 it utilizes four planetary swingby maneuvers (gravity assists) in order to get the correct Earth escape velocity to reach the comet in May 2014. The second swingby, around Mars, took place on 25 February 2007.

Procedure:

Data were obtained from the JPL Horizons system for the Earth gravity assist maneuver. The benchmark data starts about 5 min. before entry into the Earth's activity sphere and end about 7 hours later. Rosetta passed at about 5000 km altitude. The modeled forces were Earth gravity up to the J20 harmonic with Lunar and Solar perturbations and without atmosphere or radiation effects. This test exists as a run in the directory Sim_Earth_Moon. See the appendix table A.9

Results:

As can be seen in Figure 5.8, in this Earth flyby, the RSW error is small before the swingby. The radial error remains relatively small but the in-track grows to more than 8 km while the off-track is on the order of 30 km. This simulation verifies that one may set up and propagate a hyperbolic orbit about the Earth. As of this writing the source of the RSW errors is not quite understood. It may be a consequence of using the RK4 numerical integrator; however, it may be some consequence of modeling. It is noted that the simulation only missed the altitude of closest approach by less than a kilometer. The user is presented with this test and its result as a measure of this simulation. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

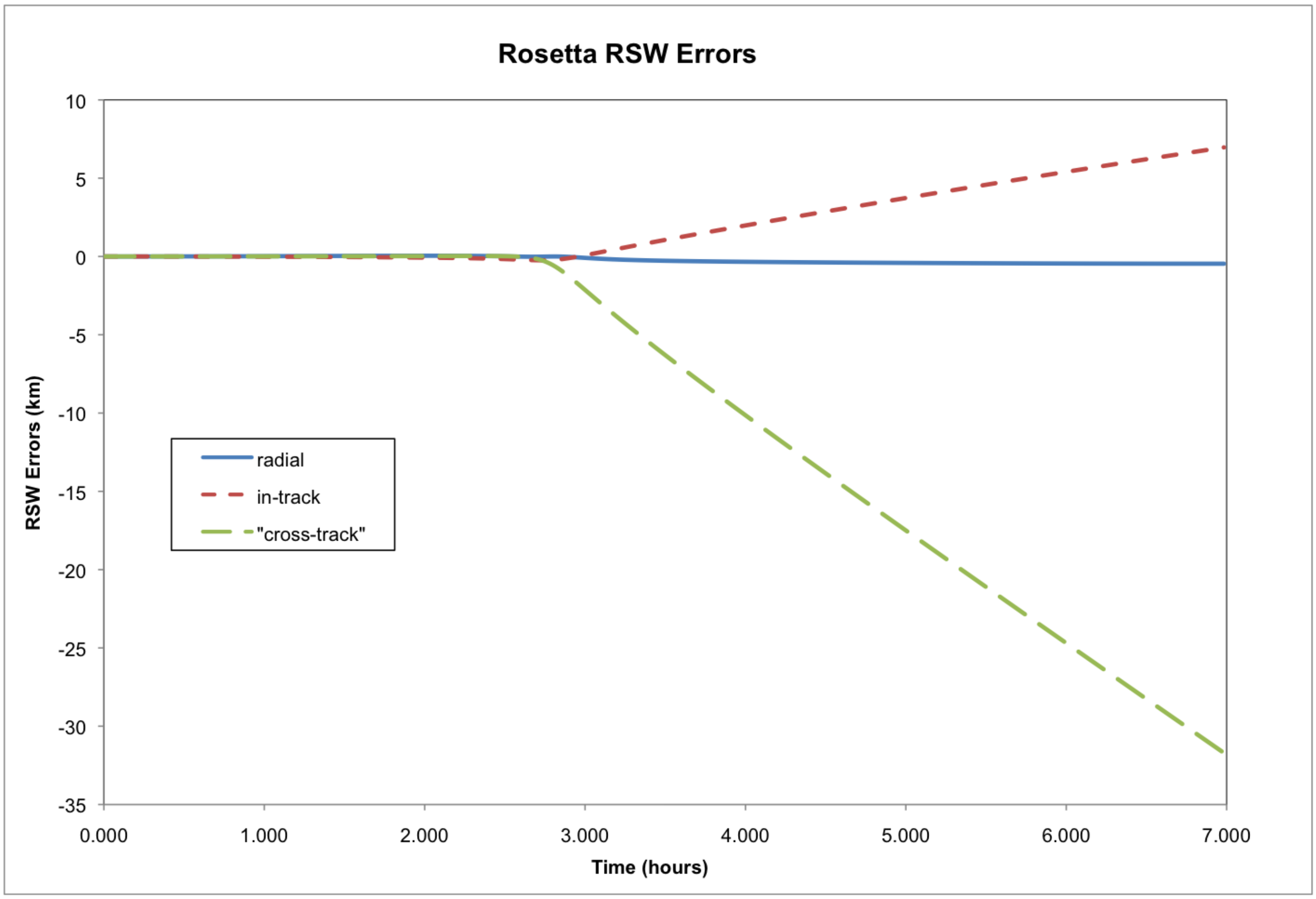

Figure 5.8: RSW errors accumulated over 7 hours .

5.2.7 Mars Orbit:

Test JEOD_9: Integrated Testing Phobos

Introduction:

Phobos is a natural satellite of Mars who's origin is debated. However, Phobos's orbit has been extensively studied and accurate models exist that describe its orbit. Phobos is orbiting Mars in a nearly circular, and near equatorial orbit. It has an inclination of 1.075 degrees with respect to the equator and an eccentricity of 0.01515. Its mean distance to Mars is only 9375 km or approximately 6000 km above the surface of Mars which has a mean radius of 3389.5 km. At this close distance it is dynamically tied to the gravity field of Mars.

Procedure:

Data was obtained from the JPL Horizons system for 24 of Phobos orbit with a data point every 10 minutes. The modeled forces were Mars non-spherical gravity with Solar perturbations. The simulation did not include atmosphere, radiation forces, Phobos libration or gravitation effects of other planets such as Jupiter.

See the appendix table A.10

Results:

As can be seen in Figure 5.9, JEOD does fairly well in tracking the motion of Phobos. The final error in the moon's in-track position of close to 200 meters is much smaller than Phobos itself, which measures 13.4 X 11.2 X 9.2 km. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

