

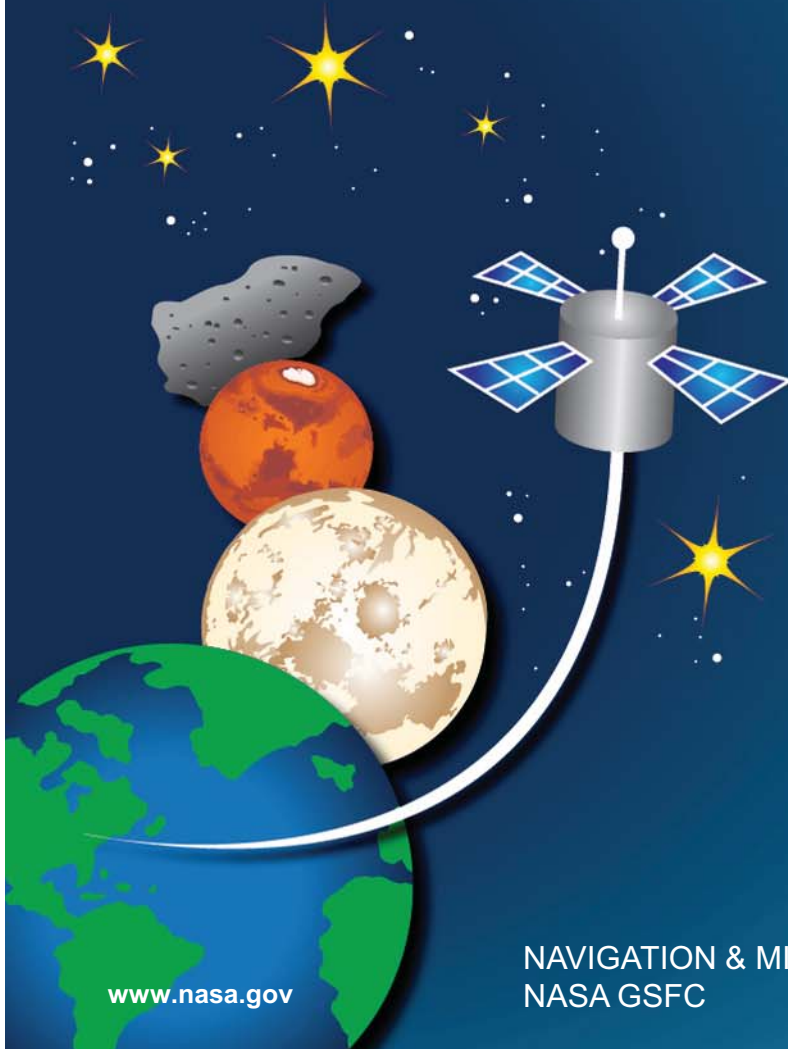
National Aeronautics and Space Administration



Preparing GMAT for Operational Maneuver Planning of the Advanced Composition Explorer (ACE)

2014 AIAA/AAS Astrodynamics Specialist Conference. San Diego, CA

Rizwan H. Qureshi and Steven P. Hughes



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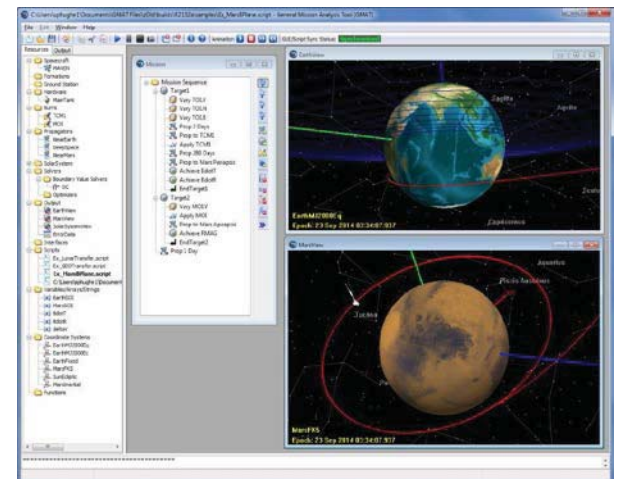
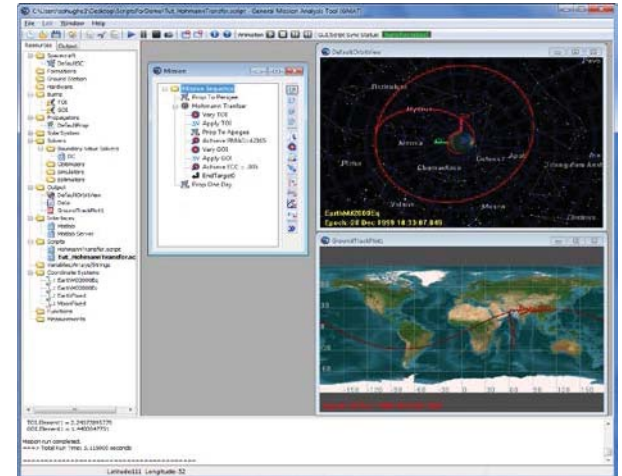
Outline

