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# DRAFT
# General Mission Analysis Tool (GMAT) Acceptance Test Plan

GMAT Build Date: May 18, 2007

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May 21, 2007

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# Chapter 1

# Acceptance Test Plan Overview

## 1.1 GMAT Introduction

The information presented in this Acceptance Test Plan document shows the current status of the General Mission Analysis Tool (GMAT). GMAT is a software system developed by NASA Goddard Space Flight Center (GSFC) in collaboration with the private sector. The GMAT development team continuously performs acceptance tests in order to verify that the software continues to operate properly after updates are made. The GMAT Development team consists of NASA/GSFC Code 583 software developers, NASA/GSFC Code 595 analysts, and contractors of varying professions.

GMAT was developed to provide a development approach that maintains involvement from the private sector and academia, encourages collaborative funding from multiple government agencies and the private sector, and promotes the transfer of technology from government funded research to the private sector.

GMAT contains many capabilities, such as integrated formation flying modeling and MATLAB compatibility. The propagation capabilities in GMAT allow for fully coupled dynamics modeling of multiple spacecraft, in any flight regime. Other capabilities in GMAT include: user definable coordinate systems, 3-D graphics in any coordinate system GMAT can calculate, 2-D plots, branch commands, solvers, optimizers, GMAT functions, planetary ephemeris sources including DE405, DE200, SLP and analytic models, script events, impulsive and finite maneuver models, and many more.

GMAT runs on Windows, Mac, and Linux platforms. Both the Graphical User Interface (GUI) and the GMAT engine were built and tested on all of the mentioned platforms. GMAT was designed for intuitive use from both the GUI and with an importable script language similar to that of MATLAB.

## 1.2 Testing Methodology

### Purpose

GMAT needs to undergo a series of rigorous tests to validate the numerical implementations of its models and establish a set of acceptable performance times. The 595 analysts created the acceptance test plan to achieve this goal by comparing GMAT with flight-operational reference software packages and documenting the results. Results can be reproduced with the initial conditions and software setups presented in this document.

#### Reference software

For this comparative study to have merit, GMAT was tested against reliable, trustworthy, and flight operational programs, such as STK-HPOP,STK-Astrogator, Free-Flyer, Swingby, and previous GMAT Builds that were comparable to the aforementioned programs. To achieve accurate comparison results, each program was compared with equivalent, or close to equivalent, test case setups.

#### Testing Categories

The Acceptance Test Plan divides into the following testing categories: Propagation, Calculation Parameters [Central body(Cb) and Coordinate System(CS) dependent], Integrators, Libration Points, Stopping Conditions, Delta V, and Performance.

#### Scripts Used

MATLAB scripts were created to make comparisons between GMAT Builds and the reference software. The majority of the comparisons involved taking the difference of the data and extracting the maximum absolute difference observed over the propagation duration. Scripts were also created to compare performance times for individual GMAT test cases to the reference software. The scripts created are as followed: Comparison_Tool1_Tool2_PV.m, Comparison_Tool1_Tool2_CS.m, Comparison_Tool1_Tool2_Cb.m, Comparison_Integ.m, TimeComparo.m, BuildRun_Script_GMAT.m, Comparison_Tool1_Tool2_Libr.m, Comparison_StopCond, and STK_Repropagate.m.

The user of the semi-automated scripts provides input when requested, in order to perform the script's core functions. For example, a user that wants to see the position and velocity differences between STK and GMAT would select a few choices from a menu. Next, the script would generate the comparisons based on the report data available. The semi-automation scripts adhere to the naming conventions outlined in their relevant testing category chapter.

Most of the scripts generate output in at least one of the following formats: ASCII, LaTex, MATLAB .mat, or Excel .xls files. The report files are in an ASCII space delimited format and contain the different test case parameters outputted after propagation. The LaTex files contain the comparison data between two programs and provide an easy way to include that data into a PDF document. The .mat and .xls file are two other methods used to save the comparison data that proved useful from the software development team.

The details of each script and how to use them are outlined in the relevant Testing Category section and/or the Comparison Scripts Guide section, located in Appendix C.

### 1.2.1 Propagation

The propagation test cases account for various orbits about Earth, as well as other celestial bodies. The main propagation parameters to monitor for differences are the position and velocity vectors. The following script was generated to perform the comparisons for this category:
Comparison_Tool1_Tool2_CS.m

See the Propagators section (Chapter 2) for more detail and comparison results.

### 1.2.2 Calculation Parameters

The calculation parameter test cases verify the internal calculations used to output the various parameters presented in the list below. This section consists of two subsections: Coordinate System(CS) and Central Body(Cb) dependent parameters. The following scripts were generated to perform the comparisons for this testing category: Comparison_Tool1_Tool2_CS.m & Comparison_Tool1_Tool2_Cb.m

- Coordinate Systems
  - Earth Fixed
  - Earth Mean J2000 Equator (MJ2000Eq)
  - Earth Mean J2000 Ecliptic (MJ2000Ec)
  - Earth Mean of Date Equator (MODEq)
  - Earth Mean of Date Ecliptic (MODEc)
  - Earth True of Date Equator (TODEq)
  - Earth True of Date Ecliptic (TODEq)
  - Earth Geocentric Solar Ecliptic (GSE)
  - Earth Geocentric Solar Magnetic (GSM)
  - Mars Fixed
  - Mars MJ2000Eq
  - Mars MJ2000Ec
  - Mercury Fixed
  - Mercury MJ2000Eq
  - Mercury MJ2000Ec
  - Moon Fixed
  - Moon MJ2000Eq
  - Moon MJ2000Ec
  - Neptune Fixed
  - Neptune MJ2000Eq
  - Neptune MJ2000Ec
  - Pluto Fixed
  - Pluto MJ2000Eq
  - Pluto MJ2000Ec
  - Saturn Fixed
  - Saturn MJ2000Eq
  - Saturn MJ2000Ec
  - Uranus Fixed
  - Uranus MJ2000Eq
  - Uranus MJ2000Ec
  - Venus Fixed
  - Venus MJ2000Eq
  - Venus MJ2000Ec
- Coordinate System Parameters
  - Position (X,Y,Z)

  - Velocity(X,Y,Z)
  - Magnitude of Velocity
  - Right Ascension of Velocity
  - Specific Angular Momentum
  - Argument of Periapsis
  - Declination
  - Declination of Velocity
  - Inclination
  - Right Ascension
  - Right Ascension of Ascending Node

- Central Body Parameters
  - Altitude
  - Beta Angle
  - C3 Energy
  - Eccentricity
  - Latitude
  - Longitude
  - Specific Angular Momentum
  - Mean Anomaly
  - Mean Motion
  - Period
  - Apoapsis Radius
  - Perigee Radius
  - Position Magnitude
  - Semi-major Axis
  - True Anomaly
  - Semilatus Rectum
  - Apoapsis Velocity
  - Periapsis Velocity
  - Greenwich Hour Angle
  - Local Sidereal Time

See the Calculation Parameters Section (Chapter 3) for more detail and comparison results.

### 1.2.3 Integrators

The integrator test cases isolate the differences that would occur when changing the integrators for the same orbit. The following script was generated to perform the test case comparisons for this category: Comparison_Integ.m

- RungaKutta(RKV) 8(9)
- DormandElMikkawyPrince(RKN) 6(8)

- RungeKuttaFehlberg(RKF) 5(6)
- PrinceDormand(PD) 4(5)
- PrinceDormand(PD) 7(8)
- BulirschStoer(BS)
- AdamsBashforthMoulton(ABM)

See the Integrators Section (Chapter 4) for more detail and comparison results.

### 1.2.4 Stopping Conditions

The stopping condition test cases determine how effective GMAT is at stopping satellite propagation on certain conditions. The following script was created to perform the test case comparisons for this category:
Comparison_StopCond.m

The stopping conditions tested are as followed:

- Epoch (A1 Modified Julian Date)
- Apoapsis
- Elapsed Days
- Mean Anomaly
- Periapsis
- Elapsed Seconds
- True Anomaly
- XY Plane Intersection
- XZ Plane Intersection
- YZ Plane Intersection

See the Stopping Conditions Section (Chapter 5) for more detail and comparison results.

### 1.2.5 Libration Point

The libration point test cases create data about the location of several libration points. Current and future satellite missions use libration points as part of their mission architecture. It is important to have accurate data for these libration points. The following script was created to perform the test case comparisons for this category:
Comparison_Tool1_Tool2_Libr.m

See the Libration Point Section (Chapter 6) for more detail and comparison results.

### 1.2.6 Delta V

The delta v test cases determine the effectiveness of the delta v capabilities built into GMAT. When thruster burns are added to the mission sequence it is important that they are added correctly. The following script was created to perform the test case comparisons for this category:
Comparison_DeltaV.m

See the Delta V Section (Chapter 7) for more detail and comparison results.

### 1.2.7 Performance

The performance test cases generate performance time data for later comparison between GMAT and the reference software packages. Numerical calculation accuracy is important, but the amount of computing time it takes for the software to run is equally as important. We extracted several test cases from previous sections and ran them on the reference software packages, in order to check to make sure GMAT can perform just as good or better.

See the Performance Section (Chapter ??) for more detail and comparison results.

### 1.2.8 Control Flow

The control flow tests generate report data that easily allows a Matlab script to produce a table of Pass and Fail cases.The following script was created to generate the Pass/Fail table for this category:
LoopTestSummary.m

See the Control Flow Section (Chapter 8) for more detail and results.

# Chapter 2

# Propagation

In order to validate the accuracy of GMAT's propagation, the fundamental unit-level components need to be combined and propagated on a system level. From a software development point of view, if the program under development is tested in a wide range of core applications, it is more likely that problems would be found before each new version is released to the public. This Acceptance Test Plan tests GMAT by comparing many possible scenarios users of GMAT would encounter to reference software packages. Although it is impossible to create all the possible scenarios each user would encounter in GMAT, this is a start to eliminate possible frustrations a user could experience if a component did not work correctly.

Propagation is one of the most important aspects of GMAT. Everything from outputting parameters to performing a thruster burns at the correct stopping condition depend on whether or not GMAT is able to propagate the satellite/object for a defined time period with acceptable accuracy.

Parts of the Initial Orbit State Conditions section are referenced from Emergent Space Technologies' Orbit Determination Toolbox (ODTBX) Spiral 1 DEMO document,[1] due to a similar objective of testing the numerical implementation of the program's base functions.

## 2.1 Initial Orbit State Conditions

### 2.1.1 Earth Based Test Cases

The initial orbit states for the Sun-Synchronous (SunSync), Geostationary (GEO), Molniya, International Space Station (ISS) and the Global Positioning Satellite (GPS) orbits were obtained from Emergent Space Technologies' ODTBX Spiral 1 Demo .[1] Emergent used STK-High Precision Orbit Propagator (STK-HPOP) models and two-Line Element (TLE) sets with an initial UTC orbit epoch of June 1st 2004, 12:00:00:00. The initial orbit states that were used for the test case orbits can be seen in Table 2.1, on Page 24. The perigee and apogee altitudes of the test case orbits can be seen in Table 2.2, on Page 24.

The propagation duration, report output step size, and integrator step sizes were varied for the different test cases. For the ISS, SunSync, GPS, Molynia, and GEO cases, the propagation length and report output step size were chosen based on a study performed by The Aerospace Corporation to validate STK-HPOP's.[2] The integrator time steps were chosen to allow for the most accurate comparison of the test case results. These time steps were based on Vallado's analysis of state vector propagation.[3]

Table 2.1: Satellite Initial Conditions

| Category | Orbit Type | X(km) | Y(km) | Z(km) | Vx(km/s) | Vy(km/s) | Vz(km/s) |
|---|---|---|---|---|---|---|---|
| LEO | ISS | -4453.783586 | -5038.203756 | -426.384456 | 3.831888 | -2.887221 | -6.018232 |
| LEO | Sun-Sync | -2290.301063 | -6379.471940 | 0 | -0.883923 | 0.317338 | 7.610832 |
| MEO | GPS | 5525.33668 | -15871.18494 | -20998.992446 | 2.750341 | 2.434198 | -1.068884 |
| HEO | Molniya | -1529.894287 | -2672.877357 | -6150.115340 | 8.717518 | -4.989709 | 0 |
| GEO | GEO | 36607.358256 | -20921.723703 | 0 | 1.525636 | 2.669451 | 0 |

Table 2.2: Apogee and Perigee Altitudes for Test Satellites

| Orbit Type | Perigee Altitude(km) | Apogee Altitude(km) |
|---|---|---|
| ISS | 358.168 | 380.387 |
| Sun-Sync | 400 | 400 |
| GPS | 19757.6 | 20603.8 |
| Molniya | 500 | 39850.5 |
| GEO | 35786 | 35786 |

The chosen parameters can be seen in Table 2.3, on Page 24.

Table 2.3: Integrator,Propagator, and Output Frequency

| Orbit Type | Integrator Step Size(s) | Propagator Length(days) | Output Frequency(mins) |
|---|---|---|---|
| ISS | 5 | 1 | 1 |
| Sun-Sync | 5 | 1 | 1 |
| GPS | 60 | 2 | 2 |
| Molniya | 5 | 3 | 5 |
| GEO | 60 | 7 | 10 |

Several test cases were created for each satellite orbit to verify GMAT's ability to perform accurately, while applying various forces. The forces used for Earth-based test cases were two-body, JGM2, EGM96, and JGM3 gravity models, third-body perturbation effects from other planets, the Jacchia-Roberts (JR) and the Mass Spectrometer and Incoherent Scatter Radar Exosphere (MSISE 1990 & 2000) Atmospheric Drag Model, and Solar Radiation Pressure (SRP). Each of the force models were run independently within GMAT to verify their individual accuracy, as well as a test case that includes an atmospheric drag model, the SRP model, a non-spherical gravity model, and third-body perturbations. These last test cases were performed to validate the capability of the GMAT to accurately propagate satellite orbits while multiple force models were applied.

The Degree and Order for Earth-based non-spherical gravity cases was set at a constant 20 by 20.

Refer to Appendix B.1 for an alternate listing of all Propagator initial orbit state conditions.

### 2.1.2 Non-Earth Based Test Cases

GMAT is designed for accuracy in non-Earth mission scenarios. Test cases for Mars, Mercury, the Moon, Neptune, Pluto, Saturn, Uranus, Venus, L2 orbits, and deep space orbits were created to test various forces,individually and jointly, affecting a spacecraft in an orbit. Many satellite parameters, such as Cd,Cr, satellite area, and satellite mass, were kept the same as the Earth test cases for simplicity and consistency. The initial Keplerian satellite state only varied in Semi-Major Axis and gravity field degree & order for the non-Earth test cases.

Refer to Table 2.4 for the initial Keplerian orbital elements and the Degree & Order used for the non-spherical gravity force cases. The integrator step size, propagation length, and output frequency for all the non-Earth cases are 5 seconds, 3 days, and 5 minutes, respectively. Table 2.4 excludes the deep space and L2 orbit test cases.

Table 2.4: Non-Earth Keplerian Orbital Elements

| Orbit Type | SMA (km) | Ecc. | Inc. (deg) | AOP (deg) | RAAN (deg) | TA (deg) | Deg. x Ord. used |
|---|---|---|---|---|---|---|---|
| Mars | 4603 | 0.2 | 45 | 45 | 90 | 45 | 20x20 |
| Mercury | 3640 | 0.2 | 45 | 45 | 90 | 45 | 4x0 |
| Moon | 2500 | 0.2 | 45 | 45 | 90 | 45 | 20x20 |
| Neptune | 34999 | 0.2 | 45 | 45 | 90 | 45 | 4x0 |
| Pluto | 1795 | 0.2 | 45 | 45 | 90 | 45 | 4x0 |
| Saturn | 80000 | 0.2 | 45 | 45 | 90 | 45 | 4x0 |
| Uranus | 45000 | 0.2 | 45 | 45 | 90 | 45 | 4x0 |
| Venus | 8125 | 0.2 | 45 | 45 | 90 | 45 | 20x20 |

SMA: Semi-Major Axis | Ecc.: Eccentricity | Inc.: Inclination | AOP: Argument of Perigee
RAAN: Right Ascension of Ascending Node | TA: True Anomaly

The DeepSpace, Earth Moon L2 (EML2), and Earth Sun L2 (ESL2) cases involve propagating about libration points and propagating deep space orbits. Table B.14, B.15, and B.16, in Appendix B, provide the initial states for the DeepSpace, EML2, and ESL2 test cases, respectively.

Refer to Appendix B.1 for a listing of all Propagator initial orbit state conditions.

## 2.2 Other Initial State Conditions

In order to reduce the complications of the comparisons, certain initial orbit parameters were kept constant throughout all of the cases. These parameters are Cd, Cr, Spacecraft Area, each programs integrator, and software settings affecting the results of various force models.

The GMAT integrator used for all the test cases was Runga Kutta 8(9), except for the STK-HPOP test cases, to avoid any additional differences that could occur from changing integrators. The Integrators Section compares the differences between the various integrators GMAT can use.

The parameters in Table 2.5 shows the differences between GMAT and the reference programs. The ideal situation would be for all the programs to match perfectly, but that is not realistic due to the different approaches each program takes to solve each problem.

Table 2.5: Universal Test Case Parameters

| Parameter | GMAT | STK-HPOP | FF | STK-Astro |
|---|---|---|---|---|
| Cd | 2.2 | 2.2 | 2.2 | 2.2 |
| Cr | 1.2 | 1.2 | 1.2 | 1.2 |
| Area($m^2$) | 20 | 20 | 20 | 20 |
| Satellite Mass(kg) | 1000 | 1000 | 1000 | 1000 |
| Integrator (excluding integrator test cases) | RK8(9) | RK7(8) | RK8(9) | RK8(9) |
| Integrator error tolerance | 1e-013 | 1e-013 | 1e-013 | 1e-013 |
| Integrator error control. Relative to | Step | Step? | ? | Step |
| Drag: Altitude Calculation | Approximate | Approximate | Exact | ? |
| Drag: Sun Position | True | True | True | True |
| SRP: Sun Position | True | True | True? | True |
| Solar Flux ($W/m^2$) at 1 AU | 1359.38857 | 1359.38857 | 1358 | 1359.38857 |
| Solid Tides | N/A | Disabled | N/A | N/A |
| Ocean Tides | N/A | Disabled | N/A | N/A |
| Daily F10.7: JR and MSISE models | 150 | 150 | N/A | 150 |
| Average F10.7 | 150 | 150 | 150 | 150 |
| Geomagnetic Index(Kp): JR and MSISE only | 3 | 3 | N/A | 3 |
| Drag: Geomagnetic Flux Update | Constant | Constant | N/A | Constant |
| Boundary Mitigation | N/A | Disabled | N/A | N/A |
| Relativistic Accelerations | N/A | Disabled | N/A | N/A |
| Shadow Modeling | Dual Cone | Dual Cone | Dual Cone | ? |
| IERS EOP format used: | Long term C04 | Bulletin A | Bulletin A | Bulletin A |
| Polar Motion calculation: | Enabled | Enabled | Enabled | Enabled? |
| Nutation update interval: Earth (sec) | 60 | 60 | 60 | 60 |
| Planetary Ephemeris update interval (sec) | 0 | 0? | 0 | 0? |

Exceptions to Table 2.5 are as followed:

- STK has trouble propagating the EML2 test case at an error tolerance of 1e-013 with a relative to step error control. The GMAT and STK cases were changed to both use relative to state error control

### 2.2.1 Earth Orientation Parameters(EOP) data

*"International Earth Rotation Service (IERS) Bulletins A and B provide current information on the Earth's orientation in the IERS Reference System. This includes Universal Time, coordinates of the terrestrial pole, and celestial pole offsets. Bulletin A gives an advanced solution updated weekly by e-mail subscription or daily by anonymous ftp; the standard solution is given monthly in Bulletin B and updated every week in the (IERS) C04 solution."*[6]

*"Bulletin A is issued by the IERS Rapid Service/Prediction Centre at the U.S. Naval Observatory(USNO), Washington, DC and Bulletin B"*, as well as the C04 data, *"is issued by the IERS Earth Orientation Centre at the Paris Observatory."*[4]

*"Bulletin A is intended for users who need accurate information before the Bulletin B finals series is available, i.e., those who reduce data in the very recent past (require rapid service) or those who operate in real-time (require predictions). Bulletin B is intended for standard use. For scientific and long-term analyses of the Earth's orientation, the long-term continuous series"*,[4] C04 (1962- present), can be used.

*"EOP (IERS) C04 is regularly recomputed to take advantage on one hand of the improvement of the various individual contributions and in the other hand of the refinement of the analysis procedures. To date, it is twice-weekly updated."*[5]

*"The EOP (IERS) C04 is given at one-day intervals, it is free from the diurnal/subdiurnal terms due to the oceanic effects and can be interpolated linearly. The oscillations in UT and duration of the days due to zonal tides for periods under 35 days are present in full size in the series."*[5]

GMAT retrieves long term earth orientation IERS EOP CO4 data, which includes UTC-UT1 data, from a file. This file includes smoothed values at 1-day intervals and data from 1962-present.

STK and FF retrieves its EOP data from the USNO series 7 / IERS Bulletin A.

The differences between the EOP data sets are displayed in Table 2.6. The Terrestrial Pole column refers to the accuracy of the pole position [x,y] and the UT1 column refers to the accuracy of the rotation angle about the pole UT1.

As shown in Table 2.6, there are differences between STK and GMAT, but the Terrestrial Pole data agrees to within the thousandth place of a milli-arcseconds and the UT1 data agrees to within the hundredth place of second.

Table 2.6: EOP Format Accuracy

| EOP Format | Pole Position (mas) | UT1 (ms) |
|---|---|---|
| Bulletin A obs. 1-d (1) | 0.10 | 0.02 |
| Bulletin A pred. 1-d (2) | 0.50 | 0.14 |
| Bulletin A pred. 4-d (2) | 1.60 | 0.52 |
| Bulletin A pred. 10-d (2) | 3.9 | 1.60 |
| Bulletin A pred. 40-d (2) | 11.2 | 7.70 |
| Bulletin B obs. smooth 5-d (3) | 0.15 | 0.02 |
| Bulletin B obs. raw 5-d (3) | 0.15 | 0.02 |
| Bulletin B pred. 5-d (3) | 1.6 | 0.60 |
| Bulletin B pred. 10-d (3) | 3.0 | 1.60 |
| Bulletin B pred. 30-d (3) | 10.0 | 4.0 |
| Long-Term C04 '62-'67 | 30.0 | 2.0 |
| Long-Term C04 '68-'71 | 20.0 | 1.5 |
| Long-Term C04 '72-'79 | 15.0 | 1.0 |
| Long-Term C04 '80-'83 | 2.0 | 0.4 |
| Long-Term C04 '84-'95 | 0.7 | 0.04 |
| Long-Term C04 '96-present | 0.2 | 0.02 |

NOTES: (1) Based on data after 1997; applies only to latest epochs in each update.
(2) Based on data since 1995.
(3) Based on data since 1996.
The Terrestrial Pole and UT1 data is free from the diurnal/subdiurnal terms due to the oceanic effects and can be interpolated linearly. These terms can be added after interpolation.

### 2.2.2 Other Planetary Parameters

#### Gravitational Constant

All programs used for comparisons utilize the DE405 Planetary Gravitational Constants listed in Table 2.7, except when non-spherical gravity was used. When non-spherical gravity files are used they typically call the gravitational constants located in the file, unless the program creates an exception.

Table 2.7: Planetary Gravitational Constants(mu values)

| Planet | mu ($km^3/s^2$) |
|---|---|
| Sun | 132712440017.99 |
| Mercury | 22032.080486418 |
| Venus | 324858.59882646 |
| Earth | 398600.44150000 |
| Moon | 4902.8005821478 |
| Mars | 42828.314258067 |
| Jupiter | 126712767.85780 |
| Saturn | 37940626.061137 |
| Uranus | 5794549.0070719 |
| Neptune | 6836534.0638793 |
| Pluto | 981.60088770700 |

#### Flattening Coefficient

Whenever possible the flattening coefficients listed in Table 2.8 were used. Without the use of these values the planetary bodies could have wildly different shapes, which would result in large differences in parameters such as longitude, latitude, and altitude.

Table 2.8: Flattening Coefficient

| Planet | Flattening Coefficient |
|---|---|
| Sun | 0.00000000 |
| Mercury | 0.00000000 |
| Venus | 0.00000000 |
| Earth | 0.00335270 |
| Moon | 0.00000000 |
| Mars | 0.00647630 |
| Jupiter | 0.06487439 |
| Saturn | 0.09796243 |
| Uranus | 0.02292734 |
| Neptune | 0.01856029 |
| Pluto | 0.00000000 |

### Equatorial Radius

The several celestial body equatorial radii used are listed in Table 2.9. Similar differences as the flattening coefficient occur when GMAT and the reference programs don't use the same values.

Table 2.9: Equatorial Radius

| Planet | Radius (km) |
|---|---|
| Sun | 695990.0 |
| Mercury | 2439.7 |
| Venus | 6051.90 |
| Earth | 6378.1363 |
| Moon | 1738.2 |
| Mars | 3397.0 |
| Jupiter | 71492.0 |
| Saturn | 60268.0 |
| Uranus | 25559.0 |
| Neptune | 25269.0 |
| Pluto | 1162.0 |

### Leap Seconds

The amount of leap seconds, or $\Delta AT$, has been used since 1972 in order to keep —UTC-UT1—$\leq$ 0.9sec. GMAT and the reference software packages use all the leap seconds up until 2004. In 2004 the amount of leap seconds in use were 32 seconds.

