Earth Global Reference Atmospheric Model 2007 (Earth-GRAM07)

Initial Assessment

Exploration Systems Mission Directorate (ESMD)

April 13, 2007
Baseline Draft Version 1.0

National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

TABLE OF CONTENTS

Place holder for list of tables and list of figures

Document Change History

Revision	Effective	Description of Changes
1.0		

MODELING AND SIMULATION (M&S)
INITIAL ASSESSMENT FOR EARTH-GRAM2007

CONCURRENCE

	Signature:	Date:
Prepared By:	Dr. Fred Leslie, Earth-GRAM2007 Lead	
Concurred By:	TBD, VV&A Broker	
Concurred By:	Dr. Carl G. Justus, Earth-GRAM2007 Developer, Stanley Associates~~Morgan Research~~	
Concurred By:	Dr. Jeff Anderson, Environments and Constraints SIG Panel	
Concurred By:	Mr. Joe Hale, VV&A TWG Chair	
Concurred By:	Mr. Randy Wallace, M&S TWG Chair	
Approved By:	Mr. Don Monell, NASA, MSFC NP-21, M&S Lead	

FOREWARD

The Environments and Constraints SIG chairs, Jeff Anderson and Dave Cheuvront, have selected Earth-GRAM2007 to define the atmospheric environment for the Constellation program. This model is described and referenced in the Natural Environments Definition for Design (NEDD) and the Design Specification for Natural Environments (DSNE) documents. Earth-GRAM2007 was developed by civil servants and contractors in the Natural Environments Branch, ~~EV13~~EV44 at the Marshall Space Flight Center.

EXECUTIVE SUMMARY

TBD

1.0 INTRODUCTION AND GENERAL OVERVIEW

The purpose of this report is to provide the Explorations Systems Mission Directorate (ESMD) with a document that aids in the assessment of the Earth-Global Reference Atmospheric Model version 2007 (Earth-GRAM07) to serve as a credible model for the Earth's atmosphere used for vehicle ascent, entry, and ground operations.

This Initial Assessment document aims to provide decision makers a general idea of the Earth-GRAM07's capability, and the major objects and functions represented. Development of Initial Assessment documentation is a systematic, disciplined method for managing, minimizing and documenting the uncertainty associated with the use of modeling and simulation.

The fundamental goal of this process is to ensure that models and simulations supporting the advancement of U.S. scientific, security, and economic interest through a robust space exploration program are sufficiently credible and have undergone a rigorous verification and validation process to mitigate risks inherent in their use. The report will assist in determining the scope of the accreditation assessment.

2.0 APPLICATION

Reference or Standard atmospheric models have long been used for design and mission planning of various aerospace systems. The NASA/MSFC Global Reference Atmospheric Model (GRAM) was developed in response to the need for a design reference atmosphere that provides complete global geographical variability, and complete altitude coverage (surface to orbital altitudes) as well as complete seasonal and monthly variability of the thermodynamic variables and wind components. Another unique feature of GRAM is that, in addition to providing the geographical, height, and monthly variation of the mean atmospheric state, it can simulate spatial and temporal perturbations of these atmospheric parameters (e.g. fluctuations due to turbulence and other atmospheric perturbation phenomena). Earth-GRAM07 is the latest development of this series. GRAM was originally developed to provide the expected environment for Shuttle re-entry. Application of these models now include defining the natural environment for ground transportation, on-pad, launch, re-entry, and recovery of space and air vehicles. For example, Earth-GRAM07 can provide winds (including fluctuations) that affect the stress on hold-down bolts for a vehicle on a mobile launch platform, air density for in-plane and out-of-plane maximum dynamic pressure, wind gusts that affect ascent performance or vehicle loads, upper air density and temperature for computing re-entry heating as well as guidance, control, and aero-braking data, etc.

3.0 M&S DESCRIPTION

Like earlier versions, Earth-GRAM07 is a compilation of several empirically-based models that represent different altitude ranges (and the geographical and temporal variations within these altitude ranges). In the region from the surface to 27 km, Earth-GRAM07 uses the Global Upper Air Climatic Atlas (GUACA) CD-ROM data of Ruth et al. (Ref 22). Alternatively Earth-GRAM07 allows optional use of an ASCII-formatted Global Gridded Upper Air Statistics (GGUAS) database for this height region. These data came from measurements taken aboard aircraft, balloons, and satellites. Another option for the lower atmosphere is to use Range Reference Atmosphere (RRA) data, which have been compiled from balloon and rocketsonde data at several launch-range locations. The middle atmospheric region (20 to 120 km) data set is compiled from the Middle Atmosphere Program (MAP) data (Ref. 8) and other sources referenced in the GRAM-90 and GRAM-95 reports (updateRefs. 5, 6). These data come from rocket and remote sensing measurements. The highest altitude region (above 90 km) is simulated by the Jacchia (1970) model (Ref. 9) and implemented in the Marshall Engineering Thermosphere (MET) model (Refs. 10, 11). Instead of the MET model, users have the option to select the Naval Research Lab Mass Spectrometer, Incoherent Scatter (MSIS) Radar Extended Model (make ref to Hedin) or the Jacchia-

Bowman 2006 (JB2006) Thermospheric Model (see ref . These data come primarily from satellite measurements. Smooth transition between the altitude regions is provided by fairing techniques. Unlike interpolation (used to "fill in" values across a gap in data), fairing is a process that provides a smooth transition from one set of data to another where they overlap (e.g., 20 to 27 km for GUACA/GGUAS and MAP data and 90 to 120 km for MAP data and MET model