- GMAT Overview
- ACE Mission Overview
- Operational Certification Cycle
- ACE Operations Overview
- Results/Analysis
- Conclusions/Impact/Benefits



What is GMAT?

- GMAT is a mission design, analysis & trajectory optimization tool that is:
 - In-house
 - Open source
 - High fidelity
- GMAT R2013a
 - Released April, 2013
 - 6th public release
 - 1st major non-beta release
- GMAT R2013b
 - Released August, 2013
 - Certification candidate
 - Meets ACE requirements



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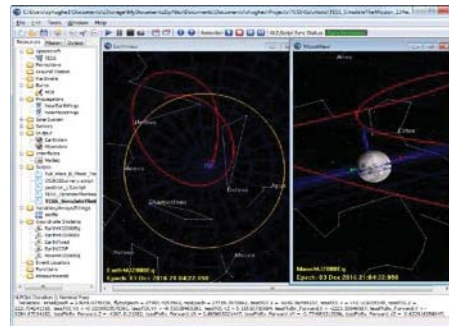
What is GMAT?... cont.

- **GMAT can support flight regimes ranging from:**

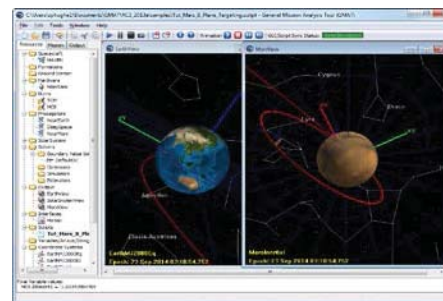
- LEO
- GEO
- HEO
- Libration
- Lunar
- Interplanetary & Deep space

- **GMAT has supported**

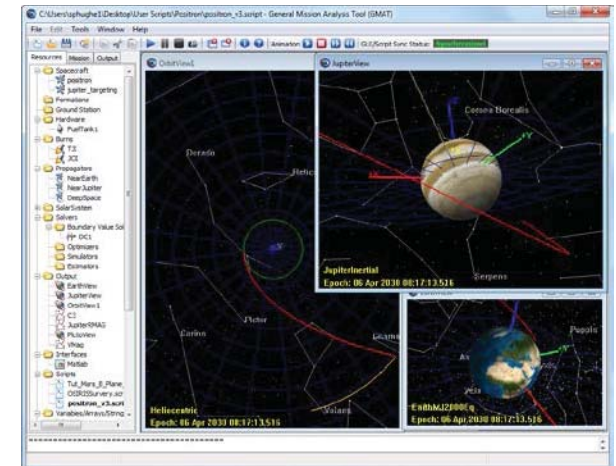
- LCROSS
- LRO
- ARTEMIS
- MAVEN
- OSIRIS
- TESS & more...