## 2.3 Naming Convention

This section describes the naming convention for propagator scripts and output reports. The naming convention consists of an ordered series of option strings, separated by underscores (_ ). Currently, options are allowed for the following fields, and will be present in the file name in order:

1. *tool* - The tool used to generate the test case
2. *traj* - The trajectory to use. This includes initial conditions, physical parameters, and time step
3. *pmg* - The point-mass gravity model to use
4. *nsg* - The non-spherical gravity model to use
5. *drag* - The atmospheric drag model to use
6. *other* - Any other forces to include, such as SRP, secondary body gravity, etc

The *tool* field should always be the first field. Future additional fields should be added to the end of the list of fields. If multiple *other* options are required, they should be added to the end of the file as required. For example, the file name will be *tool_traj_pmg_nsg_drag_other1_other2.report* (file extensions are described later.) Each field has a finite list of options, as follows (future options should be added to this list):

1. *tool*

| | |
|---|---|
| STK | - Satellite Toolkit HPOP or Astrogator |
| FF | - FreeFlyer |
| GMAT | - General Mission Analysis Tool |

2. *traj*

| | |
|---|---|
| ISS | - LEO orbit |
| SunSync | - LEO orbit |
| GPS | - MEO orbit |
| GEO | - GEO orbit |
| Molniya | - HEO orbit |
| Mars1 | - eccentric low orbit |
| Mercury1 | - eccentric low orbit |
| Moon | - eccentric low orbit |
| Neptune1 | - eccentric low orbit |
| Pluto1 | - eccentric low orbit |
| Saturn1 | - eccentric low orbit |
| Uranus1 | - eccentric low orbit |
| Venus1 | - eccentric low orbit |
| DeepSpace | deep space orbit |
| EML2 | - Earth Moon L2 orbit |
| ESL2 | - Earth Sun L2 orbit |

NOTE: Some test cases contain *traj* variations. In these cases, *traj* precedes the modification. For example, if ISS trajectory is needed with no output, then *traj* can be ISSnoOut. The lack of a report file is shortened to noOut.

3. *pmg*

| | |
|---|---|
| Earth | - Earth point mass gravity |
| Sun | - Sun point mass gravity |
| Luna | - Lunar point mass gravity |
| AllPlanets | - Sun, Mercury, Venus, Earth, Moon, Mars, Mercury, Jupiter, and Pluto point mass gravity included. |

NOTE: When dealing with a combination of *pmg*'s the first point mass is the primary body and the following are third body point masses. For example, LunaSunEarth would be a Lunar primary body with the Earth and Sun as third body point masses. The *pmg*'s after the primary body are arranged based on the order from the sun, in order to reduce repeat filenames.

4. *nsg*

| | |
|---|---|
| 0 | - no non-spherical gravity included |
| JGM2 | - Earth JGM2 20x20 gravity |
| JGM3 | - Earth JGM3 20x20 gravity |
| EGM96 | - Earth EGM96 20x20 gravity |
| MARS50C | - Mars Mars50c 20x20 gravity |
| LP165P | - Moon LP165P 20x20 gravity |

5. *drag*

| | |
|---|---|
| 0 | - drag not included |
| HP | - Harris Priester |
| JRXX | - Jacchia-Roberts |
| MSISEXX | - NRL MSISE |

NOTE: XX in the *drag* field refers to the year. For example, JR77 would be the Jacchia-Roberts 1977 model, and MSISE00 would be NRL MSISE 2000. Refer to Table 2.5 for the drag settings used.

6. *other*

| | |
|---|---|
| 0 | - no other forces included |
| SRP | - Solar Radiation Pressure |

NOTE: Any of the above options may be included as an *other* field. Refer to Table 2.5 for the SRP settings used.

### 2.3.1 Comparison Script Information

The script used to perform the position and velocity comparisons needed for the Propagator section is Comparison_Tool1_Tool2_PV.m. This script takes the normalized position and velocity vector difference between two programs.

Refer to Appendix C for more details about this script and others used in the Acceptance Test Plan document.

## 2.4 Test Case Results

The following results are for the Propagator section. The current GMAT Build is compared to STK and FreeFlyer for this section, with the maximum normalized position and velocity difference displayed in table format.

To determine if a propagator test case comparison value was acceptable, an acceptance matrix, presented in Table 2.10, was created. The values in Table 2.10 were obtained from the lower position difference bounds of David Vallados An Analysis of State Vector Propagation Using Differing Flight Dynamics Programs, presented at the 2005 American Astronomical Society (AAS)/AIAA Astrodynamics Specialist Conference. These lower bounds are difficult to meet in some orbits due to the wide range of orbits that are possible but they give a order of magnitude number to strive for. If a case has a combination of either Drag, Non-Spherical Gravity, Solar Radiation Pressure(SRP), or Point Mass gravity, the largest acceptable position difference is used.

The next step beyond this acceptance matrix is to compare GMAT's comparison data to differences seen in FF and STK comparisons, and peer reviews.

Table 2.10: Acceptance Matrix

| Difference in | Acceptable Position Difference (m) |
|---|---|
| Non-Spherical Gravity | < 0.001 |
| Point Mass Gravity | < 0.001 |
| Solar Radiation Pressure | < 0.6 |
| Drag | < 20 |

Table 2.11: GMAT/STK GEO STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.0002573600464 | 1.793784749e-008 |
| EarthLuna-0-0-0 | 0.000319469177 | 2.246260344e-008 |
| EarthSunLuna-EGM96-JR-SRP | 0.000157111986 | 1.101136958e-008 |
| EarthSunLuna-EGM96-MSISE90-SRP | 0.0001571119996 | 1.101136862e-008 |
| EarthSunLuna-JGM2-JR-SRP | 0.0001132816464 | 7.859884531e-009 |
| EarthSunLuna-JGM2-MSISE90-SRP | 0.0001132816525 | 7.859884883e-009 |
| EarthSunLuna-JGM3-JR-SRP | 0.0002438654858 | 1.730633303e-008 |
| EarthSunLuna-JGM3-MSISE90-SRP | 0.0002438654861 | 1.730633311e-008 |
| EarthSun-0-0-0 | 2.279168371e-005 | 1.614468765e-009 |
| Earth-0-0-0 | 2.111395905e-005 | 1.410324921e-009 |
| Earth-0-0-SRP | 4.571760608e-005 | 2.618694012e-009 |
| Earth-0-JR-0 | 2.111395905e-005 | 1.410324921e-009 |
| Earth-0-MSISE90-0 | 2.111395905e-005 | 1.410324921e-009 |
| Earth-EGM96-0-0 | 0.0001110202624 | 8.029310693e-009 |
| Earth-JGM2-0-0 | 2.954895496e-005 | 2.05598806e-009 |
| Earth-JGM3-0-0 | 1.603674008e-005 | 1.08902881e-009 |

Table 2.12: GMAT/STK GPS STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 1.857890303e-005 | 2.696491985e-009 |
| EarthLuna-0-0-0 | 2.280562281e-005 | 3.320021018e-009 |
| EarthSunLuna-EGM96-JR-SRP | 0.1959052443 | 2.485425413e-005 |
| EarthSunLuna-EGM96-MSISE90-SRP | 0.1959347769 | 2.485881465e-005 |
| EarthSunLuna-JGM2-JR-SRP | 0.1959143599 | 2.485563669e-005 |
| EarthSunLuna-JGM2-MSISE90-SRP | 0.1959227868 | 2.485702347e-005 |
| EarthSunLuna-JGM3-JR-SRP | 0.1959136649 | 2.485560304e-005 |
| EarthSunLuna-JGM3-MSISE90-SRP | 0.1959104274 | 2.485513888e-005 |
| EarthSun-0-0-0 | 1.81527305e-006 | 2.257416233e-010 |
| Earth-0-0-0 | 2.704817671e-006 | 3.741292798e-010 |
| Earth-0-0-SRP | 0.0878120195 | 9.617041298e-006 |
| Earth-0-JR-0 | 2.704817671e-006 | 3.741292798e-010 |
| Earth-0-MSISE90-0 | 1.54909103e-005 | 2.226217304e-009 |
| Earth-EGM96-0-0 | 3.230673797e-005 | 4.260188402e-009 |
| Earth-JGM2-0-0 | 3.207859422e-005 | 4.299912419e-009 |
| Earth-JGM3-0-0 | 3.197574489e-005 | 4.255726699e-009 |

Table 2.13: GMAT/STK ISS STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 1.236533809e-005 | 1.385493045e-008 |
| EarthLuna-0-0-0 | 2.656381117e-005 | 3.027548132e-008 |
| EarthSunLuna-EGM96-JR-SRP | 278.7490457 | 0.3182017608 |
| EarthSunLuna-EGM96-MSISE90-SRP | 56.19367014 | 0.06443183746 |
| EarthSunLuna-JGM2-JR-SRP | 265.043753 | 0.3028869043 |
| EarthSunLuna-JGM2-MSISE90-SRP | 56.19388165 | 0.06443206028 |
| EarthSunLuna-JGM3-JR-SRP | 278.7489221 | 0.3182016489 |
| EarthSunLuna-JGM3-MSISE90-SRP | 56.19332541 | 0.06443145135 |
| EarthSun-0-0-0 | 1.433764674e-005 | 1.600957323e-008 |
| Earth-0-0-0 | 2.047203147e-005 | 2.325251323e-008 |
| Earth-0-0-SRP | 0.244823116 | 0.0002550285075 |
| Earth-0-JR-0 | 251.765217 | 0.2867219205 |
| Earth-0-MSISE90-0 | 54.12970949 | 0.06180127344 |
| Earth-EGM96-0-0 | 0.0003663016096 | 4.164070917e-007 |
| Earth-JGM2-0-0 | 0.0002104591217 | 2.411877645e-007 |
| Earth-JGM3-0-0 | 0.0002166929687 | 2.47505086e-007 |

Table 2.14: GMAT/STK Molniya STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.0001645654561 | 1.252157429e-007 |
| EarthLuna-0-0-0 | 0.0001587779228 | 1.205662193e-007 |
| EarthSunLuna-EGM96-JR-SRP | 13.53119687 | 0.009730652052 |
| EarthSunLuna-EGM96-MSISE90-SRP | 7.25773273 | 0.004949260662 |
| EarthSunLuna-JGM2-JR-SRP | 13.53346199 | 0.009731885706 |
| EarthSunLuna-JGM2-MSISE90-SRP | 7.260932491 | 0.00495105133 |
| EarthSunLuna-JGM3-JR-SRP | 13.53295584 | 0.009731601686 |
| EarthSunLuna-JGM3-MSISE90-SRP | 7.260582648 | 0.004951077623 |
| EarthSun-0-0-0 | 0.000348717827 | 2.914208443e-007 |
| Earth-0-0-0 | 0.0002791429809 | 2.328568085e-007 |
| Earth-0-0-SRP | 0.571576837 | 0.0004793217459 |
| Earth-0-JR-0 | 15.70095053 | 0.01312840386 |
| Earth-0-MSISE90-0 | 7.009963698 | 0.005861407998 |
| Earth-EGM96-0-0 | 0.001747777921 | 1.46609522e-006 |
| Earth-JGM2-0-0 | 0.00156516582 | 1.313722882e-006 |
| Earth-JGM3-0-0 | 0.001286385724 | 1.080857462e-006 |

Table 2.15: GMAT/STK SunSync STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 4.699222822e-005 | 5.325204802e-008 |
| EarthLuna-0-0-0 | 1.738032476e-005 | 1.943588041e-008 |
| EarthSunLuna-EGM96-JR-SRP | 185.5519514 | 0.2108884067 |
| EarthSunLuna-EGM96-MSISE90-SRP | 45.12786362 | 0.05132420504 |
| EarthSunLuna-JGM2-JR-SRP | 185.5519345 | 0.2108883121 |
| EarthSunLuna-JGM2-MSISE90-SRP | 45.12684175 | 0.05132310311 |
| EarthSunLuna-JGM3-JR-SRP | 185.5517129 | 0.2108881509 |
| EarthSunLuna-JGM3-MSISE90-SRP | 45.12759811 | 0.0513239131 |
| EarthSun-0-0-0 | 4.687777606e-006 | 5.023688912e-009 |
| Earth-0-0-0 | 4.483249915e-005 | 5.068280737e-008 |
| Earth-0-0-SRP | 0.1578758295 | 0.0001369580266 |
| Earth-0-JR-0 | 172.0259163 | 0.1950745493 |
| Earth-0-MSISE90-0 | 42.66516434 | 0.04839009284 |
| Earth-EGM96-0-0 | 7.308356983e-005 | 8.466691171e-008 |
| Earth-JGM2-0-0 | 8.928348594e-005 | 9.655432558e-008 |
| Earth-JGM3-0-0 | 6.997911597e-005 | 7.571452902e-008 |

Table 2.16: GMAT/STK Mars1 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.1994303898 | 0.0001681334573 |
| Mars-0-0-0 | 0.1873874394 | 0.0001577557948 |
| Mars-0-0-SRP | 0.7867928767 | 0.0006572167727 |
| Mars-MARS50C-0-0 | 0.4488316637 | 0.0003800813667 |
| Mars-MARS50C-0-SRP | 1.214053862 | 0.001021133703 |

Table 2.17: GMAT/STK Mercury1 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.1124163711 | 9.591759819e-005 |
| Mercury-0-0-0 | 0.02585481636 | 2.218352736e-005 |
| Mercury-0-0-SRP | 58.83805392 | 0.05048777188 |

Table 2.18: GMAT/STK Moon STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.0002146368472 | 1.355643864e-007 |
| Luna-0-0-0 | 0.03443001175 | 2.456930533e-005 |
| Luna-0-0-SRP | 0.03471809841 | 2.413271946e-005 |
| Luna-LP165P-0-0 | 0.0002701673647 | 1.922174669e-007 |
| Luna-LP165P-0-SRP | 0.1350043985 | 9.596583571e-005 |

Table 2.19: GMAT/STK Neptune1 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.9974264518 | 0.0005074875215 |
| Neptune-0-0-0 | 1.171036908 | 0.0005920828399 |
| Neptune-0-0-SRP | 0.6214495234 | 0.0003128000507 |

Table 2.20: GMAT/STK Pluto1 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.8883195792 | 0.0004683900657 |
| Pluto-0-0-0 | 0.2632397208 | 0.0001382385307 |
| Pluto-0-0-SRP | 0.7534556636 | 0.0003932329143 |

Table 2.21: GMAT/STK Saturn1 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.1414864331 | 4.873107384e-005 |
| Saturn-0-0-0 | 0.4497282767 | 0.0001561546333 |
| Saturn-0-0-SRP | 0.3124746558 | 0.000102600788 |

Table 2.22: GMAT/STK Uranus1 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.2465709269 | 7.912323063e-005 |
| Uranus-0-0-0 | 1.320413817 | 0.0004243963023 |
| Uranus-0-0-SRP | 1.156382201 | 0.0002904419051 |

Table 2.23: GMAT/STK Venus1 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.02561929021 | 2.548815625e-005 |
| Venus-0-0-0 | 0.01793453836 | 1.768517227e-005 |
| Venus-0-0-SRP | 0.3477682342 | 0.0003453235732 |
| Venus-MGNP180U-0-0 | 0.007510965788 | 7.525754724e-006 |
| Venus-MGNP180U-0-SRP | 0.4083837321 | 0.0004049592692 |

Table 2.24: GMAT/STK DeepSpace STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.02027141264 | 3.996534351e-009 |

Table 2.25: GMAT/STK EML2 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 522765.4104 | 2.863727549 |
| AllPlanets-0-0-SRP | 162722.736 | 0.8844521611 |
| EarthSunLuna-0-0-0 | 191050.7674 | 1.043593205 |
| EarthSunLuna-JGM2-0-0 | 83170.98289 | 0.4533442704 |

Table 2.26: GMAT/STK ESL2 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 29036.76192 | 0.01713687194 |
| AllPlanets-0-0-SRP | 228360.2465 | 0.1774325007 |

Table 2.27: FF/GMAT GEO GMAT Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.02466296086 | 2.348952999e-006 |
| EarthLuna-0-0-0 | 0.02466037174 | 2.264158243e-006 |
| EarthSun-0-0-0 | 4.79785384e-005 | 8.493947765e-007 |
| Earth-0-0-0 | 5.214381207e-005 | 6.89627309e-007 |
| Earth-0-0-SRP | 2.899321865 | 0.0001245219489 |
| Earth-JGM2-0-0 | 0.02515954067 | 2.313999898e-006 |

Table 2.28: FF/GMAT GPS GMAT Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.001885974435 | 1.052020705e-006 |
| EarthLuna-0-0-0 | 0.001874007099 | 9.43361654e-007 |
| EarthSun-0-0-0 | 3.432176702e-006 | 8.317293859e-007 |
| Earth-0-0-0 | 5.489921041e-006 | 7.9829921e-007 |
| Earth-0-0-SRP | 0.5814667923 | 6.084184505e-005 |
| Earth-JGM2-0-0 | 0.01104317452 | 2.140216499e-006 |

Table 2.29: FF/GMAT ISS GMAT Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 5.610904349e-006 | 8.224014796e-007 |
| EarthLuna-0-0-0 | 1.133489824e-005 | 8.407000067e-007 |
| EarthSun-0-0-0 | 9.638402495e-006 | 8.134703987e-007 |
| Earth-0-0-0 | 2.358180759e-005 | 8.186468434e-007 |
| Earth-0-0-SRP | 0.1095353597 | 0.0001183226844 |
| Earth-JGM2-0-0 | 0.2076314901 | 0.0002404721693 |

Table 2.30: FF/GMAT Molniya GMAT Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.01444526657 | 1.203396044e-005 |
| EarthLuna-0-0-0 | 0.01424235005 | 1.19546892e-005 |
| EarthSun-0-0-0 | 0.0003311394147 | 8.232647373e-007 |
| Earth-0-0-0 | 5.789754939e-005 | 8.078947532e-007 |
| Earth-0-0-SRP | 2.735360369 | 0.002258471401 |
| Earth-JGM2-0-0 | 3.064693947 | 0.002562937467 |

Table 2.31: FF/GMAT SunSync GMAT Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 1.624452888e-005 | 8.363014362e-007 |
| EarthLuna-0-0-0 | 3.641972152e-005 | 8.139327674e-007 |
| EarthSun-0-0-0 | 1.62185169e-005 | 8.470799538e-007 |
| Earth-0-0-0 | 8.93851495e-006 | 8.215195e-007 |
| Earth-0-0-SRP | 0.04776731849 | 4.873717267e-005 |
| Earth-JGM2-0-0 | 0.09458368297 | 0.0001055216409 |

Table 2.32: FF/GMAT EML2 GMAT Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 732436.6987 | 4.007738969 |
| AllPlanets-0-0-SRP | 370563.5763 | 2.010501473 |
| EarthSunLuna-0-0-0 | 400326.9215 | 2.185454594 |
| EarthSunLuna-JGM2-0-0 | 292445.684 | 1.595241714 |

Table 2.33: FF/GMAT ESL2 GMAT Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 5690806.264 | 3.131093893 |
| AllPlanets-0-0-SRP | 6881233.15 | 5.36031143 |

## 2.5 FF/STK Comparison

Table 2.34: FF/STK GEO STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.02441863704 | 2.331184604e-006 |
| EarthLuna-0-0-0 | 0.02435631273 | 2.242954572e-006 |
| EarthSunLuna-JGM2-HP-SRP | 2.852626845 | 0.0001210061779 |
| EarthSun-0-0-0 | 4.231055926e-005 | 8.493743904e-007 |
| Earth-0-0-0 | 6.836800608e-005 | 6.88987973e-007 |
| Earth-0-0-SRP | 2.899330477 | 0.0001245232993 |
| Earth-0-HP-0 | 6.836800608e-005 | 6.88987973e-007 |
| Earth-JGM2-0-0 | 0.02513336324 | 2.312005795e-006 |

Table 2.35: FF/STK GPS STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.001903432726 | 1.05396749e-006 |
| EarthLuna-0-0-0 | 0.001896072444 | 9.455905846e-007 |
| EarthSunLuna-JGM2-HP-SRP | 0.6785588953 | 6.968633054e-005 |
| EarthSun-0-0-0 | 3.872950958e-006 | 8.316374468e-007 |
| Earth-0-0-0 | 8.164858288e-006 | 7.983002389e-007 |
| Earth-0-0-SRP | 0.6692784196 | 6.82998191e-005 |
| Earth-0-HP-0 | 8.164858288e-006 | 7.983002389e-007 |
| Earth-JGM2-0-0 | 0.01104063243 | 2.139207943e-006 |

Table 2.36: FF/STK ISS STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 1.17832665e-005 | 8.274193497e-007 |
| EarthLuna-0-0-0 | 2.023778135e-005 | 8.422716288e-007 |
| EarthSunLuna-JGM2-HP-SRP | 3.468138188 | 0.00397058468 |
| EarthSun-0-0-0 | 2.067991746e-005 | 8.179978462e-007 |
| Earth-0-0-0 | 4.404163183e-005 | 8.18654414e-007 |
| Earth-0-0-SRP | 0.1637932094 | 0.0001561216614 |
| Earth-0-HP-0 | 3.213782043 | 0.003648358687 |
| Earth-JGM2-0-0 | 0.2076446785 | 0.000240480153 |

Table 2.37: FF/STK Molniya STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 0.01457313187 | 1.215436857e-005 |
| EarthLuna-0-0-0 | 0.01409431455 | 1.184376375e-005 |
| EarthSunLuna-JGM2-HP-SRP | 7.784661066 | 0.004770671083 |
| EarthSun-0-0-0 | 0.0006798546862 | 1.003656755e-006 |
| Earth-0-0-0 | 0.0003365057467 | 8.083517746e-007 |
| Earth-0-0-SRP | 2.16384821 | 0.001779529358 |
| Earth-0-HP-0 | 15.27354394 | 0.01277094127 |
| Earth-JGM2-0-0 | 3.063128789 | 0.002561623786 |

Table 2.38: FF/STK SunSync STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 3.408772257e-005 | 8.692021282e-007 |
| EarthLuna-0-0-0 | 1.971678896e-005 | 8.200608417e-007 |
| EarthSunLuna-JGM2-HP-SRP | 0.7800584002 | 0.0008377097648 |
| EarthSun-0-0-0 | 1.533280696e-005 | 8.472033081e-007 |
| Earth-0-0-0 | 3.656123033e-005 | 8.215166636e-007 |
| Earth-0-0-SRP | 0.2052485046 | 0.0001828464608 |
| Earth-0-HP-0 | 0.6524853805 | 0.0007361489016 |
| Earth-JGM2-0-0 | 0.09463135069 | 0.0001055896859 |

Table 2.39: FF/STK EML2 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 209675.042 | 1.144026162 |
| AllPlanets-0-0-SRP | 207842.4058 | 1.126072542 |
| EarthSunLuna-0-0-0 | 209277.3283 | 1.141861547 |
| EarthSunLuna-JGM2-0-0 | 209283.0998 | 1.141942278 |

Table 2.40: FF/STK ESL2 STK Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| AllPlanets-0-0-0 | 5661795.443 | 3.114044494 |
| AllPlanets-0-0-SRP | 6652873.129 | 5.182879379 |

# Chapter 3

# Calculation Parameters

GMAT's Central Body (Cb) and Coordinate System (CS) dependent parameters were tested to verify that the internal calculations were correct. In order to minimize the effects of other forces/elements, the two-body cases from the Propagators section were used, with some modification, to test both the central body and coordinate system parameters. The only changes to the two body cases were in the report output intervals and report output parameters. Data was outputted in ten minute intervals. The ISS two-body case was used for the Earth case and each planets respective two-body case was used for the non-Earth cases.

## 3.1 Initial Orbit State Conditions

The ISS, GEO, Mars1, Mercury1, Moon, Neptune1, Pluto1, Saturn1, Uranus1 and Venus1 two-body case's initial orbit parameters were used from the Propagation section (Chapter 2) for the test cases in this section.

Refer to Appendix B.1 Tables B.1- B.13 for a listing of all Propagator initial orbit states used for the Calculation Parameter test cases.

## 3.2 Central Body Dependent Parameters

### 3.2.1 Naming Convention

This section describes the naming convention for central body dependent parameter scripts and output reports. The naming convention consists of a case sensitive ordered series of option strings, separated by underscores (_ ). Currently, options are allowed for the following fields, and will be present in the file name:

1. *tool* - The tool used to generate the test case.
2. *traj* - The trajectory to use. This includes initial conditions, physical parameters, and time step.

CbParams precedes the *tool* field and 2Body follows the *traj* field. The central body used can be determined based on the *traj* field. The final Cb file format is as followed:
CbParams_*tool*_*traj*_2Body.report

The *tool* field should always be the first option field. Each field has a finite list of options, as follows (future options should be added to this list):

1. *tool*
   STK - Satellite Toolkit HPOP or Astrogator
   FF - FreeFlyer
   GMAT - General Mission Analysis Tool

2. *traj*
   ISS - leo orbit
   Mars1 - eccentric low orbit
   Mercury1 - eccentric low orbit
   Moon - eccentric low orbit
   Pluto1 - eccentric low orbit
   Venus1 - eccentric low orbit

   NOTE: Some test cases contain *traj* variations. In this case *traj* precedes the modification. For example, if an ISS trajectory is needed with a different Cd, *traj* could be ISSdiffCd1.

### 3.2.2 Comparison Script Information

Comparison_Tool1_Tool2_Cb.m is the script used to perform the coordinate system comparisons needed for the Acceptance Test Plan. Many elements of this script were extracted from the Comparison_Tool1_Tool2_CS.m script.

Comparison_Tool1_Tool2_Cb.m was designed to allow the user to select two programs to compare to one another. The comparison involves taking the difference of the variables listed in the Acceptance Test Plan Overview Chapter->Testing Methodology->Calculation Parameters section.

Refer to Appendix C for more details on this script and others used in the Acceptance Test Plan document.

### 3.2.3 Test Case Results

The following results are for the Central Body-Calculation Parameter section. The current GMAT Build is compared to STK and FreeFlyer for this section.

FF-STK comparison results presented in Tables 3.11- 3.15 are used as a way to determine if the GMAT comparison values are acceptable. If GMAT comparison data is within the same order of magnitude as the FF-STK comparison data, that is acceptable. A more detailed acceptance metric/matrix will be developed at a later date.