3.1 GENERAL CAPABILITIES

Earth-GRAM07 is provided as both a stand-alone version, and in subroutine form, suitable for the user to integrate into user-provided applications, such as trajectory-computing programs. For any atmospheric trajectory provided by the user, stand-alone Earth-GRAM07 provides mean atmospheric values of temperature, pressure, density, east-west wind component, north-south wind component, vertical wind, water vapor pressure, water vapor density and relative humidity as well as the concentration of the following constituent gases: O_3, N_2O, CO, CH_4, CO_2, N_2, O_2, O, Ar, He, H, N. This computation is performed by an interpolation scheme using an empirical database. As an option, Earth-GRAM07 can also provide perturbed values of temperature, pressure, density, east-west wind component, north-south wind component and vertical wind. This is accomplished with a variable length-scale perturbation model which uses the observed standard deviations to drive the variability. A one step Markov technique is used for the small scale perturbations which produces the energy distribution of the Dryden power spectrum. User-provided seed values (which need not be random) drive the random components. The large scale perturbations are modeled with a cosine function to represent the wave nature of that scale. Variability in the large scale is introduced by a randomly varying horizontal and vertical length scale as well as a random wave phase. If a large number of Monte Carlo runs are performed, the resulting mean and standard deviation will match that of the observations in the internal database. All of these capabilities are also provided by the subroutine version of Earth-GRAM07, and can be produced “on the fly”, as a trajectory program uses the atmospheric parameters to dynamically calculate trajectory positions and velocities.

3.1.1 M&S SCOPE

In practice, Earth-GRAM07 is applicable from the surface out to about 1,000 km above the surface. Any month, day, and time of day can be used for input, although Earth-GRAM07 uses monthly mean values in the lower atmosphere and the daily variability within a month is computed from the observed monthly standard deviation.

3.1.2 M&S TYPE

Earth-GRAM07 is an empirically-~~-~~based model with some physical constraints such as the ideal gas law, hydrostatics, and geostrophic balance, depending on altitude. The perturbed values have~~s~~ a correlated component as well as a random contribution.

3.2 M&S ASSUMPTIONS, LIMITATIONS, AND ERRORS

3.2.1 ASSUMPTIONS

Below 27 km, Earth-GRAM07 uses a database (GUACA) of global atmospheric measurements taken between 1980 and 1991~~. It is assumed that the climate has not significantly changed between that period and date input by the use~~r. Two versions of Range Reference Atmosphere (RRA) statistics are also available for optional use. The earlier (1983) version RRA data were compiled from a period of record generally encompassing the late 1950’s to the late 1970’s. The later (2006) RRA data primarily cover the period from 1990 to early 2002. These various GUACA and RRA options allow examination of how much the atmospheric climatology may have changed over this period of several decades.

3.2.2 KNOWN LIMITATIONS / ERRORS

Since Earth-GRAM07 is empirically-based, the errors below the thermosphere are associated with errors in the measurements. These errors are approximately **xC for temperature, x for pressure, x for density, and x for wind speed. Concentration?** A potential limitation is that the model does not provide atmospheric information regarding clouds, visibility, lightning, precipitation, or thunderstorm activity.

3.2.3 POTENTIAL SOLUTIONS TO ERRORS, LIMITATIONS, AND SHORTCOMINGS

Earth-GRAM07 has two options for providing more contemporary observations. The user may choose to use the 2006 Range Reference Atmosphere (RRA) data set that is part of the software package. Alternatively, the user may provide other observations to drive the model by utilizing the Auxiliary Profile option.

3.3 USE HISTORY

3.3.1 CURRENT USER BASE

A database of users of the various versions of GRAM is maintained in the Natural Environments Branch (Mail Code: ~~EV13~~EV44) within the Engineering Directorate of the Marshall Space Flight Center.

3.3.2 MAJOR STUDIES SUPPORTED

The original GRAM was developed and released in 1974 (Ref. 14) for purposes of designing reentry guidance and control systems and thermal protection systems for the Space Shuttle. Since that time, several GRAM versions have been released, and have been used to support a wide variety of studies, both within NASA, and by "customers" from other government agencies, private companies, and universities. Major NASA studies supported by GRAM include:

Shuttle Entry Systems –
- Guidance, navigation and control systems
- Entry thermal protection systems
- Reaction Control System (RCS) thruster fuel usage during entry operations
- STS107 (Columbia) accident investigation support

Shuttle Launch Systems –
- Protuberance Air Load (PAL) ramp analysis
- "S9" launch thermal rule analysis

Other NASA Concepts or Spacecraft –
- National AeroSpace Plane (NASP), including the NASP real-time flight simulator
- X33
- X37
- X38
- X43A (Hyper-X)
- Genesis and Stardust (landing ellipse dispersion uncertainty and parachute deploy "spoofing")

Formatted: Font: Arial, 10 pt

Formatted: Font: Arial, 10 pt

3.4 CONCEPT OF OPERATIONS

Earth-GRAM07 is provided as a FORTRAN source code in order to allow the user maximum flexibility for controlling the output, trouble-shooting compiler issues, or imbedding it within another program. It is typically operated in either a stand-alone mode or within a user supplied trajectory code. In either case, the user must select parameters for the input file for the proper output. An example input file is provided with the code along with the resulting output file so the user can check that they have properly implemented the software. An executable is provided for the stand-alone version so that no further compiling is necessary. However, in order to run Earth-GRAM07 within a trajectory code, the user must merge the two programs together. An example of how to call Earth-GRAM07 from a trajectory code is also provided with the software.