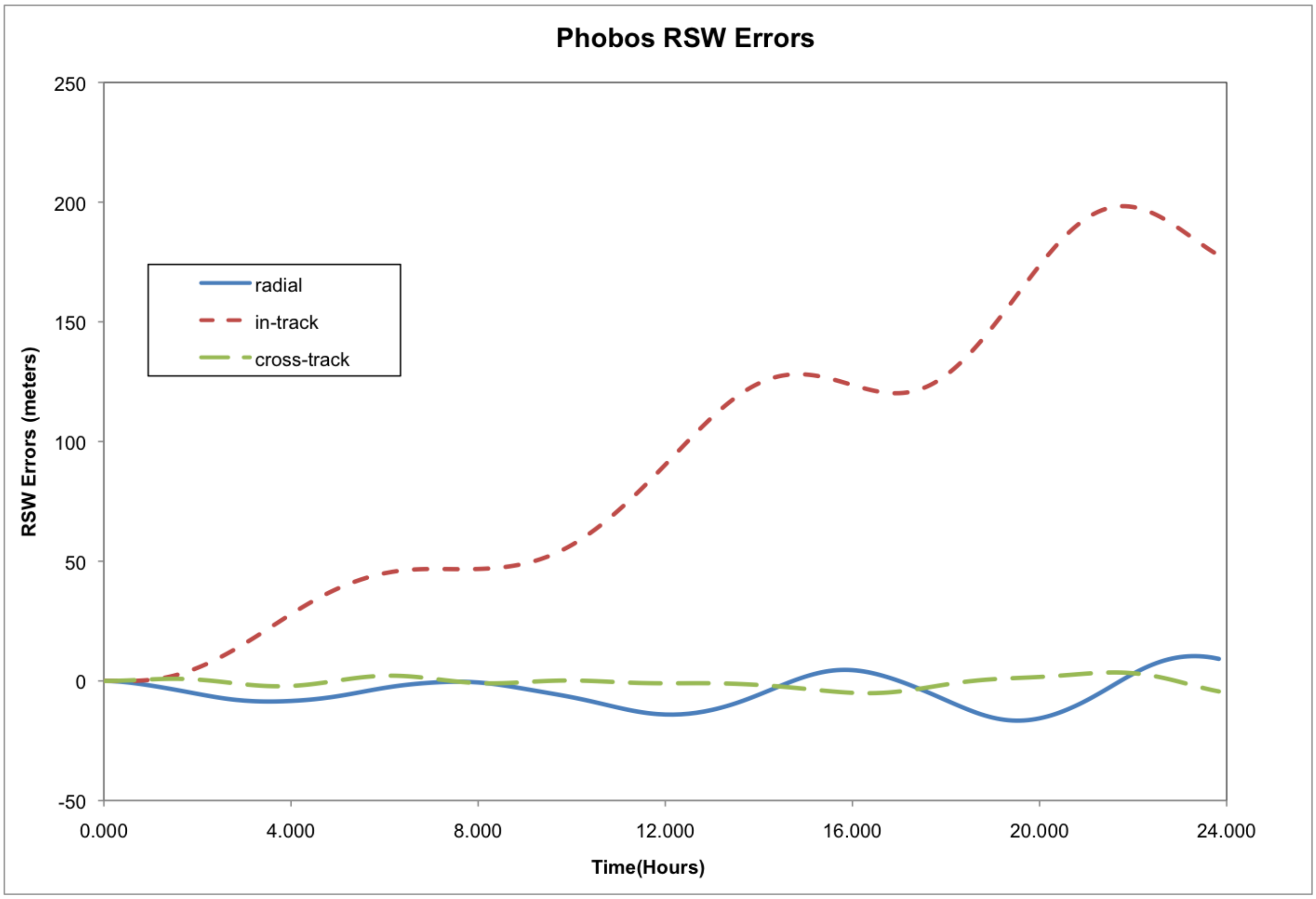

Figure 5.9: RSW errors accumulated over 24 hours.

Test JEOD_10: Integrated Testing Dawn

Introduction:

Dawn is an ion-propelled spacecraft capable of visiting multiple targets in the main asteroid belt. In the baseline mission, Dawn flies to and orbits the main belt asteroids 1 Ceres and 4 Vesta, orbiting Vesta for a period of not less than seven months and Ceres for not less than five months. The spacecraft flies by Mars in a gravity assist maneuver in 2009 en route to Vesta. The purpose of the Mars gravity assist is to add energy to the spacecraft trajectory to ensure adequate mass and power margins for the designated trajectory. The swingby event had no maneuver events.

Procedure:

Data were obtained from the JPL Horizons system for the Mars gravity assist maneuver. The benchmark data start about 1.5 hours before entry into the Mars closest approach and ends about 1.5 hours later. Dawn passed at about a 550 km altitude. The modeled forces were Mars non-spherical gravity with Solar perturbations and without atmosphere or radiation forces.

See the appendix table A.11

Results:

As can be seen in Figure 5.10, in this Mars flyby the RSW error is small before the swingby. The post encounter radial error is relativity small, the cross-track is about 3km but the in-track grows to more than 6 km. This simulation verifies that one may set up and propagate a hyperbolic orbit about Mars. As of this writing the source of the RSW errors is not quite understood, it may be a consequence of using the RK4 numerical integrator, however it may be some consequence of modeling. That the simulation only missed the altitude of closest approach by less than a kilometer. The user is presented with this test and its result as a measure of this simulation. This test partially satisfies JEOD_3, JEOD_4, and JEOD_5.