Table 3.1: GMAT/STK Central Body Dependent Parameter Differences (1)

| Test Case | Altitude (m) | Eccentricity | M. Anomaly (deg) | M. Motion (rad/sec) | Period (sec) |
|---|---|---|---|---|---|
| GEO-2Body | 1.88447e-006 | 1.71688e-014 | 1.90007e-005 | 3.0114e-015 | 3.59432e-009 |
| Hyperbolic-2Body | 0.00422986 | 1.98064e-013 | 351.401 | 0.000223215 | N/A |
| ISS-2Body | 0.00543367 | 5.95719e-014 | 5.81025e-010 | 4.99015e-015 | 2.54659e-010 |
| Mars1-2Body | 0.0144309 | 9.74698e-011 | 7.84791e-007 | 1.62511e-013 | 2.29212e-006 |
| Mercury1-2Body | 0.00224375 | 2.36836e-011 | 1.7241e-007 | 5.54375e-014 | 7.66082e-007 |
| Moon-2Body | 0.00576446 | 2.74547e-011 | 6.47192e-007 | 4.03859e-014 | 8.68182e-007 |
| Neptune1-2Body | 0.129938 | 1.31684e-010 | 6.04911e-007 | 1.00481e-013 | 4.02816e-006 |
| Pluto1-2Body | 0.19231 | 1.83823e-009 | 2.95607e-005 | 3.82792e-012 | 0.000141823 |
| Saturn1-2Body | 0.752271 | 1.05362e-011 | 6.3449e-008 | 1.11997e-014 | 1.04643e-006 |
| Uranus1-2Body | 0.216614 | 5.31596e-011 | 6.35362e-007 | 8.48005e-014 | 8.31598e-006 |
| Venus1-2Body | 0.000632367 | 1.26323e-011 | 2.13253e-008 | 1.53591e-014 | 1.51652e-007 |

Table 3.2: GMAT/STK Central Body Dependent Parameter Differences (2)

| Test Case | Semi-major Axis (m) | True Anomaly (deg) | Semilatus Rectum(m) |
|---|---|---|---|
| GEO-2Body | 1.17871e-006 | 1.90007e-005 | 7.42148e-007 |
| Hyperbolic-2Body | 1.72076e-006 | 7.41807e-012 | 1.32204e-005 |
| ISS-2Body | 2.08274e-007 | 5.77472e-010 | 1.70985e-007 |
| Mars1-2Body | 0.000741843 | 1.15747e-006 | 0.000794765 |
| Mercury1-2Body | 0.000199977 | 2.61636e-007 | 0.000175894 |
| Moon-2Body | 0.000103879 | 9.75722e-007 | 7.23717e-005 |
| Neptune1-2Body | 0.00597339 | 9.2047e-007 | 0.00497125 |
| Pluto1-2Body | 0.0111278 | 4.499e-005 | 0.0106515 |
| Saturn1-2Body | 0.00241793 | 9.55595e-008 | 0.00235179 |
| Uranus1-2Body | 0.0100126 | 9.19017e-007 | 0.00930848 |
| Venus1-2Body | 0.000101745 | 3.07957e-008 | 0.00013864 |

Table 3.3: GMAT/STK Central Body Dependent Parameter Differences (3)

| Test Case | Apoapsis Rad. (m) | Periapsis Rad. (m) | Apo. Vel. ($m/sec$) | Per. Vel. ($m/sec$) |
|---|---|---|---|---|
| GEO-2Body | 1.25146e-006 | 1.27329e-006 | 8.21565e-011 | 1.03029e-010 |
| Hyperbolic-2Body | N/A | 4.50927e-006 | N/A | 1.86873e-009 |
| ISS-2Body | 5.26597e-007 | 3.38332e-007 | 4.39648e-010 | 3.47278e-010 |
| Mars1-2Body | 0.000683647 | 0.000800039 | 2.75849e-007 | 4.86309e-007 |
| Mercury1-2Body | 0.000280259 | 0.000125894 | 7.84977e-008 | 7.33316e-008 |
| Moon-2Body | 0.000193031 | 1.47281e-005 | 7.36031e-008 | 1.26232e-008 |
| Neptune1-2Body | 0.0107941 | 0.00538058 | 2.2861e-006 | 2.18703e-006 |
| Pluto1-2Body | 0.0145814 | 0.00998796 | 2.30184e-006 | 3.55073e-006 |
| Saturn1-2Body | 0.002828 | 0.00203526 | 2.94648e-007 | 5.08262e-007 |
| Uranus1-2Body | 0.0133233 | 0.00759641 | 1.41239e-006 | 1.43534e-006 |
| Venus1-2Body | 0.000149412 | 0.000183741 | 6.66214e-008 | 1.50022e-007 |

Table 3.4: GMAT/STK Central Body Dependent Parameter Differences (4)

| Test Case | C3-Energy ($m^2/sec^2$) | Latitude (deg) | Longitude (deg) | MHA (deg) | LST (deg) |
|---|---|---|---|---|---|
| GEO-2Body | 2.6823e-007 | 3.24498e-008 | 3.14812e-007 | 0.00196854 | 0.00196864 |
| Hyperbolic-2Body | 1.64846e-006 | 5.65537e-008 | 1.35016e-007 | 0.00196849 | 0.00196858 |
| ISS-2Body | 1.74794e-006 | 1.07149e-007 | 1.3276e-007 | 0.00196849 | 0.0019686 |
| Mars1-2Body | 0.00149955 | 5.58338e-007 | 9.73051e-007 | N/A | N/A |
| Mercury1-2Body | 0.000332532 | 1.88133e-007 | 2.69651e-007 | N/A | N/A |
| Moon-2Body | 0.000140608 | 7.42402e-007 | 1.06364e-006 | N/A | N/A |
| Neptune1-2Body | 0.0333365 | 7.39515e-007 | 1.15656e-006 | N/A | N/A |
| Pluto1-2Body | 0.00339014 | 3.20069e-005 | 7.44124e-005 | N/A | N/A |
| Saturn1-2Body | 0.014334 | 1.24281e-006 | 5.18835e-007 | N/A | N/A |
| Uranus1-2Body | 0.028651 | 9.64237e-007 | 2.34538e-006 | N/A | N/A |
| Venus1-2Body | 0.000500677 | 2.22686e-008 | 3.82501e-008 | N/A | N/A |

Table 3.5: GMAT/STK Central Body Dependent Parameter Differences (5)

| Test Case | Beta Angle (deg) | (RxV)-Mag ($m^2/sec$) | R-Mag (m) |
|---|---|---|---|
| GEO-2Body | 0.000773444 | 0.00180444 | 1.88447e-006 |
| Hyperbolic-2Body | 0.000706521 | 0.025655 | 1.35624e-005 |
| ISS-2Body | 0.00344889 | 0.000749424 | 4.62933e-007 |
| Mars1-2Body | 0.00315966 | 1.23719 | 0.0126011 |
| Mercury1-2Body | 0.00511923 | 0.220796 | 0.00224375 |
| Moon-2Body | 0.00394712 | 0.000777618 | 0.00576446 |
| Neptune1-2Body | 0.000741045 | 35.4559 | 0.0763421 |
| Pluto1-2Body | 0.000530341 | 4.01956 | 0.19231 |
| Saturn1-2Body | 0.00142058 | 26.1241 | 0.0181717 |
| Uranus1-2Body | 0.000807228 | 53.902 | 0.101524 |
| Venus1-2Body | 0.00414838 | 0.447268 | 0.000632365 |

Table 3.6: FF/GMAT Central Body Dependent Parameter Differences (1)

| Test Case | Altitude (m) | Eccentricity | M. Anomaly (deg) | M. Motion (rad/sec) | Period (sec) |
|---|---|---|---|---|---|
| GEO-2Body | 8.20728e-006 | 1.93962e-010 | 6.42153e-006 | 5.69653e-016 | 7.75617e-009 |
| ISS-2Body | 0.433346 | 6.39335e-012 | 1.714e-009 | 4.2466e-015 | 7.69433e-010 |

Table 3.7: FF/GMAT Central Body Dependent Parameter Differences (2)

| Test Case | Semi-major Axis (m) | True Anomaly (deg) | Semilatus Rectum(m) |
|---|---|---|---|
| GEO-2Body | 2.23372e-006 | 6.4215e-006 | 2.4811e-006 |
| ISS-2Body | 4.09273e-007 | 1.86708e-009 | 1.7917e-007 |

Table 3.8: FF/GMAT Central Body Dependent Parameter Differences (3)

| Test Case | Apoapsis Rad. (m) | Periapsis Rad. (m) | Apo. Vel. ($m/sec$) | Per. Vel. ($m/sec$) |
|---|---|---|---|---|
| GEO-2Body | 2.72848e-006 | 3.00497e-006 | 2.39764e-008 | 2.39013e-008 |
| ISS-2Body | 3.98359e-007 | 6.89397e-007 | 2.91838e-008 | 2.88605e-008 |

Table 3.9: FF/GMAT Central Body Dependent Parameter Differences (4)

| Test Case | C3-Energy ($m^2/sec^2$) | Latitude (deg) | Longitude (deg) | MHA (deg) | LST (deg) |
|---|---|---|---|---|---|
| GEO-2Body | 0.00014728 | 5.40781e-008 | 0 | 0.00300898 | 0.00300919 |
| ISS-2Body | 0.000444231 | 6.02545e-006 | 5.81869e-007 | 0.00300898 | 0.00300919 |

Table 3.10: FF/GMAT Central Body Dependent Parameter Differences (5)

| Test Case | Beta Angle (deg) | (RxV)-Mag ($m^2/sec$) | R-Mag (m) |
|---|---|---|---|
| GEO-2Body | 45.7413 | 0.00429281 | 3.27418e-006 |
| ISS-2Body | 98.3649 | 0.00164437 | 1.18325e-006 |

Table 3.11: FF/STK Central Body Dependent Parameter Differences (1)

| Test Case | Altitude (m) | Eccentricity | M. Anomaly (deg) | M. Motion (rad/sec) | Period (sec) |
|---|---|---|---|---|---|
| GEO-2Body | 8.04721e-006 | 1.9396e-010 | 1.77052e-005 | 2.44679e-015 | 6.4756e-009 |
| ISS-2Body | 0.427915 | 6.34e-012 | 1.73014e-009 | 9.18666e-015 | 8.14907e-010 |

Table 3.12: FF/STK Central Body Dependent Parameter Differences (2)

| Test Case | Semi-major Axis (m) | True Anomaly (deg) | Semilatus Rectum(m) |
|---|---|---|---|
| GEO-2Body | 2.08092e-006 | 1.77044e-005 | 1.92085e-006 |
| ISS-2Body | 4.47471e-007 | 1.67336e-009 | 1.55524e-007 |

Table 3.13: FF/STK Central Body Dependent Parameter Differences (3)

| Test Case | Apoapsis Rad. (m) | Periapsis Rad. (m) | Apo. Vel. ($m/sec$) | Per. Vel. ($m/sec$) |
|---|---|---|---|---|
| GEO-2Body | 2.74304e-006 | 2.03727e-006 | 2.38942e-008 | 2.38796e-008 |
| ISS-2Body | 5.23869e-007 | 6.24823e-007 | 2.87441e-008 | 2.88605e-008 |

Table 3.14: FF/STK Central Body Dependent Parameter Differences (4)

| Test Case | C3-Energy ($m^2/sec^2$) | Latitude (deg) | Longitude (deg) | MHA (deg) | LST (deg) |
|---|---|---|---|---|---|
| GEO-2Body | 0.000147141 | 3.06691e-008 | 0 | 0.00497708 | 0.00497715 |
| ISS-2Body | 0.000442895 | 5.92635e-006 | 6.1431e-007 | 0.00497708 | 0.00497716 |

Table 3.15: FF/STK Central Body Dependent Parameter Differences (5)

| Test Case | Beta Angle (deg) | (RxV)-Mag ($m^2/sec$) | R-Mag (m) |
|---|---|---|---|
| GEO-2Body | 0.000773444 | 0.00355067 | 4.05998e-006 |
| ISS-2Body | 0.00344889 | 0.00178261 | 1.01772e-006 |

## 3.3 Coordinate System Dependent Parameters

### 3.3.1 Naming Convention

This section describes the naming convention for coordinate system dependent parameter scripts and output reports. The naming convention consists of a case sensitive ordered series of option strings, separated by underscores (_ ). Currently, options are allowed for the following fields, and will be present in the file name:

1. *tool* - The tool used to generate the test case
2. *traj* - The trajectory to use. This includes initial conditions, physical parameters, and time step
3. *CS* - The coordinate system to use. The celestial body to use is followed by the CS in the name

CSParams precedes the *tool* field and 2Body precedes the *CS* field. The final CS file format is as followed: CSParams_*tool*_*traj*_2Body_*CS*.report

The *tool* field should always be the first option field. Each field has a finite list of options, as follows (future options should be added to this list):

1. *tool*

| | |
|---|---|
| STK | - Satellite Toolkit HPOP or Astrogator |
| FF | - FreeFlyer |
| GMAT | - General Mission Analysis Tool |

2. *traj*

| | |
|---|---|
| ISS | - leo orbit |
| SunSync | - leo orbit |
| GPS | - meo orbit |
| GEO | - geo orbit |
| Molniya | - heo orbit |
| Mars1 | - eccentric low orbit |
| Mercury1 | - eccentric low orbit |
| Moon | - eccentric low orbit |
| Pluto1 | - eccentric low orbit |
| Venus1 | - eccentric low orbit |

NOTE: Some test cases contain *traj* variations. In this case *traj* precedes the modification. For example, if ISS trajectory is needed with no output, then *traj* can be ISSnoOut. The lack of a report file is shortened to noOut.

3. *CS*

| | | |
|---|---|---|
| EarthFixed | EarthMJ2000Eq | EarthMJ2000Ec |
| EarthTODEq | EarthTODEc | EarthMODEq |
| EarthMODEc | EarthGSM | EarthGSE |
| MarsFixed | MarsMJ2000Eq | MarsMJ2000Ec |
| MercuryFixed | MercuryMJ2000Eq | MercuryMJ2000Ec |
| MoonFixed | MoonMJ2000Eq | MoonMJ2000Ec |
| NeptuneFixed | NeptuneMJ2000Eq | NeptuneMJ2000Ec |
| PlutoFixed | PlutoMJ2000Eq | PlutoMJ2000Ec |
| SaturnFixed | SaturnMJ2000Eq | SaturnMJ2000Ec |
| UranusFixed | UranusMJ2000Eq | UranusMJ2000Ec |
| VenusFixed | VenusMJ2000Eq | VenusMJ2000Ec |

### 3.3.2 Comparison Script Information

The script used to perform the Coordinate System comparisons needed for the Acceptance Test Plan is Comparison_Tool1_Tool2_CS.m. Many elements of this script were extracted from the Comparison_Tool1_Tool2_PV.m script.

Comparison_Tool1_Tool2_CS.m was designed to allow the user to select two programs to compare to one another. The comparison involves taking the difference of the variables listed in the Acceptance Test Plan Overview Chapter->Testing Methodology->Calculation Parameters section.

Refer to Appendix C for more details of this script and others used in the Acceptance Test Plan document.

### 3.3.3 Test Case Results

The following results are for the Coordinate System-Calculation Parameter section. The current GMAT Build is compared to STK and FreeFlyer for this section.

FF-STK comparison results presented in Tables 3.26- 3.30 are used as a way to determine if the GMAT comparison values are acceptable. If GMAT comparison data is within the same order of magnitude as the FF-STK comparison data that is acceptable. A more detailed acceptance metric/matrix will be developed at a later date.

Table 3.16: GMAT/STK Coordinate System Dependent Parameter Differences (Position)

| Test Case | X-Pos (m) | Y-Pos (m) | Z-Pos (m) |
|---|---|---|---|
| GEO-2Body-EarthFixed | 0.2281413654 | 0.04023080692 | 0.02037045935 |
| GEO-2Body-EarthMJ2000Ec | 2.294098067e-005 | 0.00032580283 | 0.0007504095265 |
| GEO-2Body-EarthMJ2000Eq | 2.294098067e-005 | 2.433989721e-005 | 4.46e-009 |
| GEO-2Body-EarthMODEc | 0.001272894679 | 0.001382489927 | 8.563802112e-006 |
| GEO-2Body-EarthMODEq | 0.001272895247 | 0.001271371502 | 0.000543207701 |
| GEO-2Body-EarthMOEEc | 2.295053037e-005 | 2.237175067e-005 | 9.603354556e-006 |
| GEO-2Body-EarthMOEEq | 2.295053037e-005 | 2.433989721e-005 | 4.162467864e-009 |
| GEO-2Body-EarthTODEc | 0.006357750408 | 0.006834058695 | 0.0006267073331 |
| GEO-2Body-EarthTODEq | 0.006357749726 | 0.006271528946 | 0.003423117541 |
| GEO-2Body-EarthTOEEc | 0.005487542296 | 0.005975813906 | 9.603354556e-006 |
| GEO-2Body-EarthTOEEq | 0.005487542239 | 0.005486127634 | 0.002404046552 |
| Hyperbolic-2Body-EarthFixed | 0.3488040966 | 0.5436684769 | 0.1095402695 |
| Hyperbolic-2Body-EarthMJ2000Ec | 1.6822014e-005 | 0.001917796908 | 0.004851564881 |
| Hyperbolic-2Body-EarthMJ2000Eq | 1.6822014e-005 | 1.979060471e-006 | 2.124579623e-006 |
| Hyperbolic-2Body-EarthMODEc | 0.008121191058 | 0.01077665365 | 7.392372936e-006 |
| Hyperbolic-2Body-EarthMODEq | 0.008121191058 | 0.0098834862 | 0.004294328392 |
| Hyperbolic-2Body-EarthMOEEc | 1.693842933e-005 | 2.211891115e-006 | 2.153683454e-006 |
| Hyperbolic-2Body-EarthMOEEq | 1.693842933e-005 | 1.979060471e-006 | 2.066371962e-006 |
| Hyperbolic-2Body-EarthTODEc | 0.01367426012 | 0.01960279769 | 0.003635126632 |
| Hyperbolic-2Body-EarthTODEq | 0.01367420191 | 0.02924879664 | 0.005363341188 |
| Hyperbolic-2Body-EarthTOEEc | 0.03536941949 | 0.04713787348 | 2.153683454e-006 |
| Hyperbolic-2Body-EarthTOEEq | 0.03536941949 | 0.04508509301 | 0.01691197394 |
| ISS-2Body-EarthFixed | 0.01006907041 | 0.01444909003 | 0.002770384526 |
| ISS-2Body-EarthGSE | 5.3005067e-005 | 3.604054655e-005 | 7.67059305e-006 |
| ISS-2Body-EarthGSM | 4.954046062e-005 | 0.003799987553 | 0.00293166886 |
| ISS-2Body-EarthMJ2000Ec | 1.033299668e-005 | 8.047527444e-005 | 0.0001261635134 |
| ISS-2Body-EarthMJ2000Eq | 1.033299668e-005 | 9.667473932e-006 | 9.215000318e-006 |
| ISS-2Body-EarthMODEc | 0.000210427288 | 0.0001799348865 | 7.613095931e-006 |
| ISS-2Body-EarthMODEq | 0.0002104279702 | 0.0001652065293 | 7.136577551e-005 |
| ISS-2Body-EarthMOEEc | 1.033140506e-005 | 1.099556357e-005 | 7.695803106e-006 |
| ISS-2Body-EarthMOEEq | 1.033140506e-005 | 9.666564438e-006 | 9.215000318e-006 |
| ISS-2Body-EarthTODEc | 0.0003583738817 | 0.0002511692401 | 0.0001079586127 |
| ISS-2Body-EarthTODEq | 0.0003583786565 | 0.0003260520316 | 0.0003840964382 |
| ISS-2Body-EarthTOEEc | 0.0009193927326 | 0.0007893422662 | 7.69603048e-006 |
| ISS-2Body-EarthTOEEq | 0.0009193925052 | 0.0006983391359 | 0.0002934716576 |
| Mars1-2Body-MarsFixed | 0.05898887696 | 0.05711927406 | 0.03425882358 |
| Mars1-2Body-MarsMJ2000Ec | 0.04854124924 | 0.06378650704 | 0.05515928102 |
| Mars1-2Body-MarsMJ2000Eq | 0.04854124947 | 0.06874534654 | 0.04854127501 |
| Mercury1-2Body-MercuryFixed | 0.009607810114 | 0.01088151507 | 0.009587843124 |
| Mercury1-2Body-MercuryMJ2000Ec | 0.008947269691 | 0.01142762343 | 0.01022404834 |
| Mercury1-2Body-MercuryMJ2000Eq | 0.008947269691 | 0.01220655815 | 0.008947248972 |
| Moon-2Body-MoonFixed | 0.02659000859 | 0.01816027718 | 0.0259134155 |
| Moon-2Body-MoonMJ2000Ec | 0.02282095541 | 0.02955069925 | 0.02583996015 |
| Moon-2Body-MoonMJ2000Eq | 0.02282095546 | 0.03242772568 | 0.02282108797 |
| Neptune1-2Body-NeptuneFixed | 0.4543228424 | 0.474102093 | 0.2913599029 |
| Neptune1-2Body-NeptuneMJ2000Ec | 0.2946186363 | 0.379445413 | 0.3350099975 |
| Neptune1-2Body-NeptuneMJ2000Eq | 0.2946186363 | 0.4144292316 | 0.30129434 |
| Pluto1-2Body-PlutoFixed | 0.6182226091 | 1.111364997 | 0.7629325749 |
| Pluto1-2Body-PlutoMJ2000Ec | 0.7527405821 | 0.9494719067 | 0.8475838174 |
| Pluto1-2Body-PlutoMJ2000Eq | 0.7527405819 | 1.085654527 | 0.7521445426 |
| Saturn1-2Body-SaturnFixed | 0.6340523651 | 0.6134889563 | 0.06666205172 |
| Saturn1-2Body-SaturnMJ2000Ec | 0.07298453147 | 0.09547611444 | 0.08217663634 |
| Saturn1-2Body-SaturnMJ2000Eq | 0.07298453147 | 0.1048656477 | 0.0737594446 |
| Uranus1-2Body-UranusFixed | 0.4395935848 | 0.5642743054 | 0.5180439475 |
| Uranus1-2Body-UranusMJ2000Ec | 0.385162361 | 0.5115039512 | 0.433244951 |
| Uranus1-2Body-UranusMJ2000Eq | 0.3851623601 | 0.5548048448 | 0.3789037312 |
| Venus1-2Body-VenusFixed | 0.003286658284 | 0.002153384223 | 0.002565443879 |
| Venus1-2Body-VenusMJ2000Ec | 0.002135182285 | 0.003261576126 | 0.002492622912 |

Table 3.17: GMAT/STK Coordinate System Dependent Parameter Differences (Velocity)

| Test Case | X-Vel (m/s) | Y-Vel (m/s) | Z-Vel (m/s) |
|---|---|---|---|
| GEO-2Body-EarthFixed | 1.014408074e-005 | 1.788716823e-006 | 2.603041318e-007 |
| GEO-2Body-EarthMJ2000Ec | 1.658007065e-009 | 2.383426789e-008 | 5.472688969e-008 |
| GEO-2Body-EarthMJ2000Eq | 1.658007065e-009 | 1.708189146e-009 | 0 |
| GEO-2Body-EarthMODEc | 9.276047985e-008 | 1.009415607e-007 | 6.031009026e-010 |
| GEO-2Body-EarthMODEq | 9.276047985e-008 | 9.28549633e-008 | 3.961584403e-008 |
| GEO-2Body-EarthMOEEc | 1.658895243e-009 | 1.566302643e-009 | 6.827038934e-010 |
| GEO-2Body-EarthMOEEq | 1.658895243e-009 | 1.70885528e-009 | 3.03533858e-013 |
| GEO-2Body-EarthTODEc | 4.572472123e-007 | 5.051409152e-007 | 4.601985459e-008 |
| GEO-2Body-EarthTODEq | 4.572472123e-007 | 4.636103862e-007 | 2.603101342e-007 |
| GEO-2Body-EarthTOEEc | 4.000988846e-007 | 4.359142977e-007 | 6.827038934e-010 |
| GEO-2Body-EarthTOEEq | 4.000988846e-007 | 4.002142819e-007 | 1.75307769e-007 |
| Hyperbolic-2Body-EarthFixed | 3.961039852e-005 | 4.825957234e-005 | 7.70518005e-006 |
| Hyperbolic-2Body-EarthMJ2000Ec | 1.829647545e-010 | 2.841105129e-008 | 7.195000151e-008 |
| Hyperbolic-2Body-EarthMJ2000Eq | 1.900701818e-010 | 7.416289804e-011 | 7.505107646e-011 |
| Hyperbolic-2Body-EarthMODEc | 1.202220545e-007 | 3.21276783e-007 | 2.733924198e-010 |
| Hyperbolic-2Body-EarthMODEq | 1.202220545e-007 | 2.946597966e-007 | 1.280426876e-007 |
| Hyperbolic-2Body-EarthMOEEc | 1.829647545e-010 | 8.482103908e-011 | 5.306866058e-011 |
| Hyperbolic-2Body-EarthMOEEq | 1.829647545e-010 | 7.283063042e-011 | 7.416289804e-011 |
| Hyperbolic-2Body-EarthTODEc | 1.646727199e-007 | 2.454381143e-007 | 6.046185774e-008 |
| Hyperbolic-2Body-EarthTODEq | 1.646727199e-007 | 3.61354946e-007 | 2.50673704e-007 |
| Hyperbolic-2Body-EarthTOEEc | 5.242357659e-007 | 1.403959171e-006 | 5.306866058e-011 |
| Hyperbolic-2Body-EarthTOEEq | 5.242357659e-007 | 1.28404859e-006 | 5.625165889e-007 |
| ISS-2Body-EarthFixed | 1.122181903e-005 | 1.427654617e-005 | 3.056610076e-006 |
| ISS-2Body-EarthGSE | 3.753886091e-008 | 6.98910979e-008 | 8.158362874e-009 |
| ISS-2Body-EarthGSM | 3.523581427e-008 | 4.26608171e-006 | 3.338248789e-006 |
| ISS-2Body-EarthMJ2000Ec | 1.084418666e-008 | 9.146905455e-008 | 1.441839981e-007 |
| ISS-2Body-EarthMJ2000Eq | 1.084418666e-008 | 1.137612227e-008 | 1.016586815e-008 |
| ISS-2Body-EarthMODEc | 2.404640931e-007 | 2.0532398e-007 | 8.086198378e-009 |
| ISS-2Body-EarthMODEq | 2.404640931e-007 | 1.883493361e-007 | 8.178480115e-008 |
| ISS-2Body-EarthMOEEc | 1.084238255e-008 | 1.291988738e-008 | 8.192335699e-009 |
| ISS-2Body-EarthMOEEq | 1.084238255e-008 | 1.137490102e-008 | 1.016536855e-008 |
| ISS-2Body-EarthTODEc | 4.073232862e-007 | 2.878270955e-007 | 1.22599042e-007 |
| ISS-2Body-EarthTODEq | 4.073232862e-007 | 3.764446532e-007 | 4.359921313e-007 |
| ISS-2Body-EarthTOEEc | 1.051030152e-006 | 8.982550259e-007 | 8.192335699e-009 |
| ISS-2Body-EarthTOEEq | 1.051030152e-006 | 7.945391012e-007 | 3.338689325e-007 |
| Mars1-2Body-MarsFixed | 4.119460101e-005 | 5.040193685e-005 | 2.244996011e-005 |
| Mars1-2Body-MarsMJ2000Ec | 3.9224898e-005 | 5.612389309e-005 | 3.773446111e-005 |
| Mars1-2Body-MarsMJ2000Eq | 3.9224898e-005 | 5.5061041e-005 | 3.923428094e-005 |
| Mercury1-2Body-MercuryFixed | 8.297573739e-006 | 1.056043131e-005 | 6.28309893e-006 |
| Mercury1-2Body-MercuryMJ2000Ec | 7.406872116e-006 | 1.084578205e-005 | 6.911486272e-006 |
| Mercury1-2Body-MercuryMJ2000Eq | 7.406872116e-006 | 1.046935982e-005 | 7.379157396e-006 |
| Moon-2Body-MoonFixed | 2.015969569e-005 | 1.201479294e-005 | 1.474075317e-005 |
| Moon-2Body-MoonMJ2000Ec | 1.554381401e-005 | 2.227603246e-005 | 1.46090765e-005 |
| Moon-2Body-MoonMJ2000Eq | 1.554381401e-005 | 2.234036151e-005 | 1.554384002e-005 |
| Neptune1-2Body-NeptuneFixed | 0.002311382259 | 0.00232459858 | 0.0001281027884 |
| Neptune1-2Body-NeptuneMJ2000Ec | 0.0001425149572 | 0.0002082204933 | 0.0001364492723 |
| Neptune1-2Body-NeptuneMJ2000Eq | 0.0001425149572 | 0.0002067147653 | 0.0001464608648 |
| Pluto1-2Body-PlutoFixed | 0.0003613682175 | 0.0004667307785 | 0.0004682860251 |
| Pluto1-2Body-PlutoMJ2000Ec | 0.0003872987759 | 0.0005522331561 | 0.000344448214 |
| Pluto1-2Body-PlutoMJ2000Eq | 0.0003872987759 | 0.0005410307473 | 0.0003868007483 |
| Saturn1-2Body-SaturnFixed | 0.0001164046752 | 0.0001207579849 | 2.354126405e-005 |
| Saturn1-2Body-SaturnMJ2000Ec | 2.488907747e-005 | 3.488300981e-005 | 2.320261316e-005 |
| Saturn1-2Body-SaturnMJ2000Eq | 2.488907747e-005 | 3.502235213e-005 | 2.510042485e-005 |
| Uranus1-2Body-UranusFixed | 0.0001044264559 | 0.0001481343457 | 0.000160607621 |
| Uranus1-2Body-UranusMJ2000Ec | 0.0001229694768 | 0.000170892658 | 0.0001139574768 |
| Uranus1-2Body-UranusMJ2000Eq | 0.0001229694768 | 0.0001702024259 | 0.000120316952 |
| Venus1-2Body-VenusFixed | 3.298453583e-006 | 1.926899973e-006 | 2.241729913e-006 |
| Venus1-2Body-VenusMJ2000Ec | 2.213821571e-006 | 3.107874846e-006 | 2.148337952e-006 |