3.5 M&S ARCHITECTURE

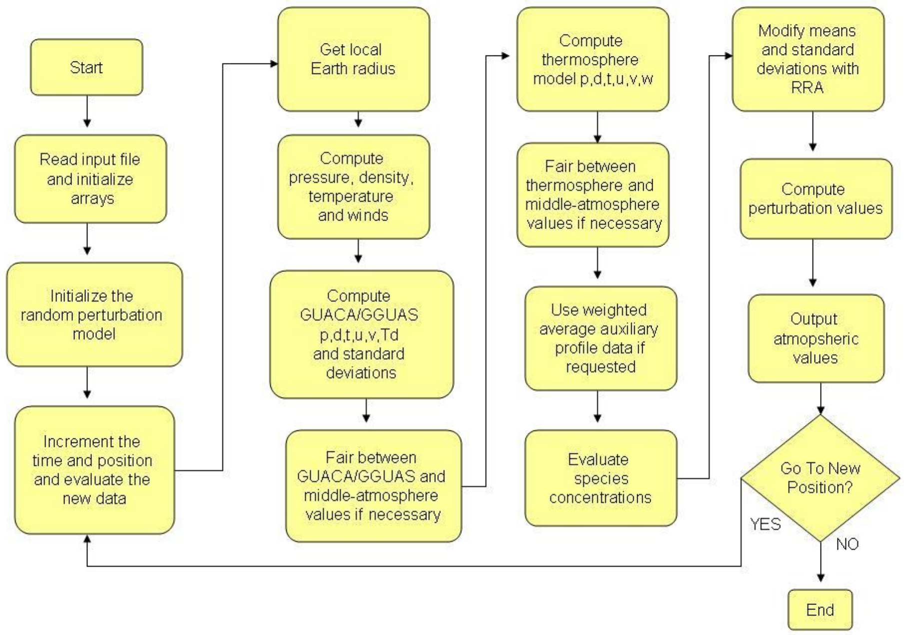
3.5.1 SUMMARY OF MODELS

Earth-GRAM07 partitions the atmosphere into 3 vertical layers and uses a different model for each one to determine environmental mean values. A fairing technique is used in regions where the models overlap. Optional use can be made of RRA's or an auxiliary profile. Dispersion about the mean can be generated at all levels using a large-scale and small-scale perturbation model driven by the observed standard deviations. Table X below summarizes the models.
(insert table ref)

Altitude Range (km)	Model Used
0 – 27	Global Upper Air Climatic Atlas (GUACA) or Global Gridded Upper Air Statistics (GGUAS) is the default
0 - 70	1983 Range Reference Atmosphere (RRA) is optional
0 - 70	2006 Range Reference Atmosphere (RRA) is optional
20 – 120	Middle Atmosphere Program (MAP)
Above 90	Marshall Engineering Thermosphere (MET) is the default
Above 90	Mass Spectrometer, Incoherent Scatter Radar Extended Model (MSIS) is optional
Above 90	Jacchia-Bowman 2006 (JB2006) is optional
Any Altitude	User supplied Auxiliary Profile is optional
All Altitudes	Markov technique for small scale perturbations driven by observed standard deviation
All Altitudes	Cosine model for large scale perturbations driven by observed standard deviation

3.5.2 SOFTWARE MODULES

Earth-GRAM07 relies on various mathematical subroutines and functions to generate the environment. Some of the internal models and subroutines are taken from publications (e.g. the pseudo-random number generator routine) and some were developed from data collected from various research efforts (e.g. the MAP data base). A coarse flow chart of the code is shown in the figure below:



3.5.3 INTERFACE CHARACTERIZATION

3.5.3.1 USER INTERFACE

Before running the Earth-GRAM07 code, the user must select values for the input file. An example of the input file is shown below and a detailed description of each parameter is given in the documentation that accompanies the software.

Table?