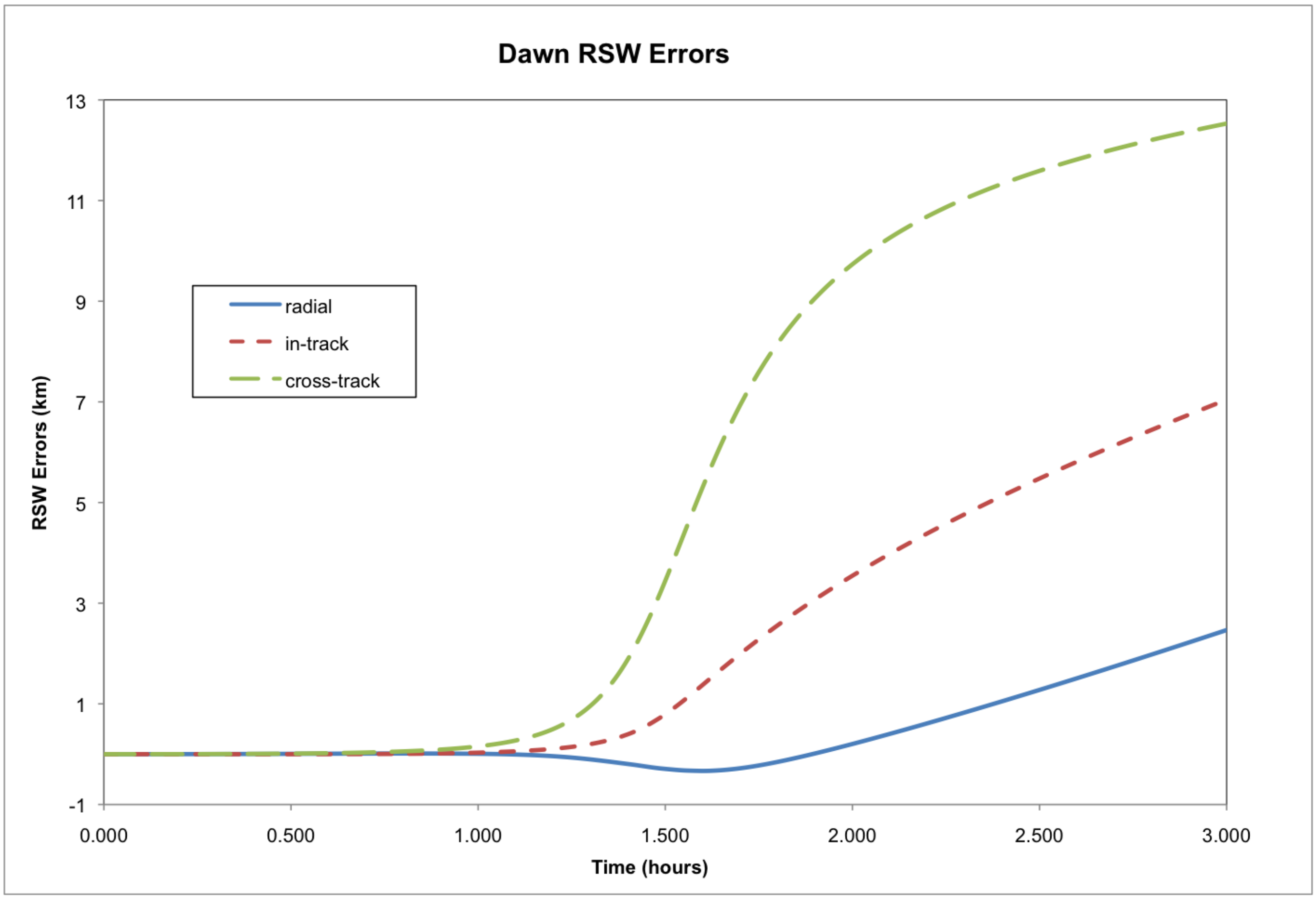

Figure 5.10: RSW errors accumulated over 3 hours.