Table 3.18: GMAT/STK Coordinate System Dependent Parameter Differences (Specific Angular Momentum)

| Test Case | X-(H) ($m^2/sec$) | Y-(H) ($m^2/sec$) | Z-(H) ($m^2/sec$) |
|---|---|---|---|
| GEO-2Body-EarthFixed | 10.77395299 | 2.103745961 | 434.3113329 |
| GEO-2Body-EarthMJ2000Ec | 1.13710075e-005 | 2.306616807 | 1.000254997 |
| GEO-2Body-EarthMJ2000Eq | 0 | 0 | 0.001542503014 |
| GEO-2Body-EarthMODEc | 1.670208945 | 0.001840817276 | 0.001789885573 |
| GEO-2Body-EarthMODEq | 1.670203311 | 0.001656591829 | 0.002357410267 |
| GEO-2Body-EarthMOEEc | 2.159488468e-005 | 0.0008076312952 | 0.001688022166 |
| GEO-2Body-EarthMOEEq | 1.279825357e-005 | 2.844632424e-021 | 0.001542503014 |
| GEO-2Body-EarthTODEc | 8.5322038 | 1.939137292 | 0.8412171155 |
| GEO-2Body-EarthTODEq | 8.532204845 | 9.575566487 | 0.004365574569 |
| GEO-2Body-EarthTOEEc | 7.285380082 | 0.001295120455 | 0.001702574082 |
| GEO-2Body-EarthTOEEq | 7.285369859 | 1.252006488 | 0.001396983862 |
| Hyperbolic-2Body-EarthFixed | 12999.11505 | 5061.392323 | 11584.82954 |
| Hyperbolic-2Body-EarthMJ2000Ec | 0.0002509729892 | 1.80931238 | 0.7227790775 |
| Hyperbolic-2Body-EarthMJ2000Eq | 0.000197488248 | 0.01781154424 | 0.01760781743 |
| Hyperbolic-2Body-EarthMODEc | 1.183702615 | 0.007530616131 | 0.02339947969 |
| Hyperbolic-2Body-EarthMODEq | 1.183709749 | 0.01674925443 | 0.01817534212 |
| Hyperbolic-2Body-EarthMOEEc | 0.00026047443 | 0.008927599993 | 0.0233121682 |
| Hyperbolic-2Body-EarthMOEEq | 0.000217340812 | 0.01784064807 | 0.01766602509 |
| Hyperbolic-2Body-EarthTODEc | 2.066649429 | 1.515742042 | 0.6022310117 |
| Hyperbolic-2Body-EarthTODEq | 2.066692929 | 5.087713362 | 5.08732046 |
| Hyperbolic-2Body-EarthTOEEc | 5.182947816 | 0.00926957 | 0.02366141416 |
| Hyperbolic-2Body-EarthTOEEq | 5.182958375 | 0.6900227163 | 0.6991467671 |
| ISS-2Body-EarthFixed | 89.91428695 | 67.10288835 | 31.77834151 |
| ISS-2Body-EarthGSE | 0.2475171641 | 0.0290456228 | 0.0004511093721 |
| ISS-2Body-EarthGSM | 3.261639904 | 22.63645729 | 29.37958561 |
| ISS-2Body-EarthMJ2000Ec | 0.0007530616131 | 0.7919024938 | 0.2579763532 |
| ISS-2Body-EarthMJ2000Eq | 0.0007603375707 | 0.0005566107575 | 0.000301952241 |
| ISS-2Body-EarthMODEc | 0.4284956958 | 0.9411305655 | 0.001266016625 |
| ISS-2Body-EarthMODEq | 0.4284956958 | 0.8629867807 | 0.3752284101 |
| ISS-2Body-EarthMOEEc | 0.0007530616131 | 0.0002983142622 | 0.0004874891602 |
| ISS-2Body-EarthMOEEq | 0.0007603375707 | 0.0005566107575 | 0.000301952241 |
| ISS-2Body-EarthTODEc | 0.7472881407 | 2.260314432 | 0.2173910616 |
| ISS-2Body-EarthTODEq | 0.7472772268 | 3.630950232 | 2.533914085 |
| ISS-2Body-EarthTOEEc | 1.879539923 | 4.109922884 | 0.0004874891602 |
| ISS-2Body-EarthTOEEq | 1.879554475 | 4.081139195 | 1.909433195 |
| Mars1-2Body-MarsFixed | 23.98886318 | 22.21717 | 10.38143819 |
| Mars1-2Body-MarsMJ2000Ec | 0.9952709661 | 0.5993915693 | 0.5886722647 |
| Mars1-2Body-MarsMJ2000Eq | 0.9952691471 | 0.2261380806 | 0.7740909496 |
| Mercury1-2Body-MercuryFixed | 0.327698217 | 0.4808271115 | 0.2502738425 |
| Mercury1-2Body-MercuryMJ2000Ec | 0.1878624971 | 0.2510159902 | 0.2059750841 |
| Mercury1-2Body-MercuryMJ2000Eq | 0.1878634066 | 0.1111429479 | 0.2888264135 |
| Moon-2Body-MoonFixed | 5.71125554 | 5.283694918 | 0.1482353582 |
| Moon-2Body-MoonMJ2000Ec | 0.001037733455 | 0.04335993253 | 0.01902935765 |
| Moon-2Body-MoonMJ2000Eq | 0.001038642949 | 0.0002576208312 | 0.0003556124284 |
| Neptune1-2Body-NeptuneFixed | 42849.13634 | 43033.72977 | 96195.52572 |
| Neptune1-2Body-NeptuneMJ2000Ec | 29.59038829 | 77.10719365 | 79.3626532 |
| Neptune1-2Body-NeptuneMJ2000Eq | 29.59038829 | 84.00197472 | 57.43693328 |
| Pluto1-2Body-PlutoFixed | 12.66916559 | 15.03451797 | 18.39295624 |
| Pluto1-2Body-PlutoMJ2000Ec | 2.923446004 | 0.8473472235 | 3.204913128 |
| Pluto1-2Body-PlutoMJ2000Eq | 2.923445891 | 0.8302175236 | 3.147571306 |
| Saturn1-2Body-SaturnFixed | 7341.511315 | 7984.995318 | 864.7177019 |
| Saturn1-2Body-SaturnMJ2000Ec | 13.2243149 | 25.11031926 | 27.86074765 |
| Saturn1-2Body-SaturnMJ2000Eq | 13.22408207 | 16.91115992 | 24.03883263 |
| Uranus1-2Body-UranusFixed | 2955.545322 | 3574.169823 | 2353.711105 |
| Uranus1-2Body-UranusMJ2000Ec | 5.186127964 | 39.40385068 | 90.66710481 |
| Uranus1-2Body-UranusMJ2000Eq | 5.186419003 | 61.77691968 | 77.83877663 |
| Venus1-2Body-VenusFixed | 0.7762544101 | 0.3817622201 | 0.2173546818 |
| Venus1-2Body-VenusMJ2000Ec | 0.2975648385 | 0.6312984624 | 0.4800604074 |

Table 3.19: GMAT/STK Coordinate System Dependent Parameter Differences (Velocity Vector-based)

| Test Case | Mag-Vel (m/s) | Right Asc. of Vel. (deg) | Dec. of Vel. (deg) |
|---|---|---|---|
| GEO-2Body-EarthFixed | 3.278583187e-006 | 1.162789617 | 0.178531639 |
| GEO-2Body-EarthMJ2000Ec | 1.07913678e-010 | 2.742908123e-010 | 1.110862513e-009 |
| GEO-2Body-EarthMJ2000Eq | 1.07913678e-010 | 3.426237072e-011 | 0 |
| GEO-2Body-EarthMODEc | 1.070254996e-010 | 1.887912049e-009 | 1.108624303e-011 |
| GEO-2Body-EarthMODEq | 1.070254996e-010 | 1.733170052e-009 | 7.381565394e-010 |
| GEO-2Body-EarthMOEEc | 1.07913678e-010 | 3.628031209e-011 | 1.261213356e-011 |
| GEO-2Body-EarthMOEEq | 1.07913678e-010 | 3.427658157e-011 | 5.656303434e-015 |
| GEO-2Body-EarthTODEc | 1.070254996e-010 | 9.472358897e-009 | 9.347012053e-010 |
| GEO-2Body-EarthTODEq | 1.070254996e-010 | 8.702897958e-009 | 4.850753133e-009 |
| GEO-2Body-EarthTOEEc | 1.07913678e-010 | 8.130868423e-009 | 1.261213356e-011 |
| GEO-2Body-EarthTOEEq | 1.07913678e-010 | 7.460869256e-009 | 3.266776493e-009 |
| Hyperbolic-2Body-EarthFixed | 4.71472088e-005 | 2.061432909e-007 | 5.501368605e-008 |
| Hyperbolic-2Body-EarthMJ2000Ec | 1.616484724e-010 | 2.155502443e-010 | 7.097700205e-010 |
| Hyperbolic-2Body-EarthMJ2000Eq | 1.616484724e-010 | 1.421085472e-012 | 9.201528428e-013 |
| Hyperbolic-2Body-EarthMODEc | 1.616484724e-010 | 1.854090215e-009 | 1.578293052e-012 |
| Hyperbolic-2Body-EarthMODEq | 1.616484724e-010 | 1.910734682e-009 | 7.375620115e-010 |
| Hyperbolic-2Body-EarthMOEEc | 1.616484724e-010 | 1.591615728e-012 | 2.415845302e-013 |
| Hyperbolic-2Body-EarthMOEEq | 1.616484724e-010 | 1.449507181e-012 | 9.166001291e-013 |
| Hyperbolic-2Body-EarthTODEc | 1.616484724e-010 | 3.401112281e-009 | 5.87760951e-010 |
| Hyperbolic-2Body-EarthTODEq | 1.616484724e-010 | 5.039368034e-009 | 1.719470788e-009 |
| Hyperbolic-2Body-EarthTOEEc | 1.616484724e-010 | 8.096151305e-009 | 2.415845302e-013 |
| Hyperbolic-2Body-EarthTOEEq | 1.616484724e-010 | 8.594184919e-009 | 3.265999027e-009 |
| ISS-2Body-EarthFixed | 1.000267424e-006 | 1.289334008e-007 | 3.871187459e-008 |
| ISS-2Body-EarthGSE | 4.574118861e-010 | 5.30000932e-010 | 6.073808123e-011 |
| ISS-2Body-EarthGSM | 3.125233405e-008 | 2.998996962e-008 | 3.987214825e-008 |
| ISS-2Body-EarthMJ2000Ec | 4.636291351e-010 | 8.293685738e-010 | 1.106641889e-009 |
| ISS-2Body-EarthMJ2000Eq | 4.636291351e-010 | 1.526245796e-010 | 7.80993048e-011 |
| ISS-2Body-EarthMODEc | 4.52970994e-010 | 1.852903608e-009 | 6.026290578e-011 |
| ISS-2Body-EarthMODEq | 4.627409567e-010 | 2.479552563e-009 | 7.349498787e-010 |
| ISS-2Body-EarthMOEEc | 4.636291351e-010 | 1.305977548e-010 | 6.103206829e-011 |
| ISS-2Body-EarthMOEEq | 4.627409567e-010 | 1.526245796e-010 | 7.80993048e-011 |
| ISS-2Body-EarthTODEc | 4.627409567e-010 | 3.180247177e-009 | 9.443787974e-010 |
| ISS-2Body-EarthTODEq | 4.627409567e-010 | 4.238856377e-009 | 4.168732914e-009 |
| ISS-2Body-EarthTOEEc | 4.627409567e-010 | 8.094446002e-009 | 6.103206829e-011 |
| ISS-2Body-EarthTOEEq | 4.627409567e-010 | 1.066266009e-008 | 3.259224002e-009 |
| Mars1-2Body-MarsFixed | 9.592806993e-006 | 9.947378707e-007 | 3.948958787e-007 |
| Mars1-2Body-MarsMJ2000Ec | 8.899687209e-006 | 1.432667602e-006 | 6.136789708e-007 |
| Mars1-2Body-MarsMJ2000Eq | 8.899676995e-006 | 1.215923845e-006 | 6.201466789e-007 |
| Mercury1-2Body-MercuryFixed | 1.59941127e-006 | 3.112265077e-007 | 1.274611101e-007 |
| Mercury1-2Body-MercuryMJ2000Ec | 1.597606047e-006 | 3.378602003e-007 | 1.397476694e-007 |
| Mercury1-2Body-MercuryMJ2000Eq | 1.597606047e-006 | 2.85895851e-007 | 1.4250252e-007 |
| Moon-2Body-MoonFixed | 3.394075021e-006 | 1.115449194e-006 | 5.325181203e-007 |
| Moon-2Body-MoonMJ2000Ec | 3.384815983e-006 | 1.24027315e-006 | 5.264534106e-007 |
| Moon-2Body-MoonMJ2000Eq | 3.384815983e-006 | 1.048296383e-006 | 5.364797317e-007 |
| Neptune1-2Body-NeptuneFixed | 0.001546170623 | 1.309179918e-005 | 1.351642366e-005 |
| Neptune1-2Body-NeptuneMJ2000Ec | 3.205422061e-005 | 1.140866715e-006 | 4.847768089e-007 |
| Neptune1-2Body-NeptuneMJ2000Eq | 3.205422949e-005 | 9.779481331e-007 | 4.998895804e-007 |
| Pluto1-2Body-PlutoFixed | 8.217843617e-005 | 4.784315172e-005 | 2.956015004e-005 |
| Pluto1-2Body-PlutoMJ2000Ec | 8.345292613e-005 | 5.652545477e-005 | 2.377500014e-005 |
| Pluto1-2Body-PlutoMJ2000Eq | 8.345292613e-005 | 4.844967677e-005 | 2.512714485e-005 |
| Saturn1-2Body-SaturnFixed | 8.716019906e-006 | 4.920609911e-007 | 9.227543885e-008 |
| Saturn1-2Body-SaturnMJ2000Ec | 5.18404164e-006 | 1.242314625e-007 | 5.306250017e-008 |
| Saturn1-2Body-SaturnMJ2000Eq | 5.18404164e-006 | 1.061025898e-007 | 5.502680978e-008 |
| Uranus1-2Body-UranusFixed | 3.448082886e-005 | 7.157807744e-006 | 7.584381549e-007 |
| Uranus1-2Body-UranusMJ2000Ec | 2.627271023e-005 | 1.159199428e-006 | 5.016063795e-007 |
| Uranus1-2Body-UranusMJ2000Eq | 2.627271023e-005 | 9.843604971e-007 | 5.082584709e-007 |
| Venus1-2Body-VenusFixed | 5.125109226e-007 | 3.693500616e-008 | 1.783747905e-008 |
| Venus1-2Body-VenusMJ2000Ec | 5.126095104e-007 | 3.734896836e-008 | 1.708282227e-008 |

Table 3.20: GMAT/STK Coordinate System Dependent Parameter Differences (Angle-based)

| Test Case | Arg. of Per. (deg) | Decl. (deg) | Inc. (deg) | RA (deg) | RAAN (deg) |
|---|---|---|---|---|---|
| GEO-2Body-EarthFixed | 3.357e-005 | 2.768e-008 | 0.2044 | 3.148e-007 | 9.529e-005 |
| GEO-2Body-EarthMJ2000Ec | 1.349e-005 | 1.111e-009 | 1.111e-009 | 2.715e-010 | 0 |
| GEO-2Body-EarthMJ2000Eq | 1.309e-005 | 0 | 1e-014 | 3.513e-011 | 0 |
| GEO-2Body-EarthMODEc | 1.381e-005 | 1.148e-011 | 3.233e-013 | 1.886e-009 | 1.864e-009 |
| GEO-2Body-EarthMODEq | 1.334e-005 | 7.381e-010 | 7.548e-010 | 1.734e-009 | 8.657e-010 |
| GEO-2Body-EarthMOEEc | 1.349e-005 | 1.291e-011 | 3.126e-013 | 3.401e-011 | 0 |
| GEO-2Body-EarthMOEEq | 1.343e-005 | 5.656e-015 | 0 | 3.513e-011 | 0 |
| GEO-2Body-EarthTODEc | 1.356e-005 | 9.281e-010 | 9.348e-010 | 9.5e-009 | 9.482e-009 |
| GEO-2Body-EarthTODEq | 1.095e-005 | 4.652e-009 | 3.537e-009 | 8.705e-009 | 1.046e-005 |
| GEO-2Body-EarthTOEEc | 1.36e-005 | 1.291e-011 | 3.233e-013 | 8.129e-009 | 8.107e-009 |
| GEO-2Body-EarthTOEEq | 8.314e-005 | 3.267e-009 | 1.764e-009 | 7.462e-009 | 6.978e-005 |
| Hyperbolic-2Body-EarthFixed | 3.504e-007 | 1.754e-008 | 2.357e-007 | 1.35e-007 | 1.528e-007 |
| Hyperbolic-2Body-EarthMJ2000Ec | 7.617e-012 | 1.096e-009 | 1.111e-009 | 2.172e-010 | 1.4e-013 |
| Hyperbolic-2Body-EarthMJ2000Eq | 7.844e-012 | 8.207e-013 | 4.334e-013 | 1.251e-012 | 2.5e-013 |
| Hyperbolic-2Body-EarthMODEc | 1.18e-011 | 1.561e-012 | 3.411e-013 | 1.854e-009 | 1.858e-009 |
| Hyperbolic-2Body-EarthMODEq | 1.052e-009 | 7.379e-010 | 5.898e-013 | 2.405e-009 | 9.757e-010 |
| Hyperbolic-2Body-EarthMOEEc | 7.518e-012 | 2.984e-013 | 3.411e-013 | 1.393e-012 | 1.4e-013 |
| Hyperbolic-2Body-EarthMOEEq | 7.674e-012 | 8.313e-013 | 1.421e-013 | 1.251e-012 | 0 |
| Hyperbolic-2Body-EarthTODEc | 9.422e-012 | 9.216e-010 | 9.348e-010 | 3.396e-009 | 3.235e-009 |
| Hyperbolic-2Body-EarthTODEq | 1.824e-009 | 3.924e-009 | 4.129e-009 | 4.887e-009 | 1.696e-009 |
| Hyperbolic-2Body-EarthTOEEc | 7.702e-012 | 2.984e-013 | 3.375e-013 | 8.096e-009 | 8.107e-009 |
| Hyperbolic-2Body-EarthTOEEq | 4.561e-009 | 3.265e-009 | 5.531e-010 | 1.062e-008 | 4.29e-009 |
| ISS-2Body-EarthFixed | 3.206e-008 | 3.275e-008 | 3.965e-008 | 1.328e-007 | 1.38e-007 |
| ISS-2Body-EarthGSE | 7.614e-010 | 6.504e-011 | 5.684e-013 | 5.681e-010 | 4.463e-010 |
| ISS-2Body-EarthGSM | 2.427e-006 | 3.92e-008 | 4.043e-008 | 2.862e-008 | 7.132e-009 |
| ISS-2Body-EarthMJ2000Ec | 2.188e-009 | 1.109e-009 | 4.623e-010 | 8.22e-010 | 1.29e-009 |
| ISS-2Body-EarthMJ2000Eq | 5.556e-010 | 7.966e-011 | 5.471e-013 | 1.525e-010 | 5.4e-013 |
| ISS-2Body-EarthMODEc | 5.451e-010 | 6.455e-011 | 1.592e-012 | 1.853e-009 | 1.852e-009 |
| ISS-2Body-EarthMODEq | 1.206e-009 | 7.378e-010 | 5.283e-010 | 2.49e-009 | 1.291e-009 |
| ISS-2Body-EarthMOEEc | 5.49e-010 | 6.525e-011 | 4.121e-013 | 1.269e-010 | 7.105e-013 |
| ISS-2Body-EarthMOEEq | 5.525e-010 | 7.966e-011 | 5.471e-013 | 1.525e-010 | 5.542e-013 |
| ISS-2Body-EarthTODEc | 1.664e-009 | 9.461e-010 | 3.891e-010 | 3.178e-009 | 4.239e-009 |
| ISS-2Body-EarthTODEq | 3.32e-009 | 4.163e-009 | 3.569e-009 | 4.248e-009 | 4.395e-009 |
| ISS-2Body-EarthTOEEc | 5.487e-010 | 6.526e-011 | 4.05e-013 | 8.095e-009 | 8.095e-009 |
| ISS-2Body-EarthTOEEq | 2.92e-009 | 3.264e-009 | 2.689e-009 | 1.063e-008 | 5.96e-009 |
| Mars1-2Body-MarsFixed | 2.247e-006 | 5.221e-007 | 5.014e-008 | 9.731e-007 | 2.604e-007 |
| Mars1-2Body-MarsMJ2000Ec | 4.431e-008 | 8.568e-007 | 2.152e-009 | 1.285e-006 | 1.562e-009 |
| Mars1-2Body-MarsMJ2000Eq | 4.543e-008 | 7.205e-007 | 2.049e-009 | 1.377e-006 | 1.332e-009 |
| Mercury1-2Body-MercuryFixed | 7.263e-009 | 1.881e-007 | 1.462e-009 | 2.697e-007 | 5.066e-009 |
| Mercury1-2Body-MercuryMJ2000Ec | 8.609e-009 | 1.99e-007 | 1.004e-009 | 3.065e-007 | 2.237e-009 |
| Mercury1-2Body-MercuryMJ2000Eq | 7.477e-009 | 1.735e-007 | 1.664e-009 | 3.307e-007 | 1.026e-009 |
| Moon-2Body-MoonFixed | 2.966e-008 | 7.424e-007 | 2.672e-009 | 1.064e-006 | 1.418e-007 |
| Moon-2Body-MoonMJ2000Ec | 4.765e-009 | 7.387e-007 | 4.114e-010 | 1.173e-006 | 8.903e-010 |
| Moon-2Body-MoonMJ2000Eq | 6.126e-009 | 6.356e-007 | 1.155e-011 | 1.246e-006 | 6.068e-012 |
| Neptune1-2Body-NeptuneFixed | 4.002e-005 | 5.911e-007 | 1.341e-005 | 1.157e-006 | 7.627e-006 |
| Neptune1-2Body-NeptuneMJ2000Ec | 2.001e-008 | 6.812e-007 | 1.011e-008 | 1.058e-006 | 1.042e-008 |
| Neptune1-2Body-NeptuneMJ2000Eq | 2.142e-008 | 6.033e-007 | 6.69e-009 | 1.147e-006 | 1.42e-008 |
| Pluto1-2Body-PlutoFixed | 5.512e-006 | 3.201e-005 | 7.484e-007 | 7.441e-005 | 8.117e-007 |
| Pluto1-2Body-PlutoMJ2000Ec | 5.338e-007 | 3.39e-005 | 4.962e-008 | 5.105e-005 | 3.472e-008 |
| Pluto1-2Body-PlutoMJ2000Eq | 5.077e-007 | 2.963e-005 | 3.899e-008 | 5.878e-005 | 5.172e-008 |
| Saturn1-2Body-SaturnFixed | 1.508e-007 | 5.809e-008 | 5.751e-008 | 5.188e-007 | 4.571e-007 |
| Saturn1-2Body-SaturnMJ2000Ec | 3.259e-009 | 7.328e-008 | 6.576e-010 | 1.179e-007 | 9.333e-010 |
| Saturn1-2Body-SaturnMJ2000Eq | 4.55e-009 | 6.548e-008 | 5.383e-010 | 1.273e-007 | 8.028e-010 |
| Uranus1-2Body-UranusFixed | 4.529e-006 | 8.4e-007 | 3.03e-007 | 2.345e-006 | 4.615e-007 |
| Uranus1-2Body-UranusMJ2000Ec | 1.129e-008 | 6.9e-007 | 8.766e-009 | 1.112e-006 | 5.248e-009 |
| Uranus1-2Body-UranusMJ2000Eq | 1.392e-008 | 6.011e-007 | 6.433e-009 | 1.201e-006 | 1e-008 |
| Venus1-2Body-VenusFixed | 1.012e-009 | 2.227e-008 | 1.379e-010 | 3.825e-008 | 1.158e-009 |
| Venus1-2Body-VenusMJ2000Ec | 2.027e-009 | 2.162e-008 | 4.209e-010 | 3.816e-008 | 8.709e-010 |