$namein
atmpath = 'D:\EarthGRAM07~~Beta~~\PC_IOfiles\atmosdat.txt'
guapath = 'D:\EarthGRAM07~~Beta~~\GUACAdata'
trapath = 'null'
prtpath = 'output.txt'
nprpath = 'special.txt'
conpath = 'species.txt'
rndpath = 'null'
rrapath = 'D:\EarthGRAM07~~Beta~~\RRAdata'
profile = 'null'
h1 = 140.
phi1 = 0.45
thet1 = -164.53
f10 = 230.
f10b = 230.
ap = 20.3

```
  s10     = 0.
  s10b    = 0.
  xm10    = 0.
  xm10b   = 0.
  mn = 1
  ida = 1
  iyr = 2007
  ihro = 0
  mino = 0
  seco = 0.0
  dphi = 0.4
  dthet = 1.2
  dhgt = -2.0
  nmax = 71
  delt = 60.0
  iopt = 0
  iopp = 17
  iu0 = 0
  iup = 6
  ius = 3
  iuc = 4
  iug = 22
  iguayr = 1
  iopr = 1
  nr1 = 1234
  iun = 0
  rpscale = 1.0
  iurra = 0
  iyrrra = 1
  sitelim = 2.5
  sitenear = 0.5
  initpert = 0
  rpinit = 0.
  rdinit = 0.
  rtinit = 0.
  ruinit = 0.
  rvinit = 0.
  rwinit = 0.
  patchy = 0.
  itherm = 1
 $End
Parameter Descriptions:
atmpath = path name for "atmosdat" atmospheric data file
guapath = path name for GUACA or GGUAS files
trapath = path name for trajectory input file ('null' if none)
prtpath = path name for standard formatted output file  ('null' if none)
nprpath = path name for the "special" format output file ('null' if none)
conpath = path name for species concentration output file ('null' if none)
rndpath = path name for file containing more  random number seeds (optional)
rrapath = DIRECTORY for Range Reference Atmosphere data
profile = path name for auxiliary profile data ('null' if none)
h1      = initial height (km).  Heights > 6000 km are interpreted as radius.
phi1    = initial latitude (degrees, N positive)
thet1   = initial longitude (degrees, East positive)
f10     = daily 10.7-cm flux
f10b    = mean 10.7-cm flux
ap      = geomagnetic index
```

```
s10     = EUV index (26-34 nm) scaled to F10 units (0.0 -> s10=f10)
s10b    = EUV 81-day center-averaged index (0.0 -> s10b = f10b)
xm10    = MG2 index scaled to F10 units (0.0 -> xm10 = f10)
xm10b   = MG2 81-day center-averaged index (0.0 -> xm10b = f10b)
mn      = month (1-12)
ida     = day of month
iyr     = 4-digit year, or 2-digit year: >56=19xx <57=20XX
ihro    = initial UTC (Greenwich) time hour (0-23)
mino    = initial UTC (Greenwich) time minutes (0-59)
seco    = initial UTC (Greenwich) time seconds (0.0-60.0)
dphi    = latitude increment (degrees, Northward positive)
dthet   = longitude increment (degrees, Eastward positive)
dhgt    = height increment (km, upward positive). If radius input is used,
            dhgt is interpreted as a radius increment.
nmax    = maximum number of positions (including initial one; 0 means read
            trajectory input file)
delt    = time increment between positions (real seconds)
iopt    = trajectory option (0 = no trajectory data; otherwise unit number
            for trajectory input file)
iopp    = "special" output option (0 = no "special" output; otherwise unit
            number of "special" output file)
iu0     = unit number for screen output (normally 6 or 0)
iup     = unit number for standard formatted output file (0 for none)
ius     = unit number for atmosdat data
iuc     = unit number for concentrations output (0 for none)
iug     = unit for GUACA or GGUAS input data, 0-27km (0 for no GUACA or
            GGUAS data)
iguayr  = Use: 1 for GUACA period of record, 2 for actual GUACA year (1985-
            1991), based on iyr from input above, 3 for binary data conver-
            ted from ASCII Global Gridded Upper Air Statistics (GGUAS) POR
            data (conversion done with GGUASRD program, provided)
iopr    = random output option (1 = random output, 2 = none)
nr1     = first starting random number (1 to 9 * 10**8)
iun     = unit number for more starting random numbers (0 for none)
rpscale = random perturbation scale; nominal=1.0, max=2.0, min=0.1
iurra   = unit number for Range Reference Atmosphere (RRA) data (0 if none)
iyrrra  = 1 for 1983 RRAs or 2 for 2006 RRAs
sitelim = lat-lon radius (deg) from RRA site, outside which RRA data are
            NOT used.  Also used, with a similar meaning, for auxiliary
            profile input.  Note that RRA and auxiliary profile input
            cannot be used simultaneously.
sitenear= lat-lon radius (deg) from RRA site, inside which RRA data is
            used with full weight of 1 (smooth transition of weight factor
            from 1 to 0 between sitenear and sitelim). Also used, with a
            similar meaning, for auxiliary profile input.
initpert= Use 1 for user-selected initial perturbations or 0 (default) for
            GRAM-derived, random initial perturbation values
rpinit  = initial pressure perturbation value (% of mean)
rdinit  = initial density perturbation value (% of mean)
rtinit  = initial temperature perturbation value (% of mean)
ruinit  = initial eastward velocity perturbation (m/s)
rvinit  = initial northward velocity perturbation (m/s)
rwinit  = initial upward velocity perturbation (m/s)
patchy  = not equal 0 for patchiness; 0 to suppress patchiness in
            perturbation model
itherm  = 1 for MET (Jacchia), 2 for MSIS, or 3 for JB2006 thermosphere
```

3.5.3.2 EXTERNAL INTERFACE

Earth-GRAM07 uses an atmospheric database called GUACA (or GGUAS) that the user must obtain separately. It is available from the National Climate Data Center and instructions for ordering it are provided in the Earth-GRAM07 accompanying documentation. A path/location to this resource must be specified in the input file.

3.5.4 INFRASTRUCTURE SUPPORT REQUIREMENTS

3.5.4.1 HARDWARE

Earth-GRAM07 was developed primarily for PC and UNIX environments, but the code may be adapted for other platforms relatively easily (section 4.7 **of Ref gram95**).

3.5.4.2 SOFTWARE

The Earth-GRAM07 software includes a PC~~n~~ executable for the stand-alone version, so no other software is required to run that version on a PC, except for a text editor to generate/edit the input file. For integrating Earth-GRAM07 into other programs or making changes to the code, an appropriate FORTRAN compiler is necessary.