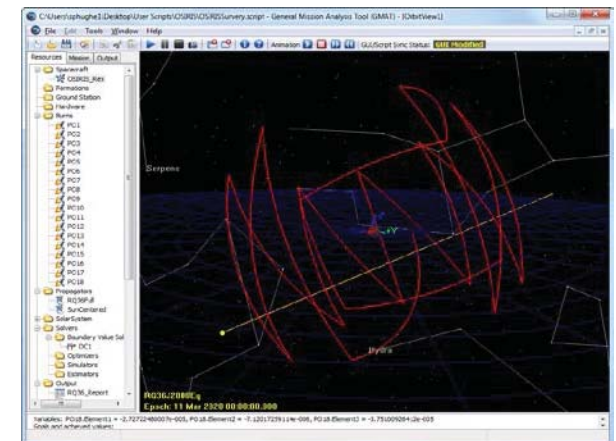
Optimal Lunar Flyby



Optimal Mars Trajectories



Outer Planet Transfers



Asteroid (RQ36) Survey

Download and find out more: gmatcentral.org

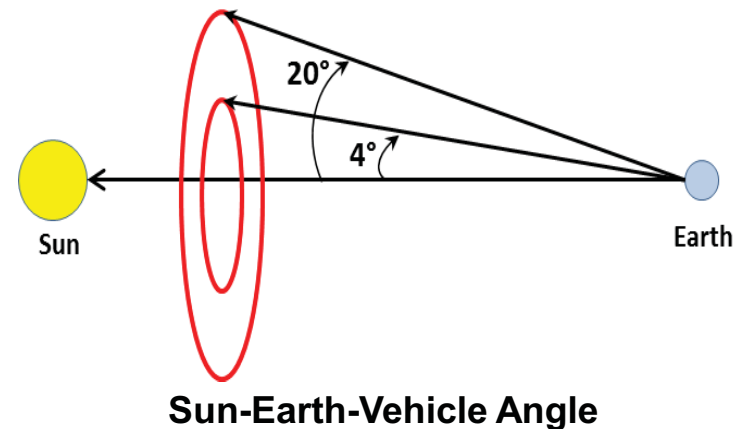
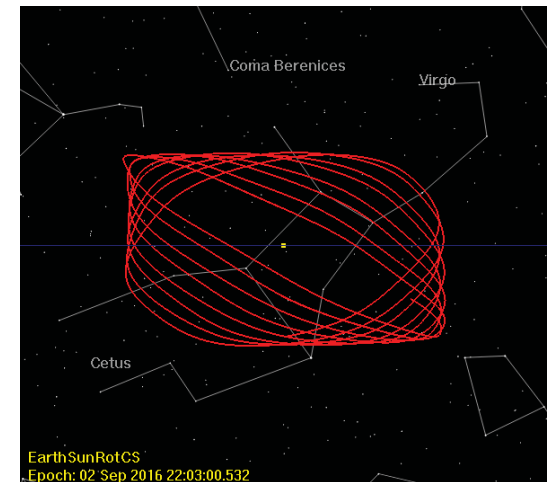
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ACE Mission Overview

- Sun-Earth L1 Orbiter (Lissajous orbit)
 - Spin stabilized & launched in August, 1997
 - Design amplitudes are:
 - $A_x = 81,755$ km
 - $A_y = 264,071$ km
 - $A_z = 157,406$ km
 - Sun-Earth-Vehicle (SEV) angle must be between 4° & 20° nominal
- Station-keeping maneuvers:
 - 2-3 months apart
 - Nominal delta-V's averaging 0.33 m/sec
- Attitude Maneuvers:
 - Performed weekly
 - Perturb ACE orbit