Table 3.21: FF/GMAT Coordinate System Dependent Parameter Differences (Position)

| Test Case | X-Pos (m) | Y-Pos (m) | Z-Pos (m) |
|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 2.54757424e-005 | 2.516884479e-005 | 2.321598913e-005 |

Table 3.22: FF/GMAT Coordinate System Dependent Parameter Differences (Velocity)

| Test Case | X-Vel (m/s) | Y-Vel (m/s) | Z-Vel (m/s) |
|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 4.993130354e-007 | 5.00476105e-007 | 4.961786537e-007 |

Table 3.23: FF/GMAT Coordinate System Dependent Parameter Differences (Specific Angular Momentum)

| Test Case | X-(H) ($m^2/sec$) | Y-(H) ($m^2/sec$) | Z-(H) ($m^2/sec$) |
|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 0.0005493347999 | 0.001349690137 | 0.001567968866 |

Table 3.24: FF/GMAT Coordinate System Dependent Parameter Differences (Velocity Vector-based)

| Test Case | Mag-Vel (m/s) | Right Asc. of Vel. (deg) | Dec. of Vel. (deg) |
|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 4.860067904e-007 | 296.2928006 | 67.36750845 |

Table 3.25: FF/GMAT Coordinate System Dependent Parameter Differences (Angle-based)

| Test Case | Arg. of Per. (deg) | Decl. (deg) | Inc. (deg) | RA (deg) | RAAN (deg) |
|---|---|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 1.681e-009 | 5.884e-010 | 4.684e-010 | 7.628e-010 | 2.418e-010 |

Table 3.26: FF/STK Coordinate System Dependent Parameter Differences (Position)

| Test Case | X-Pos (m) | Y-Pos (m) | Z-Pos (m) |
|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 3.580873909e-005 | 3.470836418e-005 | 3.243098945e-005 |

Table 3.27: FF/STK Coordinate System Dependent Parameter Differences (Velocity)

| Test Case | X-Vel (m/s) | Y-Vel (m/s) | Z-Vel (m/s) |
|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 5.092002375e-007 | 5.105600387e-007 | 5.025699856e-007 |

Table 3.28: FF/STK Coordinate System Dependent Parameter Differences (Specific Angular Momentum)

| Test Case | X-(H) ($m^2/sec$) | Y-(H) ($m^2/sec$) | Z-(H) ($m^2/sec$) |
|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 0.0005711626727 | 0.001346052159 | 0.00146246748 |

Table 3.29: FF/STK Coordinate System Dependent Parameter Differences (Velocity Vector-based)

| Test Case | Mag-Vel (m/s) | Right Asc. of Vel. (deg) | Dec. of Vel. (deg) |
|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 4.857803049e-007 | 296.2928006 | 67.36750845 |

Table 3.30: FF/STK Coordinate System Dependent Parameter Differences (Angle-based)

| Test Case | Arg. of Per. (deg) | Decl. (deg) | Inc. (deg) | RA (deg) | RAAN (deg) |
|---|---|---|---|---|---|
| ISS-2Body-EarthMJ2000Eq | 1.343e-009 | 6.518e-010 | 4.685e-010 | 8.637e-010 | 2.414e-010 |

Draft: Work in Progress

# Chapter 4

# Integrators

GMAT's integrators were tested on a system level in order to verify that all the integrators were working correctly. In order to minimize the effects of other forces/elements, the two-body cases from the Propagators section were used, with some modification, for testing the integrators. The report output interval and integrators were the only parameter changed when using the Propagator two body test cases. Data was outputted in ten minute intervals.

## 4.1 Initial Orbit Conditions

The ISS and GEO two-body case's initial orbit parameters were used from the Propagation section (Chapter 2) for the test cases in this section.

Refer to Appendix B.1 Tables B.1- B.13 for a listing of all Propagation initial orbit states used for the Integrator test cases.

## 4.2 Naming Convention

This section describes the naming convention for integrator scripts and output reports. The naming convention consists of an ordered series of option strings, separated by underscores (_ ). Currently, options are allowed for the following fields, and will be present in the file name in order:

1. *tool* - The tool used to generate the test case
2. *traj* - The trajectory to use. This includes initial conditions, physical parameters, and time step
3. *integ* - The integrator to use

The word Integrator precedes the *tool* field and 2Body follows the *integ* field. The final integrator file format is as followed:
Integrator_*tool*_*traj*_*integ*_2Body.report

The *tool* field should always be the first option field. Future additional fields should be added to the end of the list of fields. Each field has a finite list of options, as follows (future options should be added to this list):

1. *tool*
   - STK - Satellite Toolkit HPOP or Astrogator
   - FF - FreeFlyer
   - GMAT - General Mission Analysis Tool

2. *traj*
   - ISS - leo orbit
   - GEO - geo orbit

   NOTE: Some test cases contain *traj* variations. In this case *traj* precedes the modification. For example, if an ISS trajectory is needed with a different Cd, *traj* could be ISSdiffCd1.

3. *integ*
   - RKV89 - RungaKutta 8(9)
   - RKN68 - DormandElMikkawyPrince 6(8)
   - RKF56 - RungeKuttaFehlberg 5(6)
   - PD45 - PrinceDormand 4(5)
   - PD78 - PrinceDormand 7(8)
   - BS - BulirschStoer
   - ABM - AdamsBashforthMoulton

## 4.3 Comparison Script Information

Comparison_Integ.m is the script used to perform the integrator comparisons needed for the Integrators section of the Acceptance Test Plan. This script was designed to allow the user to select a GMAT Build or the exact analytic solution to compare to one another.

Refer to Appendix C for more details about this script and others used in the Acceptance Test Plan document.

## 4.4 Test Case Results

The following results are for the Integrator section. The GMAT Integrator results are being compared to an exact analytical two-body solution. We'd like the comparison data to be as close to zero as possible. A detailed acceptance metric/matrix will be developed at a later date.

Table 4.1: Exact/GMAT GEO Integrator Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| ABM-2Body | 0.0001127712184 | 8.178707643e-009 |
| BS-2Body | 6.290317204e-005 | 4.535189696e-009 |
| PD45-2Body | 3.297921562e-005 | 2.320908148e-009 |
| PD78-2Body | 1.822370346e-005 | 1.253046654e-009 |
| RKF56-2Body | 3.459697578e-005 | 2.564071918e-009 |
| RKN68-2Body | 1.793126562e-005 | 1.297793489e-009 |
| RKV89-2Body | 0.0001127712184 | 8.178707643e-009 |

Table 4.2: Exact/GMAT ISS Integrator Test Case Comparison

| Test Case | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| ABM-2Body | 1.052211123e-005 | 1.172665432e-008 |
| BS-2Body | 1.691079091e-005 | 1.926879767e-008 |
| PD45-2Body | 3.080434654e-005 | 3.521816658e-008 |
| PD78-2Body | 2.772621462e-005 | 3.15224572e-008 |
| RKF56-2Body | 3.336029534e-005 | 3.80119779e-008 |
| RKN68-2Body | 3.617025125e-006 | 3.875411333e-009 |
| RKV89-2Body | 1.052211123e-005 | 1.172665432e-008 |

# Chapter 5

# Stopping Conditions

GMAT's Stopping Conditions were tested on a system level in order to determine if it stops correctly on user selected conditions. Refer to Table 5.1 for a list of the stopping conditions tested and the units used for the output of data.

Table 5.1: Stopping Conditions

| Stopping Condition | Stopping Value | Unit Used |
|---|---|---|
| Epoch (A1 Modified Julian Date) | 23158.042037434974 | Days |
| Apoapsis | 180 | TA in degrees |
| Elapsed Days | 6 Hours | Days |
| Elapsed Days (Multiple Satellites) | 5 Hours | Days |
| Mean Anomaly | 45, 90, & 180 | MA in degrees |
| Periapsis | 0 | TA in degrees |
| Elapsed Seconds | 3600 | Seconds |
| True Anomaly | 45, 90, & 180 | TA in degrees |
| XY Plane Intersection | Z=0 | Km |
| XZ Plane Intersection | Y=0 | Km |
| YZ Plane Intersection | X=0 | Km |

## 5.1 Initial Orbit Conditions

For a listing of the initial conditions used to produce the data for the Stopping Conditions Section, refer to Table 5.2 for the Earth based non-hyperbolic point mass test cases, Table 5.3 for the Earth based non-hyperbolic all forces test cases, and Table 5.4 for the Earth based hyperbolic point mass test cases.

Table 5.2: Initial Orbit Parameters (EarthPM & EarthMJ2000EqPM)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System (CS) | Earth Mean J2000 Equator |
| X | -8043.9600382977915 (km) |
| Y | -1564.9950345568864 (km) |
| Z | 3750.9601677510364 (km) |
| VX | 0.99861303787927636 (km) |
| VY | -6.8834168529193462 (km) |
| VZ | -0.46566090709653452 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag Area | 15 ($m^2$) |
| Drag Model | None |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. StepSize | 60 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 2700 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | Only initial state |
| Report CS/Cb | Same as initial state CS |

Table 5.3: Initial Orbit Parameters (EarthAll & EarthMJ2000EqAll)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System (CS) | Earth Mean J2000 Equator |
| X | -8043.9600382977915 (km) |
| Y | -1564.9950345568864 (km) |
| Z | 3750.9601677510364 (km) |
| VX | 0.99861303787927636 (km) |
| VY | -6.8834168529193462 (km) |
| VZ | -0.46566090709653452 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag Area | 15 ($m^2$) |
| Drag Model | Jacchia Roberts |
| Drag F107/F107A | 150/150 |
| Drag Kp | 3 |
| NSG Model | JGM2 |
| Degree x Order | 4x4 |
| SRP Area | 1 ($m^2$) |
| SRP | On |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. StepSize | 60 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 2700 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | Only initial state |
| Report CS/Cb | Same as initial state CS |

Table 5.4: Initial Orbit Parameters (EarthPMhyper & EarthMJ2000EqPMhyper)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System (CS) | Earth Mean J2000 Equator |
| X | 12371.791482634855 (km) |
| Y | 5050.7627227610719 (km) |
| Z | 5050.762722761071 (km) |
| VX | -7.9859921512608487 (km) |
| VY | 2.44520073255755 (km) |
| VZ | 2.4452007325575495 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag Area | 15 ($m^2$) |
| Drag Model | None |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. StepSize | 60 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 2700 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | Only initial state |
| Report CS/Cb | Same as initial state CS |

Table 5.5: Initial Orbit Parameters (MoonPM)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System (CS) | Earth Mean J2000 Equator |
| X | -1486.792117191545200 (km) |
| Y | 0.0 (km) |
| Z | 1486.792117191543000 (km) |
| VX | -0.142927729144255 (km) |
| VY | -1.631407624437537 (km) |
| VZ | 0.142927729144255 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag Area | 15 ($m^2$) |
| Drag Model | None |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. StepSize | 60 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 2700 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | Only initial state |
| Report CS/Cb | Same as initial state CS |

Table 5.6: Initial Orbit Parameters (MarsPM)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System (CS) | Earth Mean J2000 Equator |
| X | -2737.481646173082000 (km) |
| Y | 0.0 (km) |
| Z | 2737.481646173082000 (km) |
| VX | -0.311321695052649 (km) |
| VY | -3.553492313930950 (km) |
| VZ | 0.311321695052650 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag Area | 15 ($m^2$) |
| Drag Model | None |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. StepSize | 60 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 2700 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | Only initial state |
| Report CS/Cb | Same as initial state CS |

## 5.2 Naming Convention

This section describes the naming convention for stopping condition scripts and output reports generated for use in GMAT's Acceptance Test Plan. The naming convention consists of an ordered series of option strings, separated by underscores (_ ). Currently, options are allowed for the following fields, and will be present in the file name in order:

1. *tool* - The tool used to generate the test cases.
2. *Cb* - The Central Body used for the stopping condition, including the force model setup.
3. *stopCond* - The stopping condition used for the test case.

The word StopCond precedes the *tool* field. The final stopping condition file format is as followed:
StopCond_*tool*_*Cb*_*stopCond*.report

The *tool* field should always be the first option field. Future additional fields should be added to the end of the list of fields. Each field has a finite list of options, as follows (future options should be added to this list):

| | | |
|---|---|---|
| 1. *tool* | STK | - Satellite Toolkit HPOP or Astrogator |
| | FF | - FreeFlyer |
| | GMAT | - General Mission Analysis Tool |

| | | |
|---|---|---|
| 2. *Cb* | EarthPM | - Earth central body with point mass force model |
| | EarthMJ2000EqPM | - Same as EarthPM and plane intersection calculations based on EarthMJ2000Eq |
| | EarthAll | - Earth central body with all force model types turned on |
| | EarthMJ2000EqAll | - Same as EarthAll and plane intersection calculations based on EarthMJ2000Eq |
| | Earth#MultiSatsPM | - Same as EarthPM and the test case involves # satellites |
| | MarsPM | - Mars central body with point mass force model |
| | MoonPM | - Moon central body with point mass force model |

| | | |
|---|---|---|
| 3. *stopCond* | A1ModJulian | - A1 Modified Julian Date |
| | Apoapsis | - Apoapsis of orbit based on TA |
| | Days | - Elapsed Days |
| | MA### | - ### degree Mean Anomaly |
| | Periapsis | - Periapsis of orbit based on TA |
| | Seconds | - Elapsed Seconds |
| | TA### | - ### degree True Anomaly |
| | XYplane | - XY Plane Intersection |
| | XZplane | - XZ Plane Intersection |
| | YZplane | - YZ Plane Intersection |

## 5.3 Comparison Script Information

Comparison_StopCond.m is the script used to perform the comparisons needed for the Stopping Condition chapter of the Acceptance Test Plan. This script was designed to allow the user to select a GMAT Build and/or the exact solution to compare to one another.

Refer to Appendix C for more details on this script and others used in the Acceptance Test Plan document.

## 5.4 Test Case Results

The following results are for the Stopping Condition section. The GMAT Stopping Condition results are being compared to the exact desired stopping condition. We'd like the comparison data to be as close to zero as possible. A detailed acceptance metric/matrix will be developed at a later date.

Refer to Table 5.1 to determine the units used in the Difference(s) column of the Stopping Condition comparison results.

Table 5.7: Exact/GMAT EarthPM StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| A1ModJulian | 3.637978807e-012 |
| Apoapsis | 1.207418308e-006 |
| Days | 3.637978807e-012 |
| EA180 | 1.334851106e-006 |
| EA45 | 1.122458571e-009 |
| EA90 | 5.233573575e-010 |
| MA180 | 1.468336194e-006 |
| MA90 | 5.793253877e-009 |
| Periapsis | 0 |
| Secs | 2.09548034e-007 |
| TA180 | 1.207418308e-006 |
| TA90 | 2.69331224e-009 |

Table 5.8: Exact/GMAT EarthAll StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| A1ModJulian | 7.275957614e-012 |
| Apoapsis | 0 |
| Days | 7.276013125e-012 |
| EA180 | 0 |
| EA45 | 1.370133873e-008 |
| EA90 | 1.320385934e-008 |
| MA180 | 0 |
| MA90 | 1.408977823e-008 |
| Periapsis | 0 |
| Secs | 4.190951586e-007 |
| TA180 | 0 |
| TA90 | 8.076597169e-010 |

Table 5.9: Exact/GMAT EarthPMhyper StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| A1ModJulian | 3.637978807e-012 |
| Days | 0 |
| HA45 | 5.94486238e-009 |
| HA90 | 6.062620628e-009 |
| MA45 | 4.032273182e-009 |
| MA90 | 7.014335779e-010 |
| Periapsis | 0 |
| Secs | 2.09548034e-007 |
| TA45 | 1.530786164e-008 |
| TA90 | 3.041570551e-008 |

Table 5.10: Exact/GMAT MoonPM StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| A1ModJulian | 3.637978807e-012 |
| Apoapsis | 1.207418308e-006 |
| Days | 3.637978807e-012 |
| EA180 | 0 |
| EA90 | 3.193633802e-009 |
| MA180 | 1.774535207e-006 |
| MA90 | 8.953790598e-009 |
| Periapsis | 0 |
| Secs | 2.09548034e-007 |
| TA180 | 1.207418308e-006 |
| TA90 | 9.594344874e-009 |

Table 5.11: Exact/GMAT MarsPM StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| A1ModJulian | 3.637978807e-012 |
| Apoapsis | 0 |
| Days | 0 |
| EA180 | 0 |
| EA90 | 2.220498629e-008 |
| MA180 | 0 |
| MA90 | 1.276124806e-008 |
| Periapsis | 0 |
| Secs | 2.09548034e-007 |
| TA180 | 0 |
| TA90 | 1.505739533e-008 |

Table 5.12: Exact/GMAT EarthMJ2000EqPM StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| XYplane | 1.967496619e-007 |
| XZplane | 1.187821727e-006 |
| YZplane | 4.2192789e-007 |

Table 5.13: Exact/GMAT EarthMJ2000EqAll StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| XYplane | 8.57494129e-008 |
| XZplane | 1.575498128e-006 |
| YZplane | 2.401038834e-008 |

Table 5.14: Exact/GMAT EarthMJ2000EqPMhyper StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| XYplane | 9.138221522e-007 |
| XZplane | 9.138204291e-007 |
| YZplane | 3.637831914e-006 |

Table 5.15: Exact/GMAT MoonMJ2000EqPM StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| XYplane | 1.752778189e-007 |
| XZplane | 0 |
| YZplane | 1.752923708e-007 |

Table 5.16: Exact/GMAT MarsMJ2000EqPM StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| XYplane | 2.384185791e-007 |
| XZplane | 0 |
| YZplane | 2.235174179e-007 |

Table 5.17: Exact/GMAT Earth3MultiSatsPM StopCond Test Case Comparison

| Stopping Condition | Difference(s) |
|---|---|
| Days | 7.276e-012 7.276e-012 7.276e-012 |

# Chapter 6

# Libration Points

The libration point tests are designed to verify the location of various libration points. In each software tool used the location of the libration point is defined by the tool and then converted to a MJ2000Eq representation for comparison purposes.

## 6.1 Initial Orbit Conditions

Table 6.1: Initial Orbit Parameters (Sun-Earth(SE) Libration Points)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System (CS) | Sun-Earth L#* MJ2000Eq |
| X | 0 (km) |
| Y | 0 (km) |
| Z | 0 (km) |
| VX | 0 (km) |
| VY | 0 (km) |
| VZ | 0 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag Area | 15 ($m^2$) |
| Drag Model | None |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | N/A |
| Integrator Init. StepSize | N/A |
| Integrator Accuracy | N/A |
| Integrator Max. StepSize | N/A |
| Report Precision | 16 significant figures |
| Report StepSize | Only initial state |
| Report CS/Cb | Earth MJ2000Eq |

NOTES: (*) All five libration points are defined in the test script.

Table 6.2: Initial Orbit Parameters (Sun-Earth-Moon(SEM) Libration Points)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System (CS) | Sun-Earth-Moon L#* MJ2000Eq |
| X | 0 (km) |
| Y | 0 (km) |
| Z | 0 (km) |
| VX | 0 (km) |
| VY | 0 (km) |
| VZ | 0 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag Area | 15 ($m^2$) |
| Drag Model | None |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | N/A |
| Integrator Init. StepSize | N/A |
| Integrator Accuracy | N/A |
| Integrator Max. StepSize | N/A |
| Report Precision | 16 significant figures |
| Report StepSize | Only initial state |
| Report CS/Cb | Earth MJ2000Eq |

NOTES: (*) All five libration points are defined in the test script.

## 6.2 Naming Convention

This section describes the naming convention for libration point scripts and output reports generated for use in GMAT's Acceptance Test Plan. The naming convention consists of an ordered series of option strings, separated by underscores (_ ). Currently, options are allowed for the following fields, and will be present in the file name in order:

1. *tool* - The tool used to generate the trajectory.
2. *libType* - The type of libration point used for the test case.
3. *libPoint* - The libration point used for the test case.

The word LibrationTest precedes the *tool* field. The final stopping condition file format is as followed: LibrationTest_*tool*_*libType*_*libPoint*.report

The *tool* field should always be the first option field. Future additional fields should be added to the end of the list of fields. Each field has a finite list of options, as follows (future options should be added to this list):

1. *tool*
   - STK - Satellite Toolkit HPOP or Astrogator
   - FF - FreeFlyer
   - GMAT - General Mission Analysis Tool
   - OD - Orbital Determination Toolbox
2. *libType*
   - SEML - Sun Earth Moon
   - SEL - Sun Earth
3. *libPoint*
   - # - The libration Point number

## 6.3 Comparison Script Information

Comparison_Tool1_Tool2_Libr.m is the script used to perform the comparisons needed for the Libration Points chapter of the Acceptance Test Plan. This script was designed to allow the user to select two tools from a list for comparison. The Tools available are presented in this chapter's Naming Convention section.

Refer to Appendix C for more details on this script and others used in the Acceptance Test Plan document.

## 6.4 Test Case Results

The following results are for the Libration Points section. The current GMAT Build is compared to STK for the Libration Points section. We'd like the comparison data to be as close to zero as possible. A detailed acceptance metric/matrix will be developed at a later date.

Table 6.3: GMAT/STK SEM LibrationTest Test Case Comparison

| Libration Point | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| 1 | 2.997694537e-006 | 1.082467449e-011 |
| 2 | 7.217749953e-006 | -2.896988205e-011 |
| 3 | 8.940696716e-005 | 1.548983164e-009 |
| 4 | -0.0006556510925 | 18.76805413 |
| 5 | 0.0005066394806 | -1.37023761 |

Table 6.4: GMAT/STK SE LibrationTest Test Case Comparison

| Libration Point | Position Difference(m) | Velocity Difference(m/s) |
|---|---|---|
| 1 | 2.997694537e-006 | 1.082467449e-011 |
| 2 | 7.217749953e-006 | -2.896988205e-011 |
| 3 | 8.940696716e-005 | 1.548983164e-009 |
| 4 | -0.0006556510925 | 18.76805413 |
| 5 | 0.0005066394806 | -1.37023761 |

# Chapter 7

# Delta V

Once an initial state was created for these Delta V test cases, a set amount of Delta V was applied. For the impulsive burn test cases delta V values of 0.1, 0.1, and 0.1 were applied in the X,Y, and Z axes respectively for either the Cartesian or VNB axes. Each test case generate a report that contains the Cartesian elements of the state before and after the impulsive burn.

## 7.1 Initial Orbit Conditions

Initial conditions for the impulsive burn delta V test cases are presented in Tables 7.1- 7.4.

Table 7.1: Initial Orbit Parameters (Earth Impulsive Burns)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Start & Stop Time | 01 Jan 2000 11:59:28.000 (UTCG) |
| Central Body | Earth |
| Coordinate System | Earth Mean J2000 Equator |
| X | 7378.0 (km) |
| Y | 0.0 (km) |
| Z | 0.0 (km) |
| VX | 0.0 (km) |
| VY | 5.1973811193846027 (km) |
| VZ | 5.1973811193846018 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag | 15 ($m^2$) |
| Drag Model | None |
| PMG Bodies | Only Central Body |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. | 60 (sec) |
| Integrator Max. StepSize | 2700 (sec) |
| Integrator Accuracy | 1e-13 |
| Report Precision | 16 significant figures |
| Report CS/Cb | Same as initial state CS |

Table 7.2: Initial Orbit Parameters (Mars Impulsive Burns)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Start & Stop Time | 01 Jan 2000 11:59:28.000 (UTCG) |
| Central Body | Mars |
| Coordinate System | Mars Mean J2000 Equator |
| X | 4500.0 (km) |
| Y | 0.0 (km) |
| Z | 0.0 (km) |
| VX | 0.0 (km) |
| VY | 2.1814448386859766 (km) |
| VZ | 2.1814448386859713 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag | 15 ($m^2$) |
| Drag Model | None |
| PMG Bodies | Only Central Body |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. | 60 (sec) |
| Integrator Max. StepSize | 2700 (sec) |
| Integrator Accuracy | 1e-13 |
| Report Precision | 16 significant figures |
| Report CS/Cb | Same as initial state CS |

Table 7.3: Initial Orbit Parameters (Moon Impulsive Burns)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Start & Stop Time | 01 Jan 2000 11:59:28.000 (UTCG) |
| Central Body | Moon |
| Coordinate System | Moon Mean J2000 Equator |
| X | 2050.0 (km) |
| Y | 0.0 (km) |
| Z | 0.0 (km) |
| VX | 0.0 (km) |
| VY | 1.093528701 (km) |
| VZ | 1.093528701 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag | 15 ($m^2$) |
| Drag Model | None |
| PMG Bodies | Only Central Body |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. | 60 (sec) |
| Integrator Max. StepSize | 2700 (sec) |
| Integrator Accuracy | 1e-13 |
| Report Precision | 16 significant figures |
| Report CS/Cb | Same as initial state CS |

Table 7.4: Initial Orbit Parameters (Sun Impulsive Burns)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Start & Stop Time | 01 Jan 2000 11:59:28.000 (UTCG) |
| Central Body | Sun |
| Coordinate System | Sun Mean J2000 Equator |
| X | 1000000.0 (km) |
| Y | 0.0 (km) |
| Z | 0.0 (km) |
| VX | 0.0 (km) |
| VY | 257.597010870 (km) |
| VZ | 257.597010870 (km) |
| Mass (No Fuel) | 850 (kg) |
| Cd | 2.2 |
| Cr | 1.8 |
| Drag | 15 ($m^2$) |
| Drag Model | None |
| PMG Bodies | Only Central Body |
| NSG Model | None |
| SRP Area | 1 ($m^2$) |
| SRP | Off |
| Integrator Type | RungaKutta 8(9) |
| Integrator Init. | 60 (sec) |
| Integrator Max. StepSize | 2700 (sec) |
| Integrator Accuracy | 1e-13 |
| Report Precision | 16 significant figures |
| Report CS/Cb | Same as initial state CS |

## 7.2 Naming Convention

This section describes the naming convention for Delta V scripts and output reports generated for use in GMAT's Acceptance Test Plan. The naming convention consists of an ordered series of option strings, separated by underscores (_ ). Currently, options are allowed for the following fields, and will be present in the file name in order:

1. *tool* - The tool used to generate the trajectory.
2. *deltaVbody* - The type of Delta V applied and the central body the test case uses.
3. *axes* - Axes type used for burn maneuver.