3.5.4.3 NETWORKS

Not applicable.

3.5.4.4 OPERATORS

Not applicable.

3.6 MAJOR DISCRIMINATING FEATURES RELATIVE TO SIMILAR M&S

Of all the atmospheric models listed in the AIAA's "Guide to Reference and Standard Atmosphere Models", (Ref. 1), Earth-GRAM is unique. Many models given in that report are limited in spatial range (horizontally or vertically). For example that report lists "Regional Models", "Middle Atmosphere Models", "Thermosphere Models", and launch range-specific models (such as the RRAs). Of the "Global Models" discussed in (Ref. 1), only Earth-GRAM, the COSPAR International Reference Atmosphere (CIRA) model, and the 1962 through 1976 U.S. Standard Atmospheres cover the full height range from surface to orbital altitudes. Since winds are not included in the U.S. Standard Atmospheres, only the CIRA model is comparable to Earth-GRAM in providing information about mean values for thermodynamic variables, winds, and constituents. Earth-GRAM is unique in that it also provides information on atmospheric variability (standard deviations and the option to generate realistically-correlated sequences of perturbed values about the mean atmospheric state). Earth-GRAM is further unique in the ease with which it optionally can be run as a subroutine, incorporated directly into user's applications (such as orbit-propagation code, or trajectory-calculating programs) in a way that allows Monte-Carlo simulation of this atmospheric variability.

Formatted: Font: Arial, 10 pt

Formatted: Font: Arial, 10 pt

3.7 INTEROPERABILITY STANDARD

Not applicable.

3.8 DISTRIBUTION CONDITIONS, LICENSES, OR COSTS

The model is distributed free of charge to qualified users by the Natural Environments Branch at the NASA Marshall Space Flight Center. A software usage agreement can be downloaded from the Space Environments and Effects website to request the model. Distribution is restricted by the Export Administration Regulations (EAR-99).

3.9 M&S POINTS OF CONTACT

Dr. C. G. (Jere) Justus
e-mail: jere.justus@nasa.gov
phone: (256)-544-3260
fax: (256)-544-5754
Mail Code ~~EV13~~EV44/Stanley Associates~~Morgan Research~~
NASA Marshall Space Flight Center
Huntsville, AL 35812

Dr. Fred Leslie
e-mail: Fred.W.Leslie@nasa.gov
phone: (256)-544-1633
fax: (256)-544-5754
Mail Code ~~EV13~~EV44
NASA Marshall Space Flight Center
Huntsville, AL 35812

4.0 SOFTWARE DEVELOPMENT PROCESS QUALITY

4.1 SOFTWARE DEVELOPMENT APPROACH

The GRAM series of software was developed using the Incremental and Interactive Method. The initial requirements were driven by the Space Shuttle re-entry trajectory analysis. Global atmospheric environments were needed to support a number of landing sites, impacting the vehicle's design and operation. As new databases and models became available, they were incorporated into GRAM to improve the product. Ad Hoc methods were also used to develop features that aided the user community with special problems. This lead to continuous testing and evaluation throughout GRAM's evolution. See Section 4.4.3 for a summary of its development.

4.2 DEVELOPMENT PROCESS MATURITY

GRAM was originally developed by a small team, led by a researcher at the Georgia Institute of Technology, who currently works as an in-house contractor at the Marshall Space Flight Center. At MSFC, ~~There~~ the model is maintained by the Natural Environments Brach of the Engineering Directorate. This branch has the responsibility to define the natural space and terrestrial environments for aerospace vehicle design and operation. To ensure a customer focus, the organization is managed under the ISO 9000 system.

4.3 SOFTWARE DOCUMENTATION

The most comprehensive documentation for the software can be found in **refxxxxx** . A NASA Technical Memorandum specifically for Earth-GRAM07 is currently in work that will describe the models as well as the improvements from previous versions. The software also includes a number of ReadMe files that serve as a user manual, explaining the setup, options, and running of the software.

4.4 SOFTWARE CONFIGURATION MANAGEMENT

4.4.1 PROCESS FOR REQUREMENT DEVELOPMENT

Earth-GRAM07 developers do not follow a formal process for requirement development. Suggestions for enhancements often come from the user community or within the development team. Those suggestions are then reviewed and discussed internally before modifications to the code are made. A testing and evaluation period follows prior to their adoption.

4.4.2 PROCESS FOR ADDRESSING M&S REQUIREMENTS

N/A.

4.4.3 VERSION HISTORY

Version	Date	References and Features
GRAM	1974	NASA TMX 64871 & 64872. Global coverage, but with 6-month displacement of northern hemisphere middle atmosphere to represent southern hemisphere. Speigler & Fowler four-dimensional (4-D) database for lower atmosphere. Jacchia model thermosphere. Single-scale perturbation model. Geostrophic wind approximation for winds at all levels.
MOD 2	1976	Final Report MSFC Contract NAS8-30657. Two-scale random perturbation model. Buell constraints on perturbation values. Revised quasi-biennial oscillation values. Second-order geostrophic winds near equator.
MOD 3	1980	NASA CR 3256. Spherical harmonic model represents observed rocketsonde winds in middle atmosphere.
GRAM-86	1986	Final Report USRA Project P5042-0A0 (MSFC Prime NAS8-36400/1). Revised middle atmospheric perturbation statistics.
GRAM-88	1988	NASA Special Report ES44-11-9-88. Revised atmospheric perturbation statistics. Correct various problems reported in lower altitude (4-D) database.
GRAM-90	Apr-1991	NASA TM 4268. New middle atmosphere databases for means and perturbation statistics, based on Middle Atmosphere Program (MAP) data. Observed winds global database for middle atmosphere. Jacchia thermospheric model replaced by similar Marshall Engineering Thermosphere (MET) model.
GRAM-95	Aug-1995	NASA TM 4715. Global Upper Air Climatic Atlas (GUACA) database for global coverage of lower atmosphere, including observed wind climatology. Atmospheric species concentration output. Variable-scale small-scale perturbation model.
GRAM-95	May-1996	Patch to apply rpscale factor to GUACA data. Patch for year 2000+ correction (except for year 2000 being leap year).
GRAM-95	Oct-1996	Develop changes necessary for PC (MS FORTRAN Powerstation) version.