Lissajous orbit Viewed from Earth



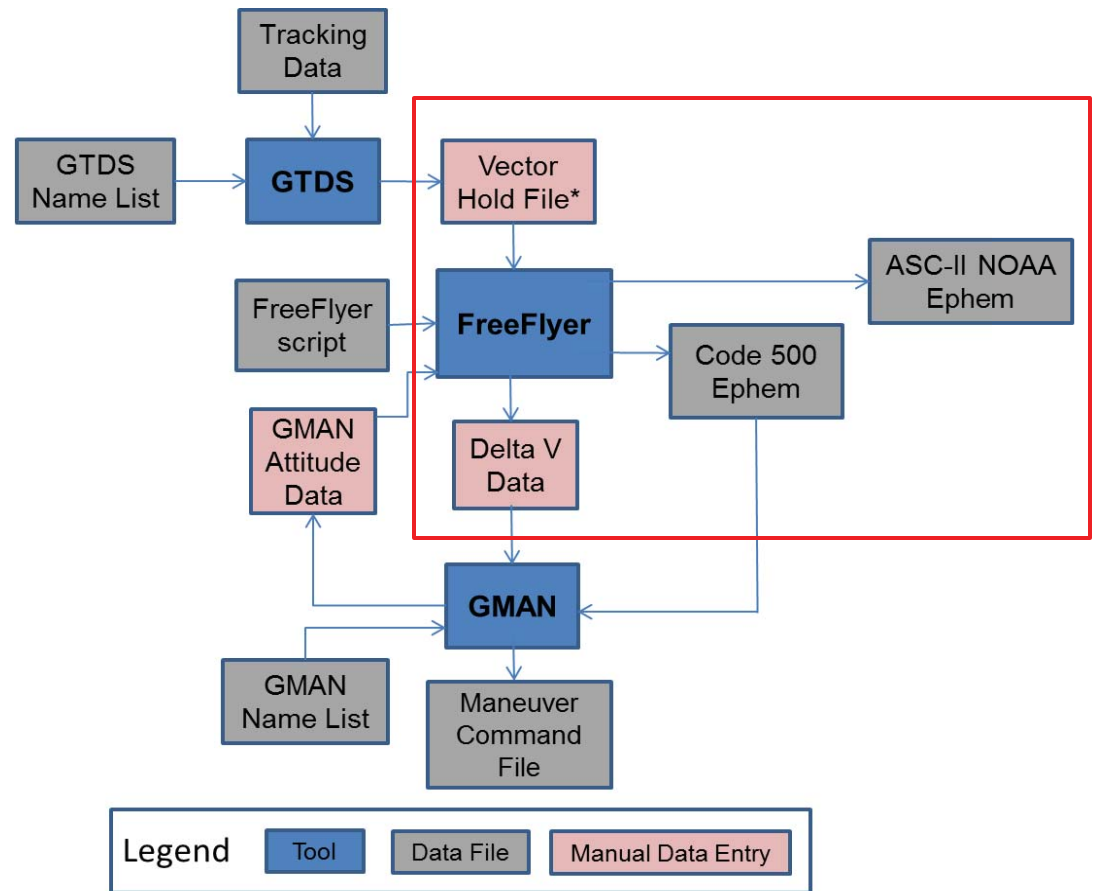
Flight Operational Certification Cycle

- Began on August 2012
- Milestones
 - Requirements gathering
 - Gaps analysis for ACE requirements
 - Development/Testing/Documentation of new ACE related features
 - Develop ACE maneuver planning/product generation scripts & validate output
 - Write/perform Operational Procedures & Test Plans documents
 - Provide training to ACE Maneuver Team
 - Test Readiness Review
 - Non-Interfering Shadow Ops
 - Operational Readiness Review



Current ACE Operations Overview

- OD performed via GTDS
- Impulsive targeting/trajectory propagation performed via FreeFlyer
- Initial targeting done in ACE Eng. Coord. sys. Final targeting done in Attitude coord. sys.
- Finite-burn modeling is performed using GMAN
- GMAN generates Maneuver Cmd. File
- FreeFlyer delivers 28 days long ephemeris to NOAA



*Some information is manually entered and some is read directly from file

We focused on tools/interfaces in red box

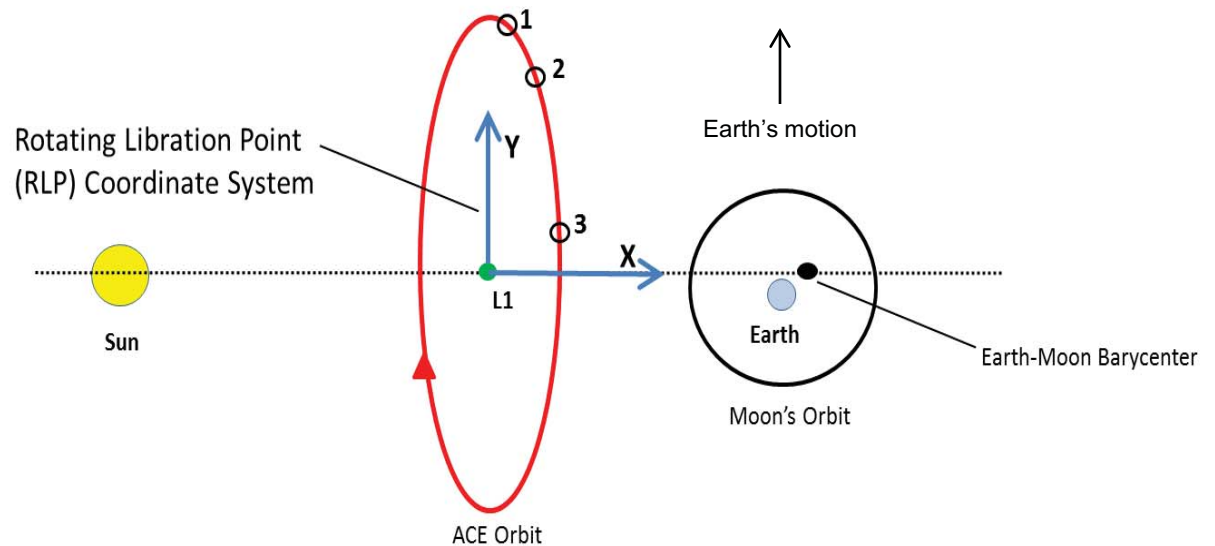


ACE Maneuver Targeting Strategy:

1. Get an updated OD state
2. Prop to attitude re-orientation epoch & apply perturbations due to att. maneuver
3. Next: Prop to maneuver epoch & enter Target Loop:

Target Loop:

Vary Z-component to Achieve RLP $V_x = 0$ @ RLP XZ plane crossing (i.e. When RLP $Y = 0$)



Requirements Gathering

- Requirements for ACE maneuver Ops gathered by working with maneuver planning team (97 requirements)
- Requirements had to be verifiable & unambiguous
- After 3.5 months of validation, final ACE Requirements approved
- ACE requirements areas:
 - Coordinate System
 - Force Model
 - Maneuver Targeting
 - Orbit Propagation
 - Product Output (SK dV, Code 500 & NOAA ephems & Maneuver summary report)
 - Spacecraft model

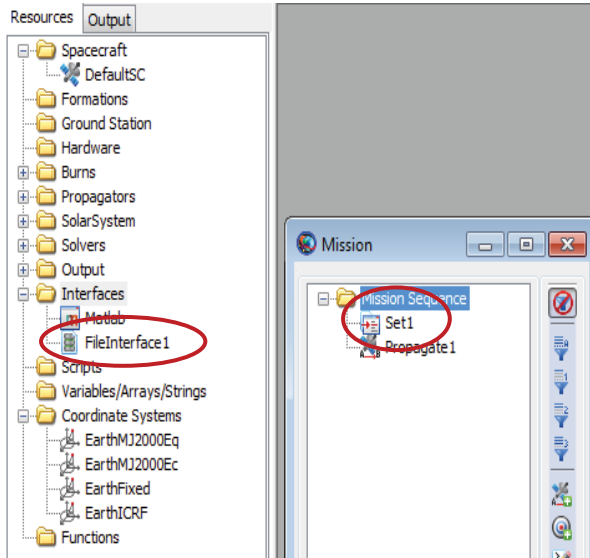


Gaps Analysis

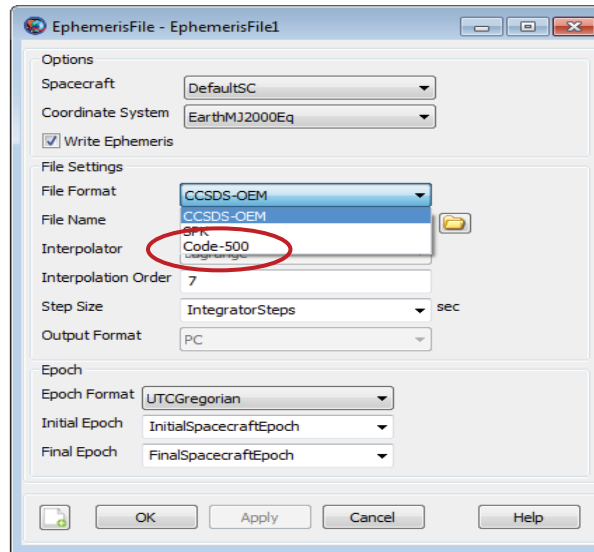
- Missing features:
 1. Parse through a vector hold file
 2. Write code-500 ephemeris file
 3. Develop new ACE Coordinate Sys. for maneuver targeting
 4. Report spacecraft acceleration
- 3 months of Development, Testing & Documentation efforts led to release of GMAT version R2013b (August, 2013)!
- R2013b is an internal release for Ops certification testing



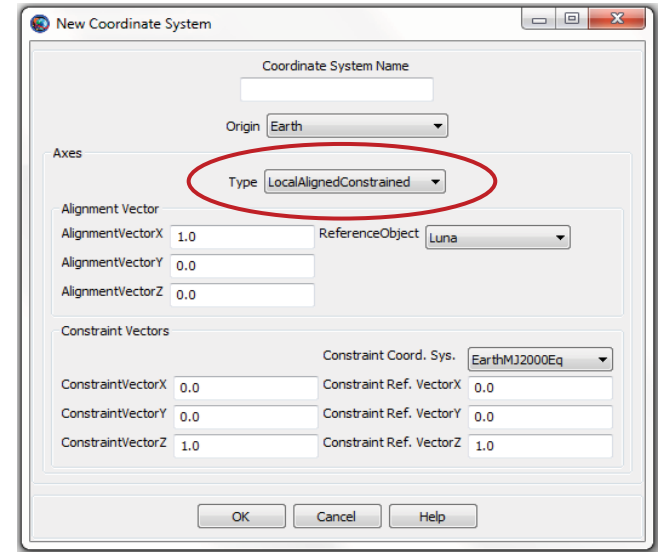
Gaps Analysis...Cont.