5.3 Requirements Traceability

Table 5.2: Requirements Traceability

Requirement	Inspection or test
JEOD_1 - Documentation	Insp. JEOD_1 - Documentation
JEOD_2 - JEOD code	Insp. JEOD_2 - JEOD Coding Standards
JEOD_3 - Main Function	Test JEOD_1 and all other JEOD Integrated Validation Simulations
JEOD_4 - Relative States	Test JEOD_1 and all other JEOD Integrated Validation Simulations
JEOD_5 - Simulation Interface	Test JEOD_1 and all other JEOD Integrated Validation Simulations

5.4 Code Coverage

JEOD contains code coverage report for the entire software in HTML format, which can be found by opening "index.html" located at top level "artifact/coverage/coverage_results" directory. Code coverage report is generated using LCOV.

Appendices

Appendix A

Test States and Simulation Tests

1. Total State for the Clementine vehicle.
2. Total State for the Rosetta vehicle.
3. Total State for Phobos
4. Total State for the Dawn vehicle.

State information for the following vehicles are only available in NASA internal release of JEOD

- Total State for the CHAMP vehicle
- Total State for the ISS vehicle
- Total State for the Envisat vehicle
- Total State for the Lageos vehicle
- Total State for the TDRS vehicle
- Total State for the GRACE A vehicle.
- Total State for the GRACE B vehicle.

Location of test simulations directory verif SIM_Integrated test runs, where (5)-(11) are only available in the NASA internal release:

```
(1)  /verif/Integrated_Validation/SIM_Earth_Moon/SET_test/SET_test/RUN_clem
(2)  /verif/Integrated_Validation/SIM_Earth_Moon/SET_test/RUN_rosetta
(3)  /verif/Integrated_Validation/SIM_Mars/SET_test/RUN_phobos
(4)  /verif/Integrated_Validation/SIM_Mars/SET_test/RUN_dawn
(5)  /verif/Integrated_Validation/SIM_Earth_Moon/SET_test/SET_test/RUN_champ
(6)  /verif/Integrated_Validation/SIM_Earth_Moon/SET_test/SET_test/RUN_iss
(7)  /verif/Integrated_Validation/SIM_Earth_Moon/SET_test/SET_test/RUN_envisat
(8)  /verif/Integrated_Validation/SIM_Earth_Moon/SET_test/SET_test/RUN_lageos
```

```
(9)  /verif/Integrated_Validation/SIM_Earth_Moon/SET_test/SET_test/RUN_tdrs
(10) /verif/Integrated_Validation/SIM_Grace/SET_test/RUN_gracea
(11) /verif/Integrated_Validation/SIM_Grace/SET_test/RUN_graceb
```

This appendix provides initial state information used in the various JSC Engineering Orbital Dynamics integrated test cases. For this set of tests, there are eleven initial orbital states with four available for public release and additional of seven available only for the internal release version:

A.1 Test 1: Champ LEO State and Environment (Internal-Only)

A.2 Test 2: ISS LEO State and Environment (Internal-Only)

A.3 Test 3: ENVISAT HEO1 State and Environment (Internal-Only)

A.4 Test 4: Lageos HEO2 State and Environment (Internal-Only)

A.5 Test 5: TDRS GEO State and Environment (Internal-Only)