GRAM-95	Dec-1997	Patch for year 2000+ compatibility including year 2000
		being leap year.
GRAM-97	Jun-1997	Contains initial versions of new features for GRAM-99.
(beta)		Details of the small-scale perturbations differ from
		GRAM-98 beta and GRAM-99 official release.
GRAM-98	Mar-1998	Contains almost all the features described for GRAM-99.
(beta)		Very minor differences in the thermosphere (MET) region
		from the GRAM-99 official release. Details of the new
		large-scale wave model are different from the GRAM-99
		official release. Four digit year input option not
		available (Y2K compatible for 1957-2056 only). Time step
		and Taylor's hypothesis not included in correlations for
		small-scale perturbations. Includes option for using GRAM
		climatology instead of fixed boundary value for MET
		(option not included in final GRAM-99 release).
GRAM-99	May-1999	NASA/TM-1999-209630. Optional Range Reference Atmosphere
		data for mean atmospheres near launch sites. Optional
		Global Gridded Upper Air Statistics (GGUAS) ASCII data
		for lower atmosphere. Wave model for large-scale
		perturbations. Option for user-selected initial
		perturbations. Complete Year 2000+ compatibility,
		including option for four digit year input. NAMELIST
		input format. Revised details of variable-scale, small-
		scale perturbation model. Includes revised Marshall
		Engineering Thermosphere 1999 version (MET-99). Time
		step and Taylor's hypothesis included in correlations
		for small-scale perturbations.
GRAM-99	Aug-2000	Add new input parameter patchy, to allow suppression of
(Ver 2)		patchiness in perturbation model. Correct calculations
		that allow wind perturbation sigmas to exceed values in
		Figure 2 of TM 4168. Correct calculations that allow
		large changes in severe turbulence perturbations relative
		to normal (non-severe) sigmas.
GRAM-99	Aug-2005	Special NASA Langley edition with option to update mean
(Ver 3 Beta)		atmosphere without updating perturbations.
GRAM-99	Oct-2006	Updates described, and example results given in file
(Ver 3)		GRAMfixVer3.doc. Other than some "cosmetic" changes,
		all updates affect only the perturbations, not the
		mean values of total standard deviations.
GRAM-2007	Jan-2007	Incorporates option to use revised Range Reference

		Atmosphere (RRA) data, developed by Air Force Combat
		Climatology Center (AFCCC) in 2006. Option is also
		retained to use previous (1983) RRA data. In addition to
		RRA option, an "auxiliary profile" feature has been
		implemented. This allows the user to input a data profile
		of pressure, density, temperature, and/or winds versus
		altitude, with the auxiliary profile values used in place
		of conventional climatology (GUACA/MAP/etc.) values.
		Includes several updates to Marshall Engineering
		Thermosphere (MET) model, now denoted MET-2007. MET
		updates include:
		(1) corrections for inconsistency between constituent
		number density and mass density [described by Justus,
		C. G., Aleta Duvall, and Vernon W. Keller, "Earth Global
		Reference Atmospheric Model (GRAM-99) and Trace Consti-
		tuents", Paper C4.1-0002-04, Presented at 35th COSPAR
		Scientific Assembly Paris, France July 18-25, 2004].
		(2) Representation of gravity above oblate spheroid,
		rather than spherical Earth approximation.
		(3) Treatment of day-of-year as continuous variable in
		semi-annual term, rather than as integer day.
		(4) Treatment of year as either 365 or 366 days in
		lengths (as appropriate), rather than all years having
		length = 365.2422 days.
		(5) Allows continuous variation of time input, rather
		than limiting time increments to integer minutes.
		(6) Additional output from MET07_TME subroutine of
		Modified Julian Day, right ascension of Sun, and right
		ascension at local lat-lon (used for input to new JB2006
		thermosphere model)
		As an alternate to MET, an option is now available to use
		the Naval Research Labs Mass Spectrometer, Incoherent
		Scatter Radar Extended Model for the thermosphere
		(NRL MSIS E-00). If the MSIS model option is used, the NRL
		Harmonic Wind Model (HWM 93) is used to compute
		thermospheric winds. The Jacchia-Bowman 2006 (JB2006)
		thermosphere model has also been added as a third option
		to compute thermosphere values. References to developmental
		papers for JB2006 are given in the code (JB2006_E07.f) and at
		the JB2006 web site http://sol.spacenvironment.net/~JB2006/.
		Starting point for the GRAM implementation of JB2006 is
		their REV-A October, 2006. Changes made, mostly cosmetic
		and to make the code more transportable among various
		compilers, are described in file JB2006fix.txt. If JB2006
		is selected for calculation of thermospheric density and
		temperature, winds are computed with the Harmonic Wind
		Model (HWM 93), used in conjunction with the MSIS model.