The word DeltaV precedes the *tool* field. The final stopping condition file format is as followed:
DeltaV_*tool*_*deltaVbody*_*axes*.report

The *tool* field should always be the first option field. Future additional fields should be added to the end of the list of fields. Each field has a finite list of options, as follows (future options should be added to this list):

1. *tool*

| | |
|---|---|
| STK | - Satellite Toolkit HPOP or Astrogator |
| FF | - FreeFlyer |
| GMAT | - General Mission Analysis Tool |
| OD | - Orbital Determination Toolbox |

2. *deltaVbody*

| | |
|---|---|
| IEarth | - Earth centered impulsive burn |
| IMars | - Mars centered impulsive burn |
| IMoon | - Moon centered impulsive burn |
| ISun | - Sun centered impulsive burn |

3. *axes*

| | |
|---|---|
| VNB | - Velocity, Velocity Normal, Velocity BiNormal axes |
| Cartesian | - Typical X,Y,Z,Vx,Vy,Vz axes |

## 7.3 Comparison Script Information

Comparison_DeltaV.m is the script used to perform the comparisons needed for the Delta V chapter of the Acceptance Test Plan. This script was designed to allow the user to select a GMAT Build and/or the exact solution to compare to one another.

Refer to Appendix C for more details on this script and others used in the Acceptance Test Plan document.

## 7.4 Test Case Results

The following results are for the Delta V section. The GMAT Delta V results are being compared to the exact desired Delta V values. We'd like the comparison data to be as close to zero as possible. A detailed acceptance metric/matrix will be developed at a later date.

Table 7.5: Exact/GMAT IEarth DeltaV Test Case Comparison

| Test Case | X-Pos (m) | Y-Pos (m) | Z-Pos (m) | X-Vel (m/s) | Y-Vel (m/s) | Z-Vel (m/s) |
|---|---|---|---|---|---|---|
| Cartesian | 0 | 0 | 0 | 0 | 8.881784197e-013 | 8.881784197e-013 |
| VNB | 0 | 0 | 0 | 0 | 2.664535259e-012 | 8.881784197e-013 |

Table 7.6: Exact/GMAT IMars DeltaV Test Case Comparison

| Test Case | X-Pos (m) | Y-Pos (m) | Z-Pos (m) | X-Vel (m/s) | Y-Vel (m/s) | Z-Vel (m/s) |
|---|---|---|---|---|---|---|
| Cartesian | 0 | 0 | 0 | 1.387778781e-012 | 8.881784197e-013 | 0 |
| VNB | 0 | 0 | 0 | 1.387778781e-012 | 3.108624469e-012 | 8.881784197e-013 |

Table 7.7: Exact/GMAT IMoon DeltaV Test Case Comparison

| Test Case | X-Pos (m) | Y-Pos (m) | Z-Pos (m) | X-Vel (m/s) | Y-Vel (m/s) | Z-Vel (m/s) |
|---|---|---|---|---|---|---|
| Cartesian | 0 | 0 | 0 | 2.775557562e-014 | 0 | 0 |
| VNB | 0 | 0 | 0 | 2.775557562e-014 | 0 | 0 |

Table 7.8: Exact/GMAT ISun DeltaV Test Case Comparison

| Test Case | X-Pos (m) | Y-Pos (m) | Z-Pos (m) | X-Vel (m/s) | Y-Vel (m/s) | Z-Vel (m/s) |
|---|---|---|---|---|---|---|
| Cartesian | 0 | 0 | 0 | 1.387778781e-012 | 0 | 0 |
| VNB | 0 | 0 | 0 | 0 | 0 | 0 |

# Chapter 8

# ControlFlow

The Control Flow tests were designed to verify that the control flow commands (If, While, and For) function as expected. There are scripts that test the control flow commands by themselves, nested, and using different user defined parameters, such as arrays, numbers, variables, and spacecraft parameters. Each test script was designed to store flags that contained details of the command execution for each test case and reported to a text file.

Due to the layout of the report, a Matlab script can easily create a pass and fail table based on the values of the flag variables. In the report output the main columns to pay attention to are the ranOK and ansFlag columns. The ansFlag variable tells us if there was an incorrect control flow execution (ansFlag=-99), correct control flow execution (ansFlag=1), or the control flow didn't get executed (ansFlag=1). The ranOK variable tells us if each test case inside the test script ran correctly (ranOK = 1) or not (ranOK = 0). The only scripts that do not generate the ranOK column are the IfLoopTest##_##, IfLoopTest##, and IfIfLoopTest##_##.m, because the ansFlag column is sufficient.

## 8.1 Test Case Results

The results in Table 8.1 display the Pass and Fail outcome of each Control Flow test script.

Table 8.1: Loop Test Case Results

| TestName | Pass/Fail | Failed/TotalTests |
|---|---|---|
| For | Pass | 0/15 |
| ForFor | Pass | 0/9 |
| ForIf41-14 | Pass | 0/20 |
| ForIf42-24 | Pass | 0/21 |
| ForIf43-34 | Pass | 0/20 |
| ForIf51-15 | Pass | 0/16 |
| ForIf52-25 | Pass | 0/20 |
| ForIf53-35 | Pass | 0/20 |
| ForWhile42 | Pass | 0/8 |
| If11 | Pass | 0/9 |
| If12-21 | Pass | 0/18 |
| If22 | Pass | 0/9 |
| If32-23 | Pass | 0/18 |
| If33 | Pass | 0/9 |
| If42-24 | Pass | 0/16 |
| If44 | Pass | 0/8 |
| If52-25 | Pass | 0/16 |
| If55 | Pass | 0/8 |
| IfFor | Pass | 0/9 |
| IfIf41-14 | Pass | 0/16 |
| IfIf42-24 | Pass | 0/16 |
| IfIf43-34 | Pass | 0/20 |
| IfIf51-15 | Pass | 0/16 |
| IfIf52-25 | Pass | 0/16 |
| IfIf53-35 | Pass | 0/16 |
| IfWhile | Pass | 0/8 |
| While42-24 | Pass | 0/16 |
| While43-34 | Pass | 0/16 |
| While52-25 | Pass | 0/16 |
| While53-35 | Pass | 0/16 |
| WhileFor | Pass | 0/9 |
| WhileIf41-14 | Pass | 0/16 |
| WhileIf42-24 | Pass | 0/16 |
| WhileIf43-34 | Pass | 0/16 |
| WhileIf51-15 | Pass | 0/17 |
| WhileIf52-25 | Pass | 0/16 |
| WhileIf53-35 | Pass | 0/16 |
| WhileTarget | Pass | 0/1 |
| WhileWhile42-24 | Pass | 0/16 |

# Appendix A

# Acronyms

| | |
|---|---|
| Cb | - Central Body |
| Cd | - Drag coefficient |
| COTS | - Commercial Off The Shelf software |
| Cr | - Coefficient of reflexivity |
| CS | - Coordinate System |
| EGM | - Earth Gravity Model |
| EOP | - Earth Orientation Parameters |
| FDAB | - Flight Dynamics Analysis Branch |
| FF | - Free Flyer |
| GEO | - Geosynchronous Orbit |
| GMAT | - General Mission Analysis Tool |
| GPS | - Global Positioning Satellite |
| HEO | - Highly Elliptical Orbit |
| HPOP | - High Precision Orbit Propagator |
| IAU | - International Astronomical Union |
| IERS | - International Earth Rotation and Reference Systems Service |
| ISS | - International Space Station |
| JGM | - Joint Gravity Model |
| JR | - Jacchia Roberts |
| GMAT | - General Mission Analysis Tool |
| LEO | - Low Earth Orbit |
| LOD | - Length of Day |
| MEO | - Medium Earth Orbit |
| mas | - milliarcseconds |
| MSISE | - Mass Spectrometer and Incoherent Scatter Radar Exosphere |
| NSG | - Non-Spherical Gravity |
| PIP | - Professional Intern Program |
| PMG | - Point Mass Gravity |
| SRP | - Solar Radiation Pressure |
| STK | - Satellite Tool Kit |
| TAI | - International Atomic Time |
| TLE | - Two Line Element |
| USNO | - U.S. Naval Observatory |
| UT | - Universal time |
| UTC | - Coordinated Universal Time |

# Appendix B

# Initial Conditions

The text and tables in this appendix allow someone to have an easier time duplicating the test case setups described in the previous chapters. The same information was presented in the previous chapters but this appendix has the information arranged different for ease of duplication reasons.

## B.1 Propagator Test Cases

Table B.1: Initial Orbit Parameters (ISS)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Earth Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 2 Jun 2004 12:00:00.000 (UTCG) |
| X | -4453.783586 (km) |
| Y | -5038.203756 (km) |
| Z | -426.384456 (km) |
| VX | 3.831888 (km) |
| VY | -2.887221 (km) |
| VZ | -6.018232 (km) |
| Mass (No Fuel) | 1000 (kg) (some exceptions) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 60 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.2: Initial Orbit Parameters (Sun-Sync)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Earth Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 2 Jun 2004 12:00:00.000 (UTCG) |
| X | -2290.301063 (km) |
| Y | -6379.471940 (km) |
| Z | 0.0 (km) |
| VX | -0.883923 (km) |
| VY | 0.317338 (km) |
| VZ | 7.610832 (km) |
| Mass (No Fuel) | 1000 (kg) (some exceptions) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 60 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.3: Initial Orbit Parameters (GPS)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Earth Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 3 Jun 2004 12:00:00.000 (UTCG) |
| X | 5525.33668 (km) |
| Y | -15871.18494 (km) |
| Z | -20998.992446 (km) |
| VX | 2.750341 (km) |
| VY | 2.434198 (km) |
| VZ | -1.068884 (km) |
| Mass (No Fuel) | 1000 (kg) (some exceptions) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 60 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 60 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 120 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.4: Initial Orbit Parameters (Molniya)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Earth Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -1529.894287 (km) |
| Y | -2672.877357 (km) |
| Z | -6150.115340 (km) |
| VX | 8.717518 (km) |
| VY | -4.989709 (km) |
| VZ | 0.0 (km) |
| Mass (No Fuel) | 1000 (kg) (some exceptions) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.5: Initial Orbit Parameters (GEO)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Earth Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 8 Jun 2004 12:00:00.000 (UTCG) |
| X | 36607.358256 (km) |
| Y | -20921.723703 (km) |
| Z | 0.0 (km) |
| VX | 1.525636 (km) |
| VY | 2.669451 (km) |
| VZ | 0.0 (km) |
| Mass (No Fuel) | 1000 (kg) (some exceptions) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 60 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 60 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 600 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.6: Initial Orbit Parameters (Mars)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Mars Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -2737.481646173082000 (km) |
| Y | 0.0 (km) |
| Z | 2737.481646173082000 (km) |
| VX | -0.311321695052649 (km) |
| VY | -3.553492313930950 (km) |
| VZ | 0.311321695052650 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.7: Initial Orbit Parameters (Mercury)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Mercury Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -2164.769322630887000 (km) |
| Y | 0.0 (km) |
| Z | 2164.769322630886100 (km) |
| VX | -0.251096955137200 (km) |
| VY | -2.866074270797602 (km) |
| VZ | 0.251096955137201 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.8: Initial Orbit Parameters (Moon)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Moon Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -1486.792117191545200 (km) |
| Y | 0.0 (km) |
| Z | 1486.792117191543000 (km) |
| VX | -0.142927729144255 (km) |
| VY | -1.631407624437537 (km) |
| VZ | 0.142927729144255 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.9: Initial Orbit Parameters (Neptune)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Neptune Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -20815.089640681723000 (km) |
| Y | 0.0 (km) |
| Z | 20815.089640681723000 (km) |
| VX | -1.426423063858300 (km) |
| VY | -16.281497481173282 (km) |
| VZ | 1.426423063858303 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.10: Initial Orbit Parameters (Pluto)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Pluto Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -1067.516740143530600 (km) |
| Y | 0.0 (km) |
| Z | 1067.516740143529700 (km) |
| VX | -0.075474392886505 (km) |
| VY | -0.861480838897026 (km) |
| VZ | 0.075474392886505 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.11: Initial Orbit Parameters (Saturn)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Saturn Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -47577.347750129338000 (km) |
| Y | 0.0 (km) |
| Z | 47577.347750129360000 (km) |
| VX | -2.222652848522210 (km) |
| VY | -25.369834288049386 (km) |
| VZ | 2.222652848522210 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.12: Initial Orbit Parameters (Uranus)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Uranus Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -26762.258109447845000 (km) |
| Y | 0.0 (km) |
| Z | 26762.258109447823000 (km) |
| VX | -1.158158360792704 (km) |
| VY | -13.219466869135891 (km) |
| VZ | 1.158158360792704 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.13: Initial Orbit Parameters (Venus)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Venus Mean J2000 Equator |
| Start Time | 1 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 4 Jun 2004 12:00:00.000 (UTCG) |
| X | -4832.074380872521000 (km) |
| Y | 0.0 (km) |
| Z | 4832.074380872517400 (km) |
| VX | -0.645356787452373 (km) |
| VY | -7.366240195908405 (km) |
| VZ | 0.645356787452373 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 300 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.14: Initial Orbit Parameters (DeepSpace)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Sun Mean J2000 Ecliptic |
| Start Time | 01 Jan 2000 12:00:00.000 (UTCG) |
| Stop Time | 01 Jan 2001 12:00:00.000 (UTCG) |
| X | 30043412.094803076000000 (km) |
| Y | 143707423.481292670000000 (km) |
| Z | 2198384.040184043300000 (km) |
| VX | -29.715920923036403 (km) |
| VY | 6.056690472247896 (km) |
| VZ | 0.123271169290614 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Variable |
| Integrator Init. StepSize | 30000 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 30000 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 86400 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.15: Initial Orbit Parameters (EML2)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Earth Mean J2000 Equator |
| Start Time | 23 Jan 2010 00:00:03.999 (UTCG) |
| Stop Time | 6 Feb 2010 00:00:03.999 (UTCG) |
| X | 406326.22661300009 (km) |
| Y | 177458.38761599999 (km) |
| Z | 145838.58078999998 (km) |
| VX | -0.517274673822 (km) |
| VY | 0.774650366561 (km) |
| VZ | 0.331416602654 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Variable |
| Integrator Init. StepSize | 1200 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 1200 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 2400 (sec) |
| Report CS/Cb | Same as initial state CS |

Table B.16: Initial Orbit Parameters (ESL2)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Earth Mean J2000 Equator |
| Start Time | 5 Feb 2006 17:05:48.772 (UTCG) |
| Stop Time | 4 Aug 2006 17:05:48.772 (UTCG) |
| X | 1010800.968074728 (km) |
| Y | -910963.5377102628 (km) |
| Z | -295145.6311353027 (km) |
| VX | 0.2642852647102676 (km) |
| VY | 0.286744175490658 (km) |
| VZ | 0.07338744995264675 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | Case dependent |
| NSG Model | Case dependent |
| SRP Area | 20 ($m^2$) |
| SRP | Case dependent |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Variable |
| Integrator Init. StepSize | 15000 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 15000 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 43200 (sec) |
| Report CS/Cb | Same as initial state CS |

## B.2 Calculation Parameter Test Cases

The Cb and CS initial orbit state conditions for the ISS, GEO, Mars1, Mercury1, Moon, Neptune1, Pluto1, Saturn1, Uranus1 and Venus1 test cases are the same as the vales presented in Tables B.1, B.5, B.6- B.13. The only exception is that the Report StepSize is 600 seconds.

Table B.17: Initial Orbit Parameters (Hyperbolic)

| Initial State Parameter | Parameter Value (unit) |
|---|---|
| Coordinate System | Earth Mean J2000 Equator |
| Start Time | 01 Jun 2004 12:00:00.000 (UTCG) |
| Stop Time | 02 Jun 2004 12:00:00.000 (UTCG) |
| X | 12371.791482634855 (km) |
| Y | 5050.7627227610719 (km) |
| Z | 5050.762722761071 (km) |
| VX | -7.9859921512608487 (km) |
| VY | 2.44520073255755 (km) |
| VZ | 2.4452007325575495 (km) |
| Mass (No Fuel) | 1000 (kg) |
| Cd | 2.2 |
| Cr | 1.2 |
| Drag Area | 20 ($m^2$) |
| Drag Model | None |
| NSG Model | None |
| SRP Area | 20 ($m^2$) |
| SRP | None |
| Integration Method | Tool/Program Dependent |
| Integrator StepSize control | Fixed |
| Integrator Init. StepSize | 5 (sec) |
| Integrator Accuracy | 1e-13 |
| Integrator Max. StepSize | 5 (sec) |
| Report Precision | 16 significant figures |
| Report StepSize | 600 (sec) |
| Report CS/Cb | Case Dependent |

## B.3 Integrator Test Cases

The integrator initial orbit state conditions for the ISS and GEO test cases are the same as the vales presented in Tables B.1 and B.5. The only exception is that each test case uses one of the following Integration Methods: ABM, BS, PD45, PD78, RKF56, RKN68, and RKV89.

## B.4 Stopping Condition Test Cases

Refer to Tables 5.2- 5.6 in Chapter 5 for initial orbit state values for the Stopping Condition test cases.

## B.5 Libration Point Test Cases

Refer to Tables 6.1- 6.2 in Chapter 6 for initial orbit state values for the Stopping Condition test cases.

## B.6 DeltaV Test Cases

Refer to Tables 7.1- 7.4 in Chapter 7 for initial orbit state values for the Performance test cases.

## B.7 Performance

Refer to Tables ??- ?? in Chapter ?? for initial orbit state values for the Performance test cases.

# Appendix C

# Comparison Scripts Guide

Using specific naming conventions, outlined in this acceptance test plan, and a folder architecture, highlighted below for the test cases, several semi-automated scripts were generated to compare all of the GMAT test case results with other tools. Most of these scripts have the ability to also compare results of older versions of GMAT.

## C.1 Folder Architecture

The folder architecture for the files needed for the comparison scripts is presented below:

- GMAT_RegSetup/
  - output/AcceptTest/CompareResults/
    - [Tool1]_[Tool2]
  - input/AcceptTest/
  - output/AcceptTest/[Tool]_reports/
  - output/AcceptTest/Good_reports/
    - FF
    - STK
- GMATDocuments/
  - AcceptTest

## C.2 Install Instructions

1. Copy the GMAT_RegSetup and GMATDocuments folders to the same location on your hard drive.
2. Check to make sure the folders listed in Section C.1
3. Make sure the GMAT executable folder has a Matlab folder with the latest GMAT commands and keywords
4. Open Matlab
5. Set the path in Matlab to include the GMAT matlab folder

6. Open GMAT and start the Matlab server
7. Make sure Excel is closed
8. Set current directory to the main GMAT_results/GMAT_scripts folder and then type BuildCompare_GMATteam in the command window or
9. Open one of the following files and run (F5 in Windows):
   *Click ok to change the current Matlab directory if prompted*
   (a) BuildRun_Script_GMAT.m
   (b) Comparison_Tool1_Tool2_PV.m
   (c) Comparison_Tool1_Tool2_CS.m
   (d) Comparison_Tool1_Tool2_Cb.m
   (e) Comparison_Tool1_Tool2_Libr.m
   (f) Comparison_Integ.m
   (g) Comparison_DeltaV.m
   (h) Comparison_StopCond.m
   (i) TimeComparo.m
   (j) LoopTestSummary.m

## C.3 Warnings/Script Hints

- The following scripts were not designed for the user to hit one button, run multiple calculations, and output data without user interaction. User interaction is necessary in all of these scripts.
- The [ ] notation indicates multiple words can be used. For example,[Tool] means replace the bracketed expression with words such as FF,STK, and GMAT.
- As of November 2005, the Excel data created by the comparison scripts will be saved in one file name [Tool1]_[Tool2]_Results_[DD-MMM-YYYY].xls in their respective [Tool1]_[Tool2] folder in the CompareResults folder.
- Be careful adding MATLAB .m files that contain the text GMAT in their file name. These scripts use the text GMAT as an indicator to know if the file is a GMAT compatible script.
- The adherence to the naming conventions are very strict in these scripts. Make sure when adding reports, scripts, or folders to use case sensitive filenames that agree with the naming conventions at all times.
- Several output formats are overwritten when running each script. The Excel documents are saved with the current date as part of the filename. If the filename exists it will be replaced. The same overwriting process occurs with the Matlab .mat files.
- In order to compare old GMAT Builds to one another, a new folder must be created with the date of the GMAT Build. For example, the [Month] [Day] build performed well so after running the scripts that generate all the comparison data for the [Month] [Day] Build, a new folder must be created. The folder can be named YYMMDDGMAT_reports with the appropriate GMAT Build Year Month and Date replacing YYMMDD. Now simply copy the contents of GMAT_reports into YYMMDDGMAT_reports and the data can be used to compare future build of GMAT to one another.
- All the .mat files, except for the TimeComparo files, are formatted in a similar way. They contain the following variables mat_Tool11, mat_Tool21, mat_header, maxDiffs, and diffMat_Tool1_Tool2 or normMat_Tool1_Tool2.

  The mat_header variable contains what parameters each column represents for the other variables The mat_Tool11 and mat_Tool21 variables contain the report file data minus any headers. Tool1 is the alphabetical first tool selected and Tool2 is the other tool selected

- Common mistakes made with these scripts:
  - Adding report files and not following the naming convention (i.e. FF_ISS_Earth_0_0_0 was misnamed as FF_ISS_Earth_0_0).
  - Outputting other tools and not following the proper ordering of parameters for comparison
  - Report files were outputted in the wrong time interval increment
  - Report files were outputted without enough numerical precision. GMAT outputs data at a fixed width of 12 numerical characters (default). Other programs should be the same or better.

## C.4 BuildRun_Script_GMAT.m script

Win compatible / Mac & Linux ?

### C.4.1 Purpose

This script was designed to send multiple GMAT scripts from Matlab to GMAT to be built and ran. In early versions of GMAT, there was no capability to run multiple scripts, but since current versions of GMAT contain this capability this script is not as vital in the Acceptance test plan.

Its secondary purpose is to record the individual time elapsed to run each test case and output the results to a .mat file for later use.

### C.4.2 Inputs

- All .m files located in the GMAT_RegSetup/input/AcceptTest/ folder that follow the GMAT comparison naming convention described in Sections 2.3, 3.2.1, 3.3.1, and 4.2

### C.4.3 Outputs

- When choosing to build multiple scripts and the all command is used a mat file is created, which keeps a log of the time it takes to run each case. The script also displays the case name and the time it takes for GMAT to run the file in Matlab's command window.
- Any other output data is dependent on the GMAT script.

### C.4.4 Script Algorithm

## C.5 Comparison_Tool1_Tool2_PV.m

Win/Mac/Linux compatible

### C.5.1 Purpose

This script is used to perform the position and velocity comparisons needed for the Propagator Section ( 2) of the Acceptance Test Plan. This script takes the normalized position and velocity vector differences between the two selected programs.

### C.5.2 Inputs

- Folder to search for files: [$RootFolder$]/[Tool]_reports.
  (Refer to Section 2.3 for the naming convention of these report files.)
- The report files must be formatted the same way. The first column is time (Mod. Julian Date), second-fourth columns are the position vector components $(x, y, z)$, and fifth-seventh columns are the velocity vector components $(Vx, Vy, Vz)$. The data must be separated by spaces.
- Currently the location of the report's first row of numerical data is coded into the script. FreeFlyer is the fourth row, STK is the seventh row, GMAT is the first row, OD toolbox is the first row, and any other tools added will automatically search the first row.

### C.5.3 Outputs

- Comparison data is displayed in MATLAB's command window for all test cases.
- Excel documents with comparison data and pass/fail information.
- MATLAB .mat files with comparison data.
- Latex documents with comparison data.

### C.5.4 Script Algorithm

- Display welcome message
- Display menu for Tool1 options based on [Tool]_reports folder
- Wait for user to choose tool from menu
  Implement error system for incorrect choice
- Display menu for Tool2 options based on [Tool]_reports folder
- Wait for user to choose tool from menu
  Implement error system for incorrect choice
- Alphabetize Tool1 and Tool2 for naming purposes and rename if necessary
- Store the row location of the first instance of numerical data for both Tools' report files
- Initialize variables and folder locations
- Display a menu of Tool1 *.report files
  Generate error report if no *.report files are located in [Tool1]_report folder
- Wait for user to choose report comparison option
  Implement error system for incorrect choice
  Open Excel Connection if compare all choice selected
- Display filename, position difference, and velocity difference header
- Begin Loop. Loop once for single comparison and several times for comparing all files.
  - Check the Tool2 folder for the same report
    Display error message if no report found

- Continue if match found or exit loop if no match found
- Read both output files and save the data to different matrices
- Check to see if the row sizes are the same in both matrices
  Display error if row sizes do not match
- Take difference of both Tools report data
- Normalize the results based on position and velocity
- Determine the maximum normalized position and velocity difference
- Store propagation duration of the test cases in a variable
- Add acceptable differences values for Excel output
- Save comparison data to .mat file
  * If compare all reports chosen, format data for output to Latex
  * Use BasicLatexTable script to save data to LaTex file
  * Save comparison results, acceptance errors, and duration to Excel
- Close Excel connection if open.

- End Loop: Allow user to rerun script

## C.6 Comparison_Tool1_Tool2_CS.m

Win/Mac/Linux compatible

### C.6.1 Purpose

This script is used to perform the coordinate system dependent comparisons needed for the Calculation Parameters Section ( 3) of the Acceptance Test Plan. The comparison involves taking the maximum absolute value of the differences of the variables listed in the Inputs section of this help guide.

### C.6.2 Inputs

- Folder to search for files: $[RootFolder]$/[Tool]_reports.
  (Refer to Section 3.3.1 for the naming convention of these report files.)
- The report files must be formatted the same way. Time, $[X, Y, andZ]$ Position(km), $[X, Y, andZ]$ Velocity(km/sec), Mag. of Velocity(km/sec), Right Ascension of Velocity(deg), $[X, Y, andZ]$ RxV-Specific Angular Momentum($km^2/sec$), Arg. of Perigee(deg), Declination(deg), Declination of Velocity(deg), Inclination(deg), Right Ascension(deg), Right Ascension of Ascending Node(deg)
- Currently the location of the reports first row of numerical data is coded into the script. FreeFlyer is the fourth row, STK is the seventh row, GMAT is the second row, OD toolbox is the first row, and any other tools added will automatically search the first row.