A.6 Test 6: Clementine Lunar Orbit State

Table A.1: Clementine State and Environment-Lunar Orbit

Epoch Data	Units	Value	Description:
Year	y	1994	Year
Month	m	03	Month
Day	d	1	Day
Hour	h	0	Hour
Min	n	0	Minute
Second	s	0.0	Second
DUT1	s	n/a	UT1 - UTC
Delta AT	s	n/a	IERS Leap Second
x_p	as	n/a2	X Polar Offset
y_p	as	n/a	Y Polar Offset
State Vector			
x_{J2000}	km	1296.94401*	X Position J2000
y_{J2000}	km	-1060.82445*	Y Position J2000
z_{J2000}	km	2522.289146*	Z Position J2000
$\dot{x}_{J2000}$	km/s	-.930578	X Component Velocity J2000
$\dot{y}_{J2000}$	km/s	-.439312	Y Component Velocity J2000
$\dot{z}_{J2000}$	km/s	.862075	Z Component Velocity J2000
Atmosphere data			
$F_{10.7}$	W/H_zm^2	n/a	UV Correlated Solar radio noise flux
$F_{10.7B}$	W/H_zm^2	n/a	90 day average UV Correlated Solar radio noise flux
a_p	NA	n/a	Geomagnetic Activity Index
Aerodynamic data			
C_d	None	n/a	Coefficient of drag
BC	kg/m^2	n/a	Ballistic Coefficient
Mass	kg	424.0	Vehicle Mass
Area	m^2	2.1432	Vehicle Reference Area
Cr	$None$	1.23	Vehicle Coefficient of Reflection

Radial error ± 1.5 meters , in-track ± 30 meters and ± 10 meters cross-track, [16] .

A.7 Test 7: GRACE Orbit State (Internal-Only)

A.8 Test 8: GRACE Orbit State (Internal-Only)

A.9 Test 9: Rosetta Orbit State

Table A.2: Rosetta State and Environment

Epoch Data	Units	Value	Description:
Year	y	2009	Year
Month	m	11	Month
Day	d	13	Day
Hour	h	05	Hour
Min	n	0	Minute
Second	s	0.0	Second
DUT1	s auto select		UT1 - UTC
Delta AT	s auto select		IERS Leap Second
x_p	as auto select		X Polar Offset
y_p	as auto select		Y Polar Offset
State Vector			
x_{J2000}	km	87396.6219145 ± 2 m*	X Position J2000
y_{J2000}	km	23042.6606938 ± 2 m*	Y Position J2000
z_{J2000}	km	-48761.8708343 ± 2 m*	Z Position J2000
$\dot{x}_{J2000}$	km/s	-7.8839651 ± .1 mm/s*	X Component Velocity J2000
$\dot{y}_{J2000}$	km/s	-3.2492092 ± .1 mm/s*	Y Component Velocity J2000
$\dot{z}_{J2000}$	km/s	4.7952127 ± .1 mm/s*	Z Component Velocity J2000
Atmosphere data			
$F_{10.7}$	$W/H_z m^2$	N/A	UV Correlated Solar radio noise flux
$F_{10.7B}$	$W/H_z m^2$	N/A	90 day average UV Correlated Solar radio noise flux
a_p	NA	N/A	Geomagnetic Activity Index
Aerodynamic data			
C_d	None	N/A	Coefficient of drag
BC	kg/m^2	N/A	Ballistic Coefficient
Mass	kg	3000.0	Vehicle Mass
Area	m^2	N/A	Vehicle Reference Area

*Error analysis [22]