		Earth radii for reference ellipsoid have been updated to
		World Geodetic System (WGS 84) values, used by the GPS
		navigation system. Input values of altitude greater than
		6000 km are treated as geocentric radius values, rather than
		heights. Both radius and height are now given on the output
		file. Although all input latitudes are geocentric, GRAM now
		outputs both geocentric and geodetic values. Several changes
		or additions have been made in the GRAM perturbation model.
		These include:
		(1) New feature to update atmospheric mean values
		without updating perturbation values.
		(2) Ability to simulate large-scale, partially-correlated
		perturbations as they progress over times for a few hours
		to a few days.
		(3) Revisions to correlations scales for time-correlation
		(4) Random variation of vertical and horizontal scales
		for large-scale perturbations
		(5) A multiple-trajectory driver routine (multtraj), that
		allows multiple trajectories and perturbations to be
		simulated in one GRAM run.
		To create unique program element names, "_E07" has been
		appended to names of all program files, subroutines,
		functions, and common blocks. All code lines have been
		re-numbered. Added subroutine radll to compute horizontal
		distance from great-circle distance between two input lat-
		lon positions. Added new subroutine CaltoJul for conversion
		from calendar date to Julian day.

4.5 SOFTWARE DEVELOPMENT TESTING

To ensure that the Earth-GRAM07 model properly represents the atmosphere, a number of tests are performed. Because Earth-GRAM07 is largely based on atmospheric measurements, Monte Carlo runs are executed to verify that the average of these runs match the observed atmospheric means. Similarly, the standard deviation of these runs must also equate to that of the database that drives the model. In addition, the power spectrum of the small scale perturbations is computed to verify that it is consistent with the Dryden spectrum of turbulence. Lastly, tests are performed to check that the wind shear computed by the model is consistent with ~~the~~ rawinsonde and Jimsphere data from Cape Canaveral.

5.0 VV&A HISTORY ON THE M&S

5.1 V&V PERFORMED

Verification and validation activities are performed by the Earth-GRAM07 development team and by the user community. Verification activities are primarily performed during code development and testing to ensure that the code provides the expected atmospheric parameters as well as dispersions of a number of quantities. Validation assessments are conducted by both the development team and user community who compare the model output to observed values found in the real atmosphere.

5.2 VERIFICATION SUMMARY

Verification of Earth-GRAM07 is straight-forward for the following reasons: there are no schemes used to solve differential equations that result is discretization errors; stability and convergence is not a factor in the computations because Earth-GRAM07 uses interpolation schemes for mean values and a one-step Markov technique for the small scale perturbed values; time-stepping in the code is~~are~~ inherently stable; extensive sensitivity studies have been performed which show the code solutions are not particularly sensitive to the time or spatial step size, within reasonable values; components of the code have been extracted into test-bed programs to ensure that they produce the expected result with known inputs.

5.3 VALIDATION SUMMARY

Because Earth-GRAM07 uses measured data to drive it, validation that the model accurately represents the natural environment is assured by simply running the model and comparing the resulting mean values and standard deviations with the measurements. The exception is in the upper atmosphere (above 90 km) where observed databases are more scarce and the user has the option of selecting among three well-documented thermosphere models for that region. For the dispersed values, validation is performed by computing the power spectrum of the perturbations to ensure that they are consistent with the Dryden spectrum, an accepted approximation to the observed Kolmogorov spectrum.

5.4 FORMAL AND INFORMAL ACCREDITATION

Earth-GRAM07 has not been formally accredited although its predecessor Earth-GRAM99 is identified as the model to use for the Constellation Program in the Design Specification for Natural Environments (DSNE). It is expected that Earth-GRAM07 will take over this role. In addition, the American National Standards Institute (ANSI) in collaboration with the American Institute of Aeronautics and Astronautics (AIAA) identifies Earth-GRAM99 in their publication "Guide to Reference and Standard Atmospheric Models". Incorporation of Earth-GRAM07 into the next version of this document is currently in work.

6.0 INTENDED USE

Earth-GRAM07 is seeking accreditation as the atmospheric model for the Constellation program, replacing the currently used Earth-GRAM99, version 3 code. The software provides mean and dispersed values for atmospheric quantities such as temperature, pressure, air density, winds, etc. from the surface to 1,000 km. This information is appropriate to use for vehicle ground shipping, pad roll-out, pad countdown phase, launch and ascent, abort scenarios, low Earth orbit, re-entry, terminal-area phase, landing, rescue, recovery, and return to launch site. The model does not provide atmospheric information regarding clouds, visibility, lightning, precipitation, or thunderstorm activity.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Appendix A: List of Acronyms and Abbreviations

AIAA – American Institute of Aeronautics and Astronautics
ANSI – American National Standards Institute
Ar – Argon
ASCII – American Standard Code for Information Interchange
CH_4 – Methane
CO – Carbon monoxide
CO_2 – Carbon dioxide
DSNE – Design Specification for Natural Environments
Earth-GRAM07 – Earth Global Reference Atmospheric Model Version 2007
ESMD - Exploration Space Mission Directorate