FileInterface resource and Set command



Code 500 ephemeris Format



LocalAlignedConstrained Coord. Axis Type

```
Spacecraft.ForceModel.Acceleration
Spacecraft.ForceModel.AccelerationX
Spacecraft.ForceModel.AccelerationY
Spacecraft.ForceModel.AccelerationZ
```

Pre-Shadow Operations

- There are two FreeFlyer scripts used for maneuver planning & product generation:
 - *ACE_impulsive_vec###.MissionPlan*
 - Generates weekly ΔV necessary to predict future SK maneuvers
 - Used for both initial and final impulsive ΔV targeting
 - *ACE_impulsive_NOAA28day_vec###.MissionPlan*
 - Generates 28 days long ephemeris delivered to NOAA
- GMAT scripts were written using similar design philosophy:
 - *ACE_impulsive_vec###.script*
 - *ACE_impulsive_NOAA28day_vec###.script*



Local Operating Procedures (LOP) Development

- ACE Maneuver team uses LOP document for End-to-End Ops support using FreeFlyer scripts
- Wrote detailed 45 page long LOP that instructs how to use GMAT scripts for ACE Ops:
 - Procedures for obtaining weekly ACE ΔV for Future Station-keeping Maneuver
 - Procedures for ACE Maneuver planning one week prior to the maneuver
 - Procedures for ACE Maneuver planning one day prior to maneuver
 - Procedures for final SK Maneuver planning (Post-Attitude Maneuver)
 - Procedures for generating NOAA 28-day Ephemeris
 - Procedures for delivering products via DataViewer
- Our LOP doc has been reviewed & approved by maneuver planning team



Test Plans Development

- Wrote test plans for 97 requirements sub-divided in 6 areas:
 - Coordinate System
 - Force Model
 - Maneuver Targeting
 - Orbit Propagation
 - Product Output
 - Spacecraft model
- Each test plan:
 - Has detailed test procedures to test & verify each requirement
 - References separate GMAT ACE scripts to test each requirement
- ACE team implemented test plans & GMAT passes all test plans & meets all requirements!



Requirements to Test Traceability

Test Plans for Maneuver Targeting area:

REQID	Object Text	Test Plans
MT01	The ground system must be capable of ingesting the state vector from the TCOPS Vector Hold Files without user input.	Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.
MT02	The ground system must be capable of ingesting the epoch from the TCOPS Vector Hold Files without user input.	Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.
MT03	The ground system must be capable of ingesting C_r from the TCOPS Vector Hold Files without user input.	Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.
MT04	The ground system shall use a user-input maneuver epoch for impulsive targeting.	Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.
MT05	The ground system shall support varying the delta-V along the spacecraft body Z-axis during differential correction of impulsive maneuver targeting.	Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.
MT06	Ground system shall propagate spacecraft to a user-specified number of XZ plane crossings in the Rotating Libration Point (RLP) frame during differential correction of impulsive maneuver targeting.	Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.
MT07	The differential corrector shall compute a delta-V vector which achieves an accuracy better than 0.00000 ± 0.000001 km/s along X component of the velocity in the RLP frame (e.g., the Earth-Sun line) on the fourth X-Z plane crossing.	Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.



Test Readiness Review (TRR)

- On 09/10/2013: Presented TRR to ACE Ops Team
- Verify environment & tools are ready for shadow operations
- GMAT passed TRR!



FDF Training

- Although GMAT ACE LOP document serves as training & instructions manual to support ACE Ops, extra hands-on training was provided
- On 09/16/2013, gave training to maneuver team & demonstrated how to use:
 - GMAT's *ACE_impulsive_vec###.script*
 - *ACE_impulsive_NOAA28day_vec###.script*
- Maneuver team now fully trained to use GMAT ACE maneuver planning & product generation scripts



Results/Analysis

- Delta-V comparisons
- Propagation comparisons
- Shadow Ops
- Operational Readiness Review



ΔV Comparisons

- SK ΔV validated against FreeFlyer using historical OD solutions

ΔV diff. (perturbations from attitude re-orientation maneuver **not** modeled):

TVHF file	Maneuver Epoch [UTCG]	GMAT SK ΔV [cm/sec]	ΔV diff. [mm/sec]
Vec424.txt	15 Jan 2013 17:30:00.000	15.01	0.024
Vec433.txt	15 Apr 2013 16:00:00.000	22.75	0.017
Vec440.txt	19 Mar 2013 16:00:00.000	12.53	0.018
Vec456.txt	25 Jun 2013 19:15:00.000	27.98	0.016

ΔV difference must be < 0.05 mm/sec



ΔV Comparisons...Cont.