### C.6.3 Outputs

- Excel documents with comparison data
- MATLAB .mat files with comparison data
- Latex documents with comparison data

### C.6.4 Script Algorithm

- Display welcome message
- Display menu for Tool1 options based on [Tool]_reports folder
- Wait for user to choose tool from menu
  Implement error system for incorrect choice
- Display menu for Tool2 options based on [Tool]_reports folder
- Wait for user to choose tool from menu
  Implement error system for incorrect choice
- Alphabetize Tool1 and Tool2 for naming purposes and rename if necessary
- Store the row location of the first instance of numerical data for both Tools' report files
- Initialize variables and folder locations
- Display a menu of Tool1 *.report files
  Generate error report if no *.report files are located in [Tool1]_report folder
- Wait for user to choose report comparison option
  Implement error system for incorrect choice
  Open Excel Connection if compare all choice selected
- Display filename, position difference, and velocity difference header
- Begin Loop. Loop once for single comparison and several times for comparing all files.
  - Check the Tool2 folder for the same report
    Display error message if no report found
  - Continue if match found or exit loop if no match found
  - Read both output files and save the data to different matrices
  - Check to see if the row sizes are the same in both matrices
    Display error if row sizes do not match
  - Take difference of both Tools report data
  - Determine the maximum difference for each coordinate system dependent parameter
  - Store propagation duration of the test cases in a variable
  - Save comparison data to .mat file
    * If compare all reports chosen, format data for output to Latex
    * Use BasicLatexTable script to save data to LaTex file
    * Save comparison results, acceptance errors, and duration to Excel
  - Close Excel connection if open.
- End Loop. Allow user to rerun script

## C.7 Comparison_Tool1_Tool2_Cb.m

Win/Mac/Linux compatible

### C.7.1 Purpose

This script is used to perform the central body dependent comparisons needed for the Calculation Parameters Section ( 3) of the Acceptance Test Plan. The comparison involves taking the maximum absolute value of the differences of the variables listed in the Inputs section of this help guide.

### C.7.2 Inputs

- Folder to search for files: $[RootFolder]/[Tool]$_reports.
  (Refer to Section 3.2.1 for the naming convention of these report files.)
- The report files must be formatted the same way. Time, Altitude (km), Beta Angle (deg), C3_Energy ($km^2/sec^2$), Eccentricity, Latitude (deg), Longitude (deg), (RxV)_Mag ($km^2/sec$), Mean Anomaly (deg), Mean Motion ($rad/sec$), Period (sec), Apoapsis Radius (km), Perigee Radius (km), R_Mag (km), Semi-major Axis (km), True Anomaly (deg), Semilatus Rectum(km), Apoapsis Velocity ($km/sec$), Periapsis Velocity ($km/sec$), Greenwich Hour Angle(deg), Local Sidereal Time
- Due to the inability of FF and STK tools to output all the parameters listed in the previous bullet, exceptions for FF and STK are built into the code.

  STK: Semilatus Rectum, Apoapsis Velocity, Perigee Velocity, Greenwich Hour Angle, and Local Sidereal Time can not be outputted in the same report file. Out of the aforementioned parameters Greenwich Hour Angle is the only parameter that can be outputted in a separate file. All the other parameters are calculated in MATLAB based on the results STK could generate.

  FF: (RxV)_Mag and R_Mag could not be outputted easily. Instead the [XYZ] components were outputted and the script computes the magnitude of the vectors. Apoapsis Velocity, Periapsis Velocity, and Local Sidereal Time are all created in this script based on available parameters.

  Modifications to the code will need to be made to add a new tool that cannot output all of the central body parameters that GMAT does.

- Currently the location of the reports first row of numerical data is coded into the script. FreeFlyer is the fourth row, STK is the seventh row, GMAT is the second row, OD toolbox is the first row, and any other tools added will automatically search the first row.

### C.7.3 Outputs

- Excel documents with comparison data
- MATLAB .mat files with comparison data
- Latex documents with comparison data

### C.7.4 Script Algorithm

- Display welcome message
- Display menu for Tool1 options based on [Tool]_reports folder
- Wait for user to choose tool from menu

  Implement error system for incorrect choice

- Display menu for Tool2 options based on [Tool]_reports folder
- Wait for user to choose tool from menu

  Implement error system for incorrect choice
- Alphabetize Tool1 and Tool2 for naming purposes and rename if necessary
- Store the row location of the first instance of numerical data for both Tools' report files
- Initialize variables and folder locations
- Display a menu of Tool1 *.report files

  Generate error report if no *.report files are located in [Tool1]_report folder
- Wait for user to choose report comparison option

  Implement error system for incorrect choice

  Open Excel Connection if compare all choice selected
- Display filename, position difference, and velocity difference header
- Begin Loop. Loop once for single comparison and several times for comparing all files.
  - Check the Tool2 folder for the same report

    Display error message if no report found
  - Continue if match found or exit loop if no match found
  - Read both output files and save the data to different matrices
  - Check to see if the row sizes are the same in both matrices

    Display error if row sizes do not match
  - Take difference of both Tools report data
  - Code in exceptions for STK, FF, and any other tools that don't output all the desired GMAT central body dependent parameters
  - Determine the maximum difference for each central body dependent parameter
  - Store propagation duration of the test cases in a variable
  - Save comparison data to .mat file
    - If compare all reports chosen, format data for output to Latex
    - Use BasicLatexTable script to save data to LaTex file
    - Save comparison results, acceptance errors, and duration to Excel
  - Close Excel connection if open.
- End Loop. Allow user to rerun script

## C.8 Comparison_Tool1_Tool2_Libr.m

Win/Mac/Linux compatible

### C.8.1 Purpose

This script is used to perform the position and velocity comparisons needed for the Libration Points Section ( 6) of the Acceptance Test Plan. This script takes the normalized position and velocity vector differences between the two selected programs.

### C.8.2 Inputs

- Folder to search for files: [Root Folder]/[Tool]_reports.
  (Refer to Section 6.2 for the naming convention of these report files.)
- The report files must be formatted the same way. The first column is time (Mod. Julian Date), second-fourth columns are the position vector components $(x, y, z)$, and fifth-seventh columns are the velocity vector components $(Vx, Vy, Vz)$. The data must be separated by spaces.
- Currently the location of the report's first row of numerical data is coded into the script. FreeFlyer is the fourth row, STK is the seventh row, GMAT is the first row, OD toolbox is the first row, and any other tools added will automatically search the first row.

### C.8.3 Outputs

- Comparison data is displayed in MATLAB's command window for all test cases.
- Excel documents with comparison data and pass/fail information.
- MATLAB .mat files with comparison data.
- Latex documents with comparison data.

### C.8.4 Script Algorithm

[INSERT script Algorithm]

## C.9 Comparison_Integ.m

Win/Mac/Linux compatible

### C.9.1 Purpose

This script is used to perform the integrator comparisons needed for the Integrator Section ( 4) of the Acceptance Test Plan. The comparison involves taking the difference of the position and velocity vector and then normalizing these two vectors to get the position and velocity difference. This script behaves similar to the Comparison_Tool1_Tool2_PV.m script but the components being varied are the integrators for two body test cases.

### C.9.2 Inputs

- Folder to search for files: $[RootFolder]/[Tool]$_reports.
- Naming convention: Integrator_$[Tool]$_$[Trajectory]$_$[IntegratorType]$_2Body.report
- The report files must be formatted the same way. The first column is time, second-fourth columns are the position vector (x,y,z), and fifth-seventh columns are the velocity vector (x,y,z). The data must be separated by spaces.
- Currently the location of the reports' first row of numerical data is coded into the script. FreeFlyer is the fourth row, STK is the seventh row, GMAT is the second row, OD toolbox is the first row, and any other tools added will automatically search the first row.

### C.9.3 Outputs

- Excel documents with comparison data into the following folder:
  $[RootFolder]$/CompareResults/$[Tool1]$_$[Tool2]$
- MATLAB .mat files with comparison data into the following folder:
  $[RootFolder]$/CompareResults/$[Tool1]$_$[Tool2]$
- Latex documents with comparison data into the following folder:
  $[RootFolder]$/Latex_Docs

### C.9.4 Script Algorithm

- Display welcome message
- Display menu for Tool1 options based on [Tool]_reports folder (Can only be Exact or GMAT folders)
- Wait for user to choose tool from menu
  Implement error system for incorrect choice
- Display menu for Tool2 options based on [Tool]_reports folder (Can only be Exact or GMAT folders)
- Wait for user to choose tool from menu
  Implement error system for incorrect choice
- Alphabetize Tool1 and Tool2 for naming purposes and rename if necessary
- Store the row location of the first instance of numerical data for both Tools' report files
- Initialize variables and folder locations
- Display a menu of Tool1 *.report files
  Generate error report if no *.report files are located in [Tool1]_report folder
- Wait for user to choose report comparison option
  Implement error system for incorrect choice
  Open Excel Connection if compare all choice selected
- Display filename, position difference, and velocity difference header
- Begin Loop. Loop once for single comparison and several times for comparing all files.
  - Check the Tool2 folder for the same report
    Display error message if no report found
  - Continue if match found or exit loop if no match found
  - Read both output files and save the data to different matrices
  - Check to see if the row sizes are the same in both matrices
    Display error if row sizes do not match
  - Take difference of both Tools report data
  - Normalize the results based on position and velocity
  - Determine the maximum normalized position and velocity difference
  - Store propagation duration of the test cases in a variable
  - Save comparison data to .mat file
    - If compare all reports chosen, format data for output to Latex
    - Use BasicLatexTable script to save data to LaTex file
    - Save comparison results, acceptance errors, and duration to Excel
  - Close Excel connection if open.
- End Loop. Allow user to rerun script

## C.10 Comparison_DeltaV.m

Win/Mac/Linux compatible

### C.10.1 Purpose

### C.10.2 Inputs

### C.10.3 Outputs

### C.10.4 Script Algorithm

## C.11 Comparison_StopCond.m

Win/Mac/Linux compatible

### C.11.1 Purpose

### C.11.2 Inputs

### C.11.3 Outputs

### C.11.4 Script Algorithm

## C.12 STK_Repropagate.m

Win compatible

### C.12.1 Purpose

The STK_Repropagate script was designed to reduce the time it took to generate STK report files, after modifications to the STK scenario were made, and obtain more accurate STK run times. Through STK's connect module Matlab connect with STK and propagates satellites, generates reports, and outputs run times.

### C.12.2 Inputs

- STK scenario folders that follow the GMAT Acceptance Test Plan naming convention, in the following folder: [*RootFolder*]/TruthFiles/STK

### C.12.3 Outputs

- STK report file saved into [*RootFolder*]/STK_reports.
- Matlab .mat file with the time taken to propagate each satellite.

### C.12.4 Script Algorithm

## C.13 TimeComparo.m

Win/Mac/Linux compatible

### C.13.1 Purpose

When running the BuildRun_Script_GMAT.m script there is an all option after selecting the build & run multiple cases choice. By using this all option, the GMAT performance times for all the test cases are saved to a .mat file. This script uses those saved performance times and, based on a pre-selected amount of test cases, creates a new excel file that contains GMAT, FF, and STK performance times for those pre-selected cases.

### C.13.2 Inputs

- Template file containing pre-selected cases: [*RootFolder*]/NonGMATrunTimes.xls
- Folder to search for files: [*RootFolder*]/CompareResults
- Naming convention:
  [*Date*]/_Time2RunAll.mat

### C.13.3 Outputs

- Excel document with comparison data

### C.13.4 Script Algorithm

# Appendix D

# STK Setup

The STK setups were very crucial in determining a preliminary standard to compare GMAT to. In the initial stages of the Acceptance Test Plan STK scenarios were obtained from Emergent Space, as mentioned in Section 2.1. These Earth based cases were created in STK-HPOP and modified to provide a setup that was as equivalent to GMAT as was possible. Non-Earth test cases could not be created with STK-HPOP, so STK-Astrogator was used. In order to use STK-Astrogator several Astrogator elements needed to be created. Section D.4 details all the elements needed for the non-Earth STK test cases.

## D.1 Support Files Needed

All alterations to STK scenarios were performed with STK 6.1 on the desktop machine described in the Performance Section (Section ??).

In order to duplicate data generated by STK for this Acceptance Test Plan, the same files presented in Table D.1 are needed.

Table D.1: STK support files

| Filename(s) | File('s) and/or Folder('s) Location | Information in Section |
|---|---|---|
| EOP.dat | [STK Root Directory]\DynamicEarthData | 2.2.1 |
| EOP.dat.all | [STK Root Directory]\DynamicEarthData | 2.2.1 |
| All planetary cb files | [STK Root Directory]\STKData\CentralBodies | 2.2.2 |
| Non-spherical grav (nsg) files | [STK Root Directory]\STKData\CentralBodies | 2.3 |
| Report Styles | [STK individual user folder]\Config\Styles | D.5 |
| Non-Earth Astrogator Elements | [STK Root Directory]\STKData\Astrogator | D.4 |
| Leap Seconds File | [STK Root Directory]\STKData\Astro | 2.2.2 |

## D.2 STK modules used

Refer to Appendix B for a easy initial orbit state format to use as input into STK. Table D.2 displays the STK module to use in order to duplicate the results seen in theis Acceptance Test Plan document.

Table D.2: STK modules used

| Test Cases | Test Group(s) | STK-type |
|---|---|---|
| ISS, GEO, SunSync, Molniya, GPS, Hyperbolic | Propagator, Cb, CS | STK-HPOP |
| DeepSpace, EML2, ESL2, All non-Earth cases | Propagator | STK-Astrogator |
| ISS, GEO | Integrator | STK-2Body |

## D.3 Scenario Setup

The following are guidelines we followed when creating STK Scenarios, excluding HPOP or Astrogator specific guidelines:

- Initial Scenario Epoch is the same as the satellite epoch
- Make sure all support files (Table D.1) are present and match the information in this document.
- *.cb planetary files need to contain the values in Tables 2.5, 2.7, and 2.9
- Remember the Modified Julian Date used in GMAT and STK are different.
  (i.e. UTC_GMAT_ModJulian = UTC_STK_ModJulian + 29999.5)

### D.3.1 HPOP

- Planetary information should be taken from the JPL DE file
- Satellite properties must be consistent with table the values in Table 2.5

[INSERT Screen captures of HPOP]

### D.3.2 STK

- All Astrogator support files (Table D.1) are essential in reproducing the values in this document.
- Make sure the maximum propagation is greater than the test case propagation duration or turn off the feature in STK.

[INSERT Screen captures of Astrogator]

## D.4 Astrogator Elements

For the non-Earth cases a large number of Astrogator elements were created in order to compare STK to GMAT's results.

### D.4.1 Calculation Objects: Cartesian Elements

Vx_EarthMJ2000Ec
Vx_EarthMODEc
Vx_EarthMODEq
Vx_EarthMOEEc
Vx_EarthMOEEq
Vx_EarthTODEc
Vx_EarthTODEq
Vx_EarthTOEEc
Vx_EarthTOEEq
Vy_EarthMJ2000Ec
Vy_EarthMODEc
Vy_EarthMODEq
Vy_EarthMOEEc
Vy_EarthMOEEq
Vy_EarthTODEc
Vy_EarthTODEq
Vy_EarthTOEEc
Vy_EarthTOEEq
Vz_EarthMJ2000Ec
Vz_EarthMODEc
Vz_EarthMODEq
Vz_EarthMOEEc
Vz_EarthMOEEq
Vz_EarthTODEc
Vz_EarthTODEq
Vz_EarthTOEEc
Vz_EarthTOEEq
Vx_Mars_Centered_Mean_J2000_Earth_Ec
Vx_Mars_Centered_Mean_J2000_Earth_Eq
Vy_Mars_Centered_Mean_J2000_Earth_Ec
Vy_Mars_Centered_Mean_J2000_Earth_Eq
Vz_Mars_Centered_Mean_J2000_Earth_Ec
Vz_Mars_Centered_Mean_J2000_Earth_Eq
Vx_MarsFixed
Vy_MarsFixed
Vz_MarsFixed
Vx_Mercury_Centered_Mean_J2000_Earth_Ec
Vx_Mercury_Centered_Mean_J2000_Earth_Eq
Vy_Mercury_Centered_Mean_J2000_Earth_Ec
Vy_Mercury_Centered_Mean_J2000_Earth_Eq
Vz_Mercury_Centered_Mean_J2000_Earth_Ec
Vz_Mercury_Centered_Mean_J2000_Earth_Eq
Vx_MercuryFixed
Vy_MercuryFixed
Vz_MercuryFixed
Vx_Neptune_Centered_Mean_J2000_Earth_Ec
Vx_Neptune_Centered_Mean_J2000_Earth_Eq
Vy_Neptune_Centered_Mean_J2000_Earth_Ec
Vy_Neptune_Centered_Mean_J2000_Earth_Eq
Vz_Neptune_Centered_Mean_J2000_Earth_Ec
Vz_Neptune_Centered_Mean_J2000_Earth_Eq
Vx_NeptuneFixed
Vy_NeptuneFixed
Vz_NeptuneFixed
Vx_Pluto_Centered_Mean_J2000_Earth_Ec
Vx_Pluto_Centered_Mean_J2000_Earth_Eq
Vy_Pluto_Centered_Mean_J2000_Earth_Ec
Vy_Pluto_Centered_Mean_J2000_Earth_Eq
Vz_Pluto_Centered_Mean_J2000_Earth_Ec
Vz_Pluto_Centered_Mean_J2000_Earth_Eq
Vx_PlutoFixed
Vy_PlutoFixed
Vz_PlutoFixed
Vx_Saturn_Centered_Mean_J2000_Earth_Ec
Vx_Saturn_Centered_Mean_J2000_Earth_Eq
Vy_Saturn_Centered_Mean_J2000_Earth_Ec
Vy_Saturn_Centered_Mean_J2000_Earth_Eq
Vz_Saturn_Centered_Mean_J2000_Earth_Ec
Vz_Saturn_Centered_Mean_J2000_Earth_Eq
Vx_SaturnFixed
Vy_SaturnFixed
Vz_SaturnFixed
Vx_Sun_Centered_Mean_J2000_Earth_Ec
Vx_Sun_Centered_Mean_J2000_Earth_Eq
Vy_Sun_Centered_Mean_J2000_Earth_Ec
Vy_Sun_Centered_Mean_J2000_Earth_Eq
Vz_Sun_Centered_Mean_J2000_Earth_Ec
Vz_Sun_Centered_Mean_J2000_Earth_Eq
Vx_SunFixed
Vy_SunFixed
Vz_SunFixed
Vx_Uranus_Centered_Mean_J2000_Earth_Ec
Vx_Uranus_Centered_Mean_J2000_Earth_Eq
Vy_Uranus_Centered_Mean_J2000_Earth_Ec
Vy_Uranus_Centered_Mean_J2000_Earth_Eq
Vz_Uranus_Centered_Mean_J2000_Earth_Ec
Vz_Uranus_Centered_Mean_J2000_Earth_Eq
Vx_UranusFixed
Vy_UranusFixed
Vz_UranusFixed

Vx_Moon_Centered_Mean_J2000_Earth_Ec
Vx_Moon_Centered_Mean_J2000_Earth_Eq
Vy_Moon_Centered_Mean_J2000_Earth_Ec
Vy_Moon_Centered_Mean_J2000_Earth_Eq
Vz_Moon_Centered_Mean_J2000_Earth_Ec
Vz_Moon_Centered_Mean_J2000_Earth_Eq
Vx_MoonFixed
Vy_MoonFixed
Vz_MoonFixed
X_EarthGSE
Y_EarthGSE
Z_EarthGSE
Vx_EarthGSE
Vy_EarthGSE
Vz_EarthGSE
Vx_Venus_Centered_Mean_J2000_Earth_Ec
Vx_Venus_Centered_Mean_J2000_Earth_Eq
Vy_Venus_Centered_Mean_J2000_Earth_Ec
Vy_Venus_Centered_Mean_J2000_Earth_Eq
Vz_Venus_Centered_Mean_J2000_Earth_Ec
Vz_Venus_Centered_Mean_J2000_Earth_Eq
Vx_VenusFixed
Vy_VenusFixed
Vz_VenusFixed
X_EarthGSM
Y_EarthGSM
Z_EarthGSM
Vx_EarthGSM
Vy_EarthGSM
Vz_EarthGSM

### D.4.2 Calculation Objects: Geodetic Elements

Altitude_Mars
Latitude_Mars
Longitude_Mars
Altitude_Mercury
Latitude_Mercury
Longitude_Mercury
Altitude_Moon
Latitude_Moon
Longitude_Moon
Altitude_Neptune
Latitude_Neptune
Longitude_Neptune
Altitude_Pluto
Latitude_Pluto
Longitude_Pluto
Altitude_Saturn
Latitude_Saturn
Longitude_Saturn
Altitude_Uranus
Latitude_Uranus
Longitude_Uranus
Altitude_Venus
Latitude_Venus
Longitude_Venus

### D.4.3 Calculation Objects: Keplerian Elements

Argument_of_Periapsis_(fixed)
Argument_of_Periapsis_(MJ2000Ec)
Argument_of_Periapsis_(MODEc)
Argument_of_Periapsis_(MOEEc)
Argument_of_Periapsis_(MOEEq)
Argument_of_Periapsis_(TODEc)
Argument_of_Periapsis_(TOEEc)
Argument_of_Periapsis_(TOEEq)
Argument_of_Periapsis_(EarthGSE)
Argument_of_Periapsis_(EarthGSM)
Argument_of_Periapsis_(MarsFixed)
Argument_of_Periapsis_(MarsMJ2000Ec)
Argument_of_Periapsis_Mars_(MJ2000Eq)
Argument_of_Periapsis_(MercuryFixed)
Argument_of_Periapsis_(MercuryMJ2000Ec)
Argument_of_Periapsis_Mercury_(MJ2000Eq)
Argument_of_Periapsis_(MoonFixed)
Argument_of_Periapsis_(MoonMJ2000Ec)
Argument_of_Periapsis_Moon_(MJ2000Eq)
Argument_of_Periapsis_(NeptuneFixed)
Argument_of_Periapsis_(NeptuneMJ2000Ec)
Argument_of_Periapsis_Neptune_(MJ2000Eq)
Argument_of_Periapsis_(PlutoFixed)
Argument_of_Periapsis_(PlutoMJ2000Ec)
Argument_of_Periapsis_Pluto_(MJ2000Eq)
Argument_of_Periapsis_(SaturnFixed)
Argument_of_Periapsis_(SaturnMJ2000Ec)
Argument_of_Periapsis_Saturn_(MJ2000Eq)
Argument_of_Periapsis_(UranusFixed)
Argument_of_Periapsis_(UranusMJ2000Ec)
Argument_of_Periapsis_Uranus_(MJ2000Eq)
Argument_of_Periapsis_(VenusFixed)
Argument_of_Periapsis_(VenusMJ2000Ec)
Argument_of_Periapsis_Venus_(MJ2000Eq)
Eccentricity_Mars
Eccentricity_Mercury
Eccentricity_Moon
Eccentricity_Neptune
Eccentricity_Pluto
Eccentricity_Saturn
Eccentricity_Uranus
Eccentricity_Venus
Inclination_(fixed)
Inclination_(MJ2000Ec)
Inclination_(MODEc)
Inclination_(MOEEc)
Inclination_(MOEEq)
Inclination_(TODEc)
Inclination_(TOEEc)
Inclination_(TOEEq)
Inclination_(EarthGSE)
Inclination_(EarthGSM)
Inclination_(MarsFixed)
Inclination_(MarsMJ2000Ec)
Inclination_Mars_(MJ2000Eq)
Inclination_(MercuryFixed)
Inclination_(MercuryMJ2000Ec)
Inclination_Mercury_(MJ2000Eq)
Inclination_(MoonFixed)
Inclination_(MoonMJ2000Ec)
Inclination_Moon_(MJ2000Eq)
Inclination_(NeptuneFixed)
Inclination_(NeptuneMJ2000Ec)
Inclination_Neptune_(MJ2000Eq)
Inclination_(PlutoFixed)
Inclination_(PlutoMJ2000Ec)
Inclination_Pluto_(MJ2000Eq)
Inclination_(SaturnFixed)
Inclination_(SaturnMJ2000Ec)
Inclination_Saturn_(MJ2000Eq)
Inclination_(UranusFixed)
Inclination_(UranusMJ2000Ec)
Inclination
Inclination_(VenusFixed)
Inclination_(VenusMJ2000Ec)
Inclination_Venus_(MJ2000Eq)
Mean_Motion_Mars
Mean_Motion_Mercury
Mean_Motion_Moon
Mean_Motion_Neptune
Mean_Motion_Pluto
Mean_Motion_Saturn
Mean_Motion_Uranus
Mean_Motion_Venus