GUACA – Global Upper Air Climatic Atlas
GGUAS – Global Gridded Upper Air Statistics
GRAM – Global Reference Atmospheric Model, generic
H – Atomic hydrogen
He – Helium
JB2006 – Jacchia-Bowman 2006 thermosphere model
km – kilometer
M&S – Modeling and Simulation
MAP – Middle Atmosphere Program
MET – Marshall Engineering Thermosphere
MSIS – Mass Spectrometer, Incoherent Scatter Radar Extended Model for the thermosphere
N – Atomic nitrogen
N_2 – Molecular nitrogen
N_2O – Nitrous oxide
O – Atomic oxygen
O_2 – Molecular oxygen
O_3 – Ozone
VV&V – Verification, Validation, and Accreditation

Appendix B: Reference and Bibliography

1. AIAA (2004~~1997~~): “Guide to Reference and Standard Atmosphere Models”, American National Standards Institute/American Institute of Aeronautics and Astronautics report ANSI/AIAA G-003B~~A~~-2004~~1996~~.

2. Anderson, G.P., et. al. (1986): “AFGL Atmospheric Constituent Profiles (0 to 120 km)”, AFGL-TR-86-0110, Env. Res. Papers No. 954, May.

3. ANSI/AIAA (2004): “American National Standard Guide to Reference and Standard Atmospheric Models”, G-003B-2004.

4. Bowman, B.R., Tobiska, W.K., F.A. Marcos, “A New Thermospheric Density Model JB2006 Using New Solar Indices”, AIAA 2006-6166.

5. Hedin, A.E., “A Revised Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data: MSIS-83”, *J. Geophys. Res.*, **88,** 10170, 1983.

6. Hedin, A.E., “MSIS-86 Thermospheric Model”, *J. Geophys. Res.*, **92**, 4649, 1987.

7. Hedin, A.E., “Extension of the MSIS Thermosphere Model into the Middle and Lower Atmosphere”, *J. Geophys. Res.*, **96**, 1159, 1991.

8. Hickey, M.P. (1988a): “The NASA Marshall Engineering Thermosphere Model”, NASA CR 179359.

9. Hickey, M.P. (1988b): “An Improvement in the Numerical Integration Procedure Used in the NASA Marshall Engineering Thermosphere Model”, NASA CR 179389.

10. Hickey, M.P. (1994): “A Simulation of Small-Scale Thermospheric Density Variations for Engineering Applications”, NASA CR 4605.

11. Hickey, M.P. (1996): “An Engineering Model for the Simulation of Small-Scale Thermospheric Density Variations for Orbital Inclinations Greater Than 40 Degrees”, NASA CR 201140.

12. Inter-Range Instrumentation Group Range Commanders Council (1983): "Cape Canaveral Range Reference Atmosphere 0-70 km Altitude", IRIG Document 361-83.

13. Jacchia, L.G. (1970): "New Static Models of the Thermosphere and Exosphere with Empirical Temperature Profiles." Smithsonian Astrophysical Observatory, Special Report 313.

14. Justus, C.G., A. Woodrum, R.G. Roper, and O.E. Smith (1974): "A Global Scale Engineering Atmospheric Model for Surface to Orbital Altitudes, 1: Technical Description", NASA TMX-64871.

15. Justus, C.G., G.R. Fletcher, F.E. Gramling, and W.B. Pace (1980): "The NASA/MSFC Global Reference Atmospheric Model--MOD 3 (With Spherical Harmonic Wind Model)." NASA CR-3256, Contract NAS8-32897.

16. Justus, C.G., F.N. Alyea, D.M. Cunnold, R.A. Blocker, and D.L. Johnson (1988): "GRAM-88 Improvements in the Perturbation Simulations of the Global Reference Atmospheric Model", NASA Special Report ES44-11-9-88.

17. Justus, C.G., C.W. Campbell, M.K. Doubleday, and D.L. Johnson (1990): "New Atmospheric Turbulence Model for Shuttle Applications." NASA TM-4168.

18. Justus, C.G., F.N. Alyea, D.M. Cunnold, W.R. Jeffries III, and D.L. Johnson (1991): "The NASA/MSFC Global Reference Atmospheric Model--1990 Version (GRAM-90), Part I: Technical/Users Manual." NASA TM-4268, Grant NAG8-078.

19. Justus, C.G., W.R. Jeffries III, S.P. Yung, and D.L. Johnson (1995): "The NASA/MSFC Global Reference Atmospheric Model - 1995 Version (GRAM-95)", NASA TM-4715.

20. Keating, G.M., ed. (1989): "Middle Atmosphere Program - Reference Models of Trace Species for the COSPAR International Reference Atmosphere (Draft)", Handbook for MAP, vol. 31, 180 pp., December.

21. Labitzke, K., et al. (1985): "Middle Atmosphere Program - Atmospheric Structure and its Variation in the Region 20 to 120 km - Draft of a New Reference Middle Atmosphere", Handbook for MAP, Vol. 16, 318 pp., July.

22. Ruth, D.B., et al. (1993): "Global Upper Air Climatic Atlas (GUACA)", CD ROM data set, Version 1.0 (Vol. 1, 1980-1987, Vol. 2 1985-1991), US Navy-U.S. Department of Commerce (NOAA/NCDC), April.

23. Suggs, Ron (2007): "NASA Marshall Engineering Thermosphere Model – 2007", NASA Technical Memorandum NASA Technical Memorandum TBD, 2007.