A.10 Test 10: Phobos Orbit State

Table A.3: Phobos State and Environment

Epoch Data	Units	Value	Description:
Year	y	2010	Year
Month	m	09	Month
Day	d	10	Day
Hour	h	0	Hour
Min	n	0	Minute
Second	s	0.0	Second
DUT1	s auto select		UT1 - UTC
Delta AT	s auto select		IERS Leap Second
x_p	as auto select		X Polar Offset
y_p	as auto select		Y Polar Offset
State Vector			
x_{J2000}	km	8240.7901108 $\pm$ 2 m*	X Position J2000
y_{J2000}	km	605.0716371 $\pm$ 2 m*	Y Position J2000
z_{J2000}	km	-4152.5375845 $\pm$ 2 m*	Z Position J2000
$\dot{x}_{J2000}$	km/s	0.3077392 $\pm$ .1 mm/s*	X Component Velocity J2000
$\dot{y}_{J2000}$	km/s	1.9627295 $\pm$ .1 mm/s*	Y Component Velocity J2000
$\dot{z}_{J2000}$	km/s	0.8655744 $\pm$ .1 mm/s*	Z Component Velocity J2000
Atmosphere data			
$F_{10.7}$	W/H_zm^2	N/A	UV Correlated Solar radio noise flux
$F_{10.7B}$	W/H_zm^2	N/A	90 day average UV Correlated Solar radio noise flux
a_p	NA	N/A	Geomagnetic Activity Index
Aerodynamic data			
C_d	None	N/A	Coefficient of drag
BC	kg/m^2	N/A	Ballistic Coefficient
Mass	kg	1.08e+16	Vehicle Mass
Area	m^2	N/A	Vehicle Reference Area

*Error analysis [22]

A.11 Test 11: Dawn Orbit State

Table A.4: Dawn State and Environment

Epoch Data	Units	Value	Description:
Year	y	2009	Year
Month	m	02	Month
Day	d	17	Day
Hour	h	23	Hour
Min	n	0	Minute
Second	s	0.0	Second
DUT1	s auto select		UT1 - UTC
Delta AT	s auto select		IERS Leap Second
x_p	as auto select		X Polar Offset
y_p	as auto select		Y Polar Offset
State Vector			
x_{J2000}	km	11563.3556802 $\pm$ 2 m*	X Position J2000
y_{J2000}	km	-14356.6688977 $\pm$ 2 m*	Y Position J2000
z_{J2000}	km	6293.7046169 $\pm$ 2 m*	Z Position J2000
$\dot{x}_{J2000}$	km/s	-2.2731078 $\pm$ .1 mm/s*	X Component Velocity J2000
$\dot{y}_{J2000}$	km/s	2.3801324 $\pm$ .1 mm/s*	Y Component Velocity J2000
$\dot{z}_{J2000}$	km/s	-.0229110 $\pm$ .1 mm/s*	Z Component Velocity J2000
Atmosphere data			
$F_{10.7}$	$W/H_z m^2$	N/A	UV Correlated Solar radio noise flux
$F_{10.7B}$	$W/H_z m^2$	N/A	90 day average UV Correlated Solar radio noise flux
a_p	NA	N/A	Geomagnetic Activity Index
Aerodynamic data			
C_d	None	N/A	Coefficient of drag
BC	kg/m^2	N/A	Ballistic Coefficient
Mass	kg	1250.0	Vehicle Mass
Area	m^2	N/A	Vehicle Reference Area

*Error analysis [22]

Appendix B

Assumptions and Limitations on Earth Orientation

The use of GGM02C has important implications due to requirements contained in the GRACE geopotential campaign [34]. A non-spherical gravity field was fit using a model of the Earth's orientation that differs from the one in JEOD. The difference as of the present time is quite small. JEOD uses an Earth orientation known as the IAU-76/FK5 [3] and the Explanatory Supplement to the Astronomical Almanac [29], which conformed to an older Goddard gravity model used in Trick Dynamics in the 1990's. However in 2003 the International Earth Rotational Service (IERS) and the Jet Propulsion Laboratory adopted a system under the name J2000. The Earth orientation model simplifies polar motion and introduces a new formulation for the construction of a new RNP [20]. Vallado [42] notes that as time goes by IAU-76/FK and J2000 models will diverge. This has been noted as a JEOD issue and will be addressed in later releases. The J2000 coordinate system is defined by(see reference [20]):

1. Coordinate Frame: Non-Rotating Inertial,
2. Z-axis: Defined as the pole vector of the Earth Mean Equator of J2000 (where J2000 = Julian date 2451545.0 TDB (Barycentric Dynamical Time)),
3. X-axis: Defined as the cross product of the Z-axis (as defined above) and the Earth mean orbit pole of J2000 (i.e. the ecliptic pole of J2000). The X-axis of this coordinate frame is the Earth vernal equinox of J2000,
4. Y-axis: Completes a standard, right-handed coordinate frame.