ΔV diff. (perturbations from attitude maneuver modeled):

TVHF file	Att. Re-orientation Epoch [UTCG]	Maneuver Epoch [UTCG]	GMAT SK ΔV [cm/sec]	ΔV diff. [mm/sec]
Vec420	19 Nov 2012 15:59:50.000	19 Nov 2012 17:30:00.000	29.65	0.021
Vec430	15 Jan 2013 16:03:08.000	15 Jan 2013 17:30:00.000	19.97	0.015
Vec450	02 Apr 2013 17:49:36.899	02 Apr 2013 19:15:00.000	19.47	0.018
Vec472	09 Jul 2013 16:42:37.000	09 Jul 2013 17:40:00.000	15.30	0.012

ΔV difference must be < 0.05 mm/sec



Propagation Comparisons

- Propagation compares using OD solutions from 4 TVHF files

Short & Long term propagation comparison between GMAT & FreeFlyer:

TVHF file used	RSS position error after 28 days in EarthMJ2000Eq [mm]	RSS position error after 180 days in EarthMJ2000Eq [meters]
Vec433.txt	0.50	2.72
Vec440.txt	2.9	3.04
Vec450.txt	6.1	2.62
Vec456.txt	1.6	4.73

RSS pos. error (28 Days) must be < 10 mm

RSS pos. error (180 Days) must be < 5 meters



Non-Interfering Shadow Ops

- On 09/23/2013, ACE maneuver team used GMAT & performed shadow operations during ACE SK maneuver:
 - Delivery products from GMAT verified against FreeFlyer

ΔV diff. (perturbations from attitude re-orientation maneuver modeled):

TVHF file used	Initial State Epoch [UTCG]	ΔV diff. [mm/sec]	RSS position error after 28 days in EarthMJ2000Eq [mm]
Vec493.txt	23 Sep 2013 00:00:00.000	0.015	1.83

ΔV difference must be < 0.05 mm/s

RSS pos. error (28 Days) must be < 10 mm



Operational Readiness Review (ORR)

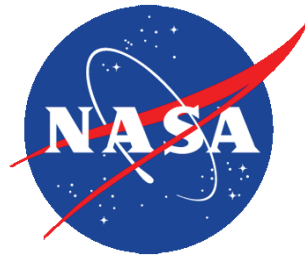
- On 11/19/2013: Presented ORR to ACE Maneuver Team
- Presented results from shadow Ops & test plans:
 - GMAT meets all requirements & passes all tests for ACE Maneuver Planning
- GMAT was deemed Flight Certified to support operational maneuver planning for ACE!



Conclusions/Impact/Benefits

- Demonstrated GMAT is flight quality software & is now Ops certified for ACE
- Laid groundwork for broad adoption of GMAT as an Ops tool for other GSFC missions
- Goddard's GMAT R2013b and recently R2014a:
 - Robust trajectory optimization tool available to all!
 - Provided a tool that Goddard controls to meet its unique and strategic needs
 - Provided a system for development of new mission design and nav. technology
 - In-house tool that complements other tools like FreeFlyer and STK