Orbit_Period_Mars
Orbit_Period_Mercury
Orbit_Period_Moon
Orbit_Period_Neptune
Orbit_Period_Pluto
Orbit_Period_Saturn
Orbit_Period_Uranus
Orbit_Period_Venus
RAAN_(fixed)
RAAN_(MJ2000Ec)
RAAN_(MODEc)
RAAN_(MOEEc)
RAAN_(MOEEq)
RAAN_(TODEc)
RAAN_(TOEEc)
RAAN_(TOEEq)
RAAN_(MarsFixed)
RAAN_(MarsMJ2000Ec)
RAAN_Mars_(MJ2000Eq)
RAAN_(MercuryFixed)
RAAN_(MercuryMJ2000Ec)
RAAN_Mercury_(MJ2000Eq)
RAAN_(MoonFixed)
RAAN_(MoonMJ2000Ec)
RAAN_Moon_(MJ2000Eq)
RAAN_(NeptuneFixed)
RAAN_(NeptuneMJ2000Ec)
RAAN_Neptune_(MJ2000Eq)
RAAN_(PlutoFixed)
RAAN_(PlutoMJ2000Ec)
RAAN_Pluto_(MJ2000Eq)
RAAN_(SaturnFixed)
RAAN_(SaturnMJ2000Ec)
RAAN_Saturn_(MJ2000Eq)
RAAN_(UranusFixed)
RAAN_(UranusMJ2000Ec)
RAAN_Uranus_(MJ2000Eq)
RAAN_(VenusFixed)
RAAN_(VenusMJ2000Ec)
RAAN_Venus_(MJ2000Eq)
Radius_Of_Apoapsis_Mars
Radius_Of_Apoapsis_Mercury
Radius_Of_Apoapsis_Moon
Radius_Of_Apoapsis_Neptune
Radius_Of_Apoapsis_Pluto
Radius_Of_Apoapsis_Saturn
Radius_Of_Apoapsis_Uranus
Radius_Of_Apoapsis_Venus
Radius_Of_Periapsis_Mars
Radius_Of_Periapsis_Mercury
Radius_Of_Periapsis_Moon
Radius_Of_Periapsis_Neptune
Radius_Of_Periapsis_Pluto
Radius_Of_Periapsis_Saturn
Radius_Of_Periapsis_Uranus
Radius_Of_Periapsis_Venus
Semimajor_Axis_Mars
Semimajor_Axis_Mercury
Semimajor_Axis_Moon
Semimajor_Axis_Neptune
Semimajor_Axis_Pluto
Semimajor_Axis_Saturn
Semimajor_Axis_Uranus
Semimajor_Axis_Venus
True_Anomaly_Mars
True_Anomaly_Mercury
True_Anomaly_Moon
True_Anomaly_Neptune
True_Anomaly_Pluto
True_Anomaly_Saturn
True_Anomaly_Uranus
True_Anomaly_Venus
RAAN_(EarthGSE)
RAAN_(EarthGSM)

### D.4.4 Calculation Objects: Other Orbit Elements

Beta_Angle_Mars
Beta_Angle_Mercury
Beta_Angle_Moon
Beta_Angle_Neptune
Beta_Angle_Pluto
Beta_Angle_Saturn
Beta_Angle_Uranus
Beta_Angle_Venus

### D.4.5 Calculation Objects: Target Vector Elements

C3_Energy_Mars
C3_Energy_Mercury
C3_Energy_Moon
C3_Energy_Neptune
C3_Energy_Pluto
C3_Energy_Saturn
C3_Energy_Uranus
C3_Energy_Venus

### D.4.6 Calculation Objects: Spherical Elements

Declination_(EarthGSE)
Declination_(EarthGSM)
Declination_(MJ2000Ec)
Declination_(MODEc)
Declination_(MOEEc)
Declination_(MOEEq)
Declination_(MarsFixed)
Declination_(MarsMJ2000Ec)
Declination_(MercuryFixed)
Declination_(MercuryMJ2000Ec)
Declination_(MoonFixed)
Declination_(MoonMJ2000Ec)
Declination_(NeptuneFixed)
Declination_(NeptuneMJ2000Ec)
Declination_(PlutoFixed)
Declination_(PlutoMJ2000Ec)
Declination_(SaturnMJ2000Ec)
Declination_(SaturnsFixed)
Declination_(TODEc)
Declination_(TOEEc)
Right_Asc_(MercuryMJ2000Ec)
Right_Asc_(MoonFixed)
Right_Asc_(MoonMJ2000Ec)
Right_Asc_(NeptuneFixed)
Right_Asc_(NeptuneMJ2000Ec)
Right_Asc_(PlutoFixed)
Right_Asc_(PlutoMJ2000Ec)
Right_Asc_(SaturnFixed)
Right_Asc_(SaturnMJ2000Ec)
Right_Asc_(TODEc)
Right_Asc_(TOEEc)
Right_Asc_(TOEEq)
Right_Asc_(UranusFixed)
Right_Asc_(UranusMJ2000Ec)
Right_Asc_(VenusFixed)
Right_Asc_(VenusMJ2000Ec)
Right_Asc_Mars_(MJ2000Eq)
Right_Asc_Mercury_(MJ2000Eq)
Right_Asc_Moon_(MJ2000Eq)
Right_Asc_Neptune_(MJ2000Eq)

Declination_(TOEEq)
Declination_(UranusFixed)
Declination_(UranusMJ2000Ec)
Declination_(VenusFixed)
Declination_(VenusMJ2000Ec)
Declination_Mars_(MJ2000Eq)
Declination_Mercury_(MJ2000Eq)
Declination_Moon_(MJ2000Eq)
Declination_Neptune_(MJ2000Eq)
Declination_Pluto_(MJ2000Eq)
Declination_Saturn_(MJ2000Eq)
Declination_Uranus_(MJ2000Eq)
Declination_Venus_(MJ2000Eq)
R_Mag_(MarsFixed)
R_Mag_(MercuryFixed)
R_Mag_(MoonFixed)
R_Mag_(NeptuneFixed)
R_Mag_(PlutoFixed)
R_Mag_(SaturnFixed)
R_Mag_(UranusFixed)
R_Mag_(VenusFixed)
R_Mag_Mars
R_Mag_Mercury
R_Mag_Moon
R_Mag_Neptune
R_Mag_Pluto
R_Mag_Saturn
R_Mag_Uranus
R_Mag_Venus
R_Mag_(EarthGSE)
R_Mag_(EarthGSM)
Right_Asc_(MJ2000Ec)
Right_Asc_(MODEc)
Right_Asc_(MOEEc)
Right_Asc_(MOEEq)
Right_Asc_(MarsFixed)
Right_Asc_(MarsMJ2000Ec)
Right_Asc_(MercuryFixed)
Right_Asc_(EarthGSM)
Right_Asc_Pluto_(MJ2000Eq)
Right_Asc_Saturn_(MJ2000Eq)
Right_Asc_Uranus_(MJ2000Eq)
Right_Asc_Venus_(MJ2000Eq)
V_Mag_(MJ2000Ec)
V_Mag_(MODEc)
V_Mag_(MOEEc)
V_Mag_(MOEEq)
V_Mag_(MarsFixed)
V_Mag_(MarsMJ2000Ec)
V_Mag_(MercuryFixed)
V_Mag_(MercuryMJ2000Ec)
V_Mag_(MoonFixed)
V_Mag_(MoonMJ2000Ec)
V_Mag_(NeptuneFixed)
V_Mag_(NeptuneMJ2000Ec)
V_Mag_(PlutoFixed)
V_Mag_(PlutoMJ2000Ec)
V_Mag_(SaturnMJ2000Ec)
V_Mag_(SaturnsFixed)
V_Mag_(TODEc)
V_Mag_(TOEEc)
V_Mag_(TOEEq)
V_Mag_(UranusFixed)
V_Mag_(UranusMJ2000Ec)
V_Mag_(VenusFixed)
V_Mag_(VenusMJ2000Ec)
V_Mag_Mars_(MJ2000Eq)
V_Mag_Mercury_(MJ2000Eq)
V_Mag_(EarthGSE)
V_Mag_(EarthGSM)
V_Mag_Moon_(MJ2000Eq)
V_Mag_Neptune_(MJ2000Eq)
V_Mag_Pluto_(MJ2000Eq)
V_Mag_Saturn_(MJ2000Eq)
V_Mag_Uranus_(MJ2000Eq)
V_Mag_Venus_(MJ2000Eq)
Right_Asc_(EarthGSE)

### D.4.7 Calculation Objects: Vector Elements

(RxV)_Mag
(RxV)_Mag_(MarsFixed)
(RxV)_Mag_(MarsMJ2000)
(RxV)_Mag_(MarsMJ2000Ec)
(RxV)_Mag_(MercuryFixed)
(RxV)_Mag_(MercuryMJ2000)
(RxV)_Mag_(MercuryMJ2000Ec)
(RxV)_Mag_(MoonFixed)
(RxV)_Mag_(MoonMJ2000)
(RxV)_Mag_(MoonMJ2000Ec)
(RxV)_Mag_(NeptuneFixed)
(RxV)_Mag_(NeptuneMJ2000)
(RxV)_Mag_(NeptuneMJ2000Ec)
(RxV)_Mag_(PlutoFixed)
(RxV)_Mag_(PlutoMJ2000)
(RxV)_Mag_(PlutoMJ2000Ec)
(RxV)_Mag_(SaturnFixed)
(RxV)_Mag_(SaturnMJ2000)
(RxV)_Mag_(SaturnMJ2000Ec)
(RxV)_Mag_(UranusFixed)
(RxV)_Mag_(UranusMJ2000)
(RxV)_Mag_(UranussMJ2000Ec)
(RxV)_Mag_(VenusFixed)
(RxV)_Mag_(VenusMJ2000)
(RxV)_Mag_(VenusMJ2000Ec)
(RxV)_X
(RxV)_X_(Fixed)
(RxV)_X_(MJ2000Ec)
(RxV)_X_(MODEc)
(RxV)_X_(MODEq)
(RxV)_X_(MOEEq)
(RxV)_X_(MarsFixed)
(RxV)_X_(MarsMJ2000Ec)
(RxV)_X_(MarsMJ2000Eq)
(RxV)_X_(MercuryFixed)
(RxV)_X_(MercuryMJ2000Ec)
(RxV)_X_(MercuryMJ2000Eq)
(RxV)_X_(MoonFixed)
(RxV)_X_(MoonMJ2000Ec)
(RxV)_X_(MoonMJ2000Eq)
(RxV)_X_(NeptuneFixed)
(RxV)_X_(NeptuneMJ2000Ec)
(RxV)_X_(NeptuneMJ2000Eq)
(RxV)_X_(PlutoFixed)
(RxV)_X_(PlutoMJ2000Ec)
(RxV)_X_(PlutoMJ2000Eq)
(RxV)_X_(SaturnFixed)
(RxV)_X_(SaturnMJ2000Ec)
(RxV)_X_(SaturnMJ2000Eq)
(RxV)_X_(EarthGSE)
(RxV)_Y_(EarthGSE)
(RxV)_Z_(EarthGSE)
EarthGSM_Position_X
(RxV)_Z_(MOEEq)
(RxV)_Z_(MarsFixed)
(RxV)_Z_(MarsMJ2000Ec)
(RxV)_Z_(MarsMJ2000Eq)
(RxV)_Z_(MercuryFixed)
(RxV)_Z_(MercuryMJ2000Ec)
(RxV)_Z_(MercuryMJ2000Eq)
(RxV)_Z_(MoonFixed)
(RxV)_Z_(MoonMJ2000Ec)
(RxV)_Z_(MoonMJ2000Eq)
(RxV)_Z_(NeptuneFixed)
(RxV)_Z_(NeptuneMJ2000Ec)
(RxV)_Z_(NeptuneMJ2000Eq)
(RxV)_Z_(PlutoFixed)
(RxV)_Z_(PlutoMJ2000Ec)
(RxV)_Z_(PlutoMJ2000Eq)
(RxV)_Z_(SaturnFixed)
(RxV)_Z_(SaturnMJ2000Ec)
(RxV)_Z_(SaturnMJ2000Eq)
(RxV)_Z_(TODEc)
(RxV)_Z_(TODEq)
(RxV)_Z_(TOEEc)
(RxV)_Z_(TOEEq)
(RxV)_Z_(UranusFixed)
(RxV)_Z_(UranusMJ2000Ec)
(RxV)_Z_(UranusMJ2000Eq)
(RxV)_Z_(VenusFixed)
(RxV)_Z_(VenusMJ2000Ec)
(RxV)_Z_(VenusMJ2000Eq)
(RxV)_X_(MOEEc)
Vector_Dec_(Fixed)
Vector_Dec_(MJ2000Ec)
Vector_Dec_(MODEc)
Vector_Dec_(MODEq)
Vector_Dec_(MOEEc)
Vector_Dec_(MOEEq)
Vector_Dec_(MarsFixed)
Vector_Dec_(MarsMJ2000Ec)
Vector_Dec_(MarsMJ2000Eq)
Vector_Dec_(MercuryFixed)
Vector_Dec_(MercuryMJ2000Ec)
Vector_Dec_(MercuryMJ2000Eq)
Vector_Dec_(MoonFixed)
Vector_Dec_(MoonMJ2000Ec)
Vector_Dec_(MoonMJ2000Eq)
Vector_Dec_(NeptuneFixed)
Vector_Dec_(NeptuneMJ2000Ec)
Vector_Dec_(NeptuneMJ2000Eq)
(RxV)_Z_(MOEEc)
(RxV)_X_(EarthGSM)
(RxV)_Y_(EarthGSM)
(RxV)_Z_(EarthGSM)
EarthGSM_Velocity_X

EarthGSM_Position_Y
EarthGSM_Position_Z
Vector_Dec_(EarthGSE)
Vector_RA_(EarthGSE)
Vector_Dec_(PlutoFixed)
Vector_Dec_(PlutoMJ2000Ec)
Vector_Dec_(PlutoMJ2000Eq)
Vector_Dec_(SaturnFixed)
Vector_Dec_(SaturnMJ2000Ec)
Vector_Dec_(SaturnMJ2000Eq)
Vector_Dec_(TODEc)
Vector_Dec_(TODEq)
Vector_Dec_(TOEEc)
Vector_Dec_(TOEEq)
Vector_Dec_(UranusFixed)
Vector_Dec_(UranusMJ2000Ec)
Vector_Dec_(UranusMJ2000Eq)
Vector_Dec_(VenusFixed)
Vector_Dec_(VenusMJ2000Ec)
Vector_Dec_(VenusMJ2000Eq)
Vector_RA_(Fixed)
Vector_RA_(MJ2000Ec)
Vector_RA_(MODEc)
Vector_RA_(MODEq)
Vector_RA_(MOEEc)
Vector_RA_(MOEEq)
Vector_RA_(MarsFixed)
Vector_RA_(MarsMJ2000Ec)
Vector_RA_(MarsMJ2000Eq)
Vector_RA_(MercuryFixed)
Vector_RA_(MercuryMJ2000Ec)
Vector_RA_(MercuryMJ2000Eq)
Vector_RA_(MoonFixed)
Vector_RA_(MoonMJ2000Ec)
Vector_RA_(MoonMJ2000Eq)
Vector_RA_(NeptuneFixed)
Vector_RA_(NeptuneMJ2000Ec)
Vector_RA_(NeptuneMJ2000Eq)
Vector_RA_(PlutoFixed)
Vector_RA_(PlutoMJ2000Ec)
Vector_RA_(PlutoMJ2000Eq)
Vector_RA_(SaturnFixed)
Vector_RA_(SaturnMJ2000Ec)
Vector_RA_(SaturnMJ2000Eq)
Vector_RA_(TODEc)
Vector_RA_(TODEq)
Vector_RA_(TOEEc)
Vector_RA_(TOEEq)
Vector_RA_(UranusFixed)
Vector_RA_(UranusMJ2000Ec)
Vector_RA_(UranusMJ2000Eq)
Vector_RA_(VenusFixed)
Vector_RA_(VenusMJ2000Ec)
Vector_RA_(VenusMJ2000Eq)
EarthGSM_Velocity_Y
EarthGSM_Velocity_Z
Vector_Dec_(EarthGSM)
Vector_RA_(EarthGSM)
(RxV)_X_(TODEc)
(RxV)_X_(TODEq)
(RxV)_X_(TOEEc)
(RxV)_X_(TOEEq)
(RxV)_X_(UranusFixed)
(RxV)_X_(UranusMJ2000Ec)
(RxV)_X_(UranusMJ2000Eq)
(RxV)_X_(VenusFixed)
(RxV)_X_(VenusMJ2000Ec)
(RxV)_X_(VenusMJ2000Eq)
(RxV)_Y
(RxV)_Y_(Fixed)
(RxV)_Y_(MJ2000Ec)
(RxV)_Y_(MODEc)
(RxV)_Y_(MODEq)
(RxV)_Y_(MOEEc)
(RxV)_Y_(MOEEq)
(RxV)_Y_(MarsFixed)
(RxV)_Y_(MarsMJ2000Ec)
(RxV)_Y_(MarsMJ2000Eq)
(RxV)_Y_(MercuryFixed)
(RxV)_Y_(MercuryMJ2000Ec)
(RxV)_Y_(MercuryMJ2000Eq)
(RxV)_Y_(MoonFixed)
(RxV)_Y_(MoonMJ2000Ec)
(RxV)_Y_(MoonMJ2000Eq)
(RxV)_Y_(NeptuneFixed)
(RxV)_Y_(NeptuneMJ2000Ec)
(RxV)_Y_(NeptuneMJ2000Eq)
(RxV)_Y_(PlutoFixed)
(RxV)_Y_(PlutoMJ2000Ec)
(RxV)_Y_(PlutoMJ2000Eq)
(RxV)_Y_(SaturnFixed)
(RxV)_Y_(SaturnMJ2000Ec)
(RxV)_Y_(SaturnMJ2000Eq)
(RxV)_Y_(TODEc)
(RxV)_Y_(TODEq)
(RxV)_Y_(TOEEc)
(RxV)_Y_(TOEEq)
(RxV)_Y_(UranusMJ2000Ec)
(RxV)_Y_(UranusMJ2000Eq)
(RxV)_Y_(UranussFixed)
(RxV)_Y_(VenusFixed)
(RxV)_Y_(VenusMJ2000Ec)
(RxV)_Y_(VenusMJ2000Eq)
(RxV)_Z
(RxV)_Z_(Fixed)
(RxV)_Z_(MJ2000Ec)
(RxV)_Z_(MODEc)
(RxV)_Z_(MODEq)

### D.4.8 Coordinate Systems: Central Body Inertial Elements

Mars_Centered_Mean_J2000
Mercury_Centered_Mean_J2000
Moon_Centered_Mean_J2000
Neptune_Centered_Mean_J2000
Pluto_Centered_Mean_J2000
Saturn_Centered_Mean_J2000
Uranus_Centered_Mean_J2000
Venus_Centered_Mean_J2000
Sune_Centered_MJ2000Ec
Mars_Centered_MJ2000Ec
Mercury_Centered_MJ2000Ec
Moon_Centered_MJ2000Ec
Neptune_Centered_MJ2000Ec
Pluto_Centered_MJ2000Ec
Saturn_Centered_MJ2000Ec
Uranus_Centered_MJ2000Ec
Venus_Centered_MJ2000Ec

### D.4.9 Propagators Elements

Moon_LP165P
CisLunar
EarthMoon_L2_AllPlanets
EarthMoon_L2_AllPlanets_and_SRP
EarthMoon_L2_ESM
EarthMoon_L2_ESM_JGM
EarthMoon_L2_ESM_LP165P
EarthSun_L2_AllPlanets
EarthSun_L2_AllPlanets_and_SRP
Earth_J2
Earth_Point_Mass
Heliocentric
Lunar
Mars_2-Body
Mars_AllPlanets
Mars_MARS50C
Mars_MARS50C_and_SRP
Mars_SRP
Mercury_2-Body
Mercury_AllPlanets
Mercury_SRP
Moon_2-Body
Moon_LP165P_and_SRP
Moon_SRP
Neptune_2-Body
Neptune_AllPlanets
Neptune_SRP
Pluto_2-Body
Pluto_AllPlanets
Pluto_SRP
Saturn_2-Body
Saturn_AllPlanets
Saturn_SRP
Sun_AllPlanets
Sun_AllPlanets_and_SRP
Uranus_2-Body
Uranus_AllPlanets
Uranus_SRP
Venus_2-Body
Venus_AllPlanets
Venus_MGNP180U
Venus_MGNP180U_and_SRP
Venus_SRP
Moon_AllPlanets

### D.4.10 Axes Elements

Earth_GSE Earth_GSM

### D.4.11 Coordinate System Elements

Earth_GSE Earth_GSM

### D.4.12 Vectors Elements

Cross_Product_(RxV)
Cross_Product_(RxV)_(fixed)
Cross_Product_(RxV)_(MarsFixed)
Cross_Product_(RxV)_(MarsMJ2000)
Cross_Product_(RxV)_(MarsMJ2000Ec)
Cross_Product_(RxV)_(MercuryFixed)
Cross_Product_(RxV)_(MercuryMJ2000)
Cross_Product_(RxV)_(MercuryMJ2000Ec)
Cross_Product_(RxV)_(MoonFixed)
Cross_Product_(RxV)_(MoonMJ2000)
Cross_Product_(RxV)_(MoonMJ2000Ec)
Cross_Product_(RxV)_(NeptuneFixed)
Cross_Product_(RxV)_(NeptuneMJ2000)
Cross_Product_(RxV)_(NeptuneMJ2000Ec)
Cross_Product_(YofGSM)
EarthSun_J2K_Velocity
DiPole_Vector_GSM
Cross_Product_(RxV)_(PlutoFixed)
Cross_Product_(RxV)_(PlutoMJ2000)
Cross_Product_(RxV)_(PlutoMJ2000Ec)
Cross_Product_(RxV)_(SaturnFixed)
Cross_Product_(RxV)_(SaturnMJ2000)
Cross_Product_(RxV)_(SaturnMJ2000Ec)
Cross_Product_(RxV)_(UranusFixed)
Cross_Product_(RxV)_(UranusMJ2000)
Cross_Product_(RxV)_(UranusMJ2000Ec)
Cross_Product_(RxV)_(VenusFixed)
Cross_Product_(RxV)_(VenusMJ2000)
Cross_Product_(RxV)_(VenusMJ2000Ec)
Cross_Product_(RxV)_(EarthGSE)
Cross_Product_(RxV)_(EarthGSM)
Cross_Product_(ZofGSE)
EarthSun_Vector

### D.4.13 Vectors: Vehicle Local Elements

Position_(MarsFixed)
Position_(MarsMJ2000Ec)
Position_(MercuryFixed)
Position_(MercuryMJ2000Ec)
Position_(MoonFixed)
Position_(MoonMJ2000Ec)
Position_(NeptuneFixed)
Position_(NeptuneMJ2000Ec)
Position_(PlutoFixed)
Position_(PlutoMJ2000Ec)
Position_(SaturnFixed)
Position_(SaturnMJ2000Ec)
Position_(UranusFixed)
Position_(UranusMJ2000Ec)
Position_(VenusFixed)
Position_(VenusMJ2000Ec)
Position_Mars_(MJ2000)
Position_Mercury_(MJ2000)
Position_Moon_(MJ2000)
Position_Neptune_(MJ2000)
Position_Saturn_(MJ2000)
Position_Uranus_(MJ2000)
Position_Venus_(MJ2000)
Position_(EarthGSE)
Position_(EarthGSM)
Velocity_(MarsFixed)
Velocity_(MarsMJ2000Ec)
Velocity_(MercuryFixed)
Velocity_(MercuryMJ2000Ec)
Velocity_(MoonFixed)
Velocity_(MoonMJ2000Ec)
Velocity_(NeptuneFixed)
Velocity_(NeptuneMJ2000Ec)
Velocity_(PlutoFixed)
Velocity_(PlutoMJ2000Ec)
Velocity_(SaturnFixed)
Velocity_(SaturnMJ2000Ec)
Velocity_(UranusFixed)
Velocity_(UranusMJ2000Ec)
Velocity_(VenusFixed)
Velocity_(VenusMJ2000Ec)
Velocity_Mars_(MJ2000)
Velocity_Mercury_(MJ2000)
Velocity_Moon_(MJ2000)
Velocity_Neptune_(MJ2000)
Velocity_Saturn_(MJ2000)
Velocity_Uranus_(MJ2000)
Velocity_Venus_(MJ2000)
Velocity_(EarthGSE)
Velocity_(EarthGSM)

## D.5 Report Styles

Classical_Orbit_Elements
Earth_MJ2000_Position_Velocity
GMAT_Apoapsis_Periapsis
GMAT_CSParameters_Fixed
GMAT_CSParameters_MJ2000Ec
GMAT_CSParameters_MJ2000Eq
GMAT_CSParameters_MODEc
GMAT_CSParameters_MODEq
GMAT_CbParameters
GMAT_CbParameters_Mars
GMAT_CSParameters_MOEEq
GMAT_CSParameters_MarsFixed
GMAT_CSParameters_Mars_MJ2000Ec
GMAT_CSParameters_Mars_MJ2000Eq
GMAT_CSParameters_MercuryFixed
GMAT_CSParameters_Mercury_MJ2000Ec
GMAT_CSParameters_Mercury_MJ2000Eq
GMAT_CSParameters_MoonFixed
GMAT_CSParameters_Moon_MJ2000Ec
GMAT_CSParameters_Moon_MJ2000Eq
GMAT_CSParameters_NeptuneFixed
GMAT_CSParameters_Neptune_MJ2000Ec
GMAT_CSParameters_Neptune_MJ2000Eq
Pluto_MJ2000_Position_Velocity
Saturn_MJ2000_Position_Velocity
Sun_MJ2000Ec_Position_Velocity
Sun_MJ2000_Position_Velocity
Uranus_MJ2000_Position_Velocity
Venus_MJ2000_Position_Velocity
Greenwich_Hour_Angle
GMAT_CSParameters_TODEq
GMAT_CSParameters_TOEEc
GMAT_CSParameters_TOEEq
GMAT_CSParameters_UranusFixed
GMAT_CSParameters_Uranus_MJ2000Ec
GMAT_CSParameters_Uranus_MJ2000Eq
GMAT_CSParameters_VenusFixed
GMAT_CSParameters_Venus_MJ2000Ec
GMAT_CSParameters_Venus_MJ2000Eq
GMAT_CSParameters_MOEEc
GMAT_CbParameters_Mercury
GMAT_CbParameters_Moon
GMAT_CbParameters_Neptune
GMAT_CbParameters_Pluto
GMAT_CbParameters_Saturn
GMAT_CbParameters_Uranus
GMAT_CbParameters_Venus
J2000_ECI_Position_Velocity
Mars_MJ2000_Position_Velocity
Mercury_MJ2000_Position_Velocity
Moon_MJ2000_Position_Velocity
Neptune_MJ2000_Position_Velocity
GMAT_CSParameters_PlutoFixed
GMAT_CSParameters_Pluto_MJ2000Ec
GMAT_CSParameters_Pluto_MJ2000Eq
GMAT_CSParameters_SaturnFixed
GMAT_CSParameters_Saturn_MJ2000Ec
GMAT_CSParameters_Saturn_MJ2000Eq
GMAT_CSParameters_TODEc

## D.6 Scripts Used

The main script used with STK is the STK_Repropagate.m Matlab script. STK_Repropagate.m connects to STK, propagates satellites in the scenario, generates reports, and outputs performance run times. The STK_Repropagate script was designed to reduce the time it took to generate STK report files, after modifications to the STK scenario were made, and obtain accurate STK run times.

Refer to Appendix C for more details of this script and others used in the Acceptance Test Plan document.

# Appendix E

# FF Setup

[INSERT explanation of how the FF scenarios were setup]

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