For futher information on coordinate systems see Constellation Program Level 2 Coordinate Systems

Appendix C

Assumptions about Lunar Orientation

The Lunar orientation is extracted from the JPL Development Ephemeris by extraction from fitted data. It should be noted that the specified non-spherical Lunar gravity model does not have an analytic RNP model similar to the Earth. The lunar libration (lunar orientation) data are present on the JPL Development Ephemeris file, and this software uses this libration data to determine the directions of the Moon's pole and prime meridian. Further information from JPL is linked to this document see the JPL Lunar Constants document Lunar Constants and Models Document.

Appendix D

Definition of RSW System

The radial, in-track and cross-track coordinate system is defined by Vallado [42]: (The term RSW is somewhat arbitrary and of historical origin; the designation R is 'radial', S and W.) Origin: Any Point of Interest Orientation: The R-S plane is the instantaneous orbit plane at epoch. The R axis lies along the geocentric radius vector to the point of interest and is positive radially outward. The W axis lies along the instantaneous orbital angular momentum vector at epoch and is positive in the direction of the angular momentum vector. The S axis completes the right-handed triad (See Figure D.1).

$\mathbf{r}$ = position vector
$\mathbf{v}$ = velocity vector

$$\hat{\mathrm{r}} = \frac{\mathbf{r}}{\mathrm{r}}$$

$$\hat{\mathbf{w}} = \frac{\mathbf{r} \times \mathbf{v}}{|\mathbf{r} \times \mathbf{v}|}$$

$$\hat{\mathbf{s}} = \mathbf{w} \times \mathbf{r}$$

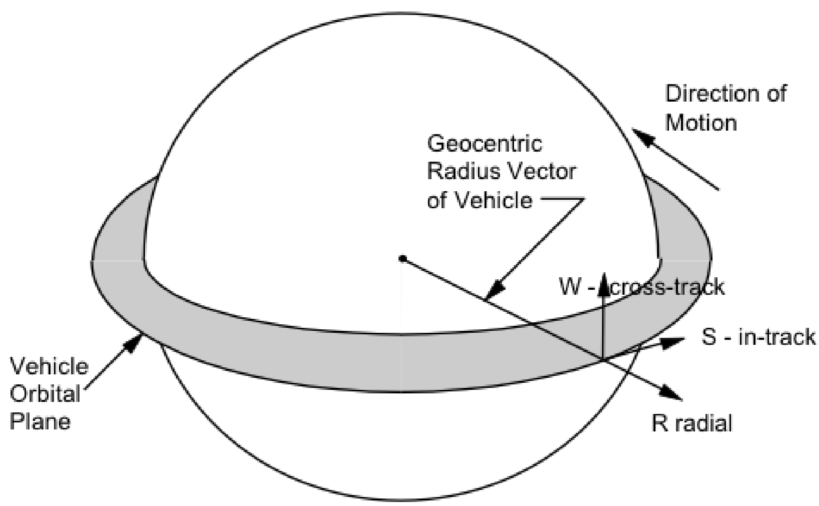

Figure D.1: RSW Coordinate System .

Appendix E

Benchmarks

The Integrated testing precision measured orbit fit data are located in directory:

```
/verif/Integrated_Validation/Benchmarks
the directories are:
 ROSETTA_benchmark/
 DAWN_benchmark/
 Clementine_benchmark/

 (NASA Internal Release)
 TDRS_benchmark/
 LAGEOS_benchmark/
 ISS_benchmark/
 ENVISAT_benchmark/
 CHAMP_benchmark/
 GRACE_benchmark/
```

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