Backup Slides



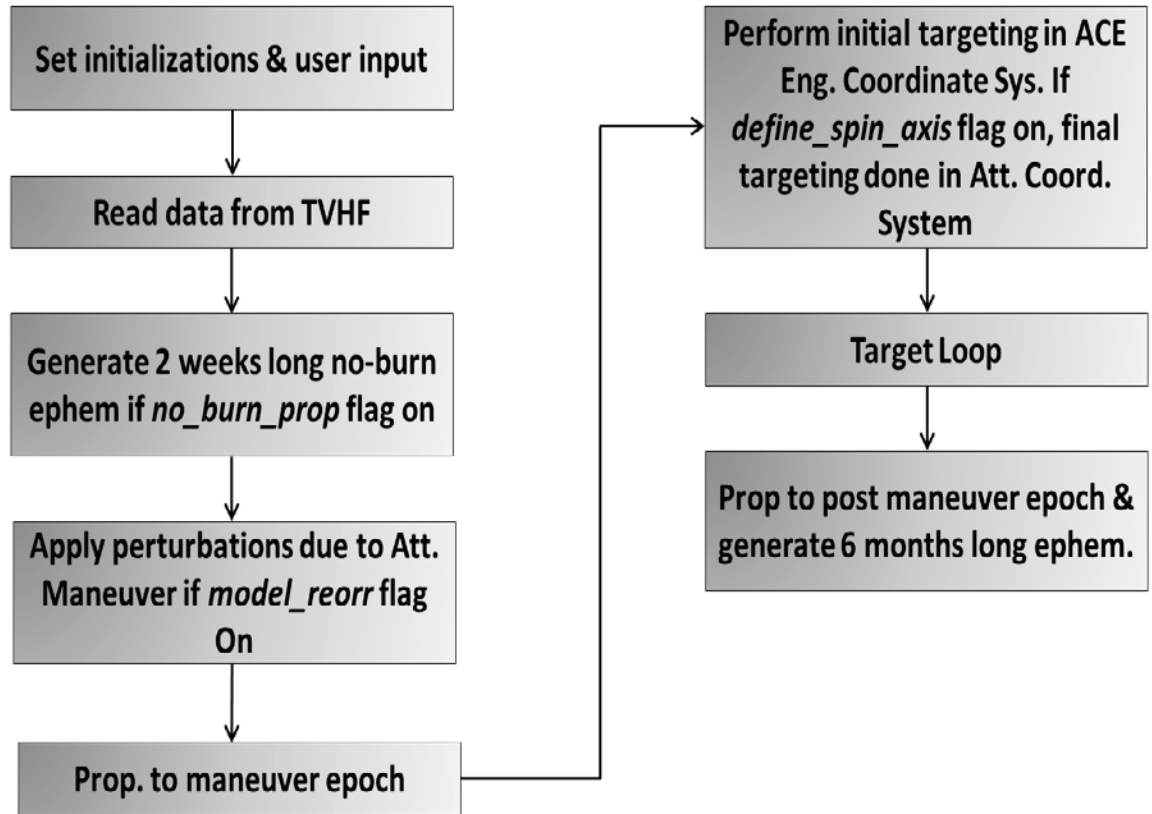
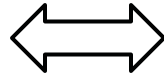
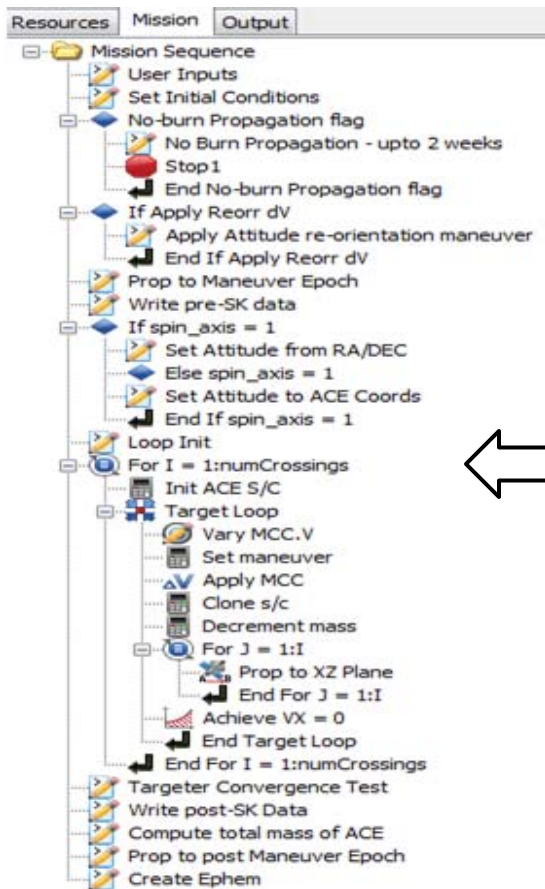
Software Development History/Status

- Requirements Gathering, 2001
- Architectural design, 2002
- Implementation of System Core, 2003
- First Beta Release, 2007
- Second Beta Release, 2008
- Decision to use as Primary Operational Software, 2010
- R2011a Release, 2011
- R2012a Release, 2012
- R2013a Release, April 2013 (Production Release)
- R2013b Release, Aug 2013 (Ready for Ops Testing)
- Sep. 2013: NPR/GPR 7150.2 compliant
- R2014a Release, May 2014



Pre-Shadow Ops...Cont.

Basic Design methodology for GMAT's *ACE_impulsive_vec###.script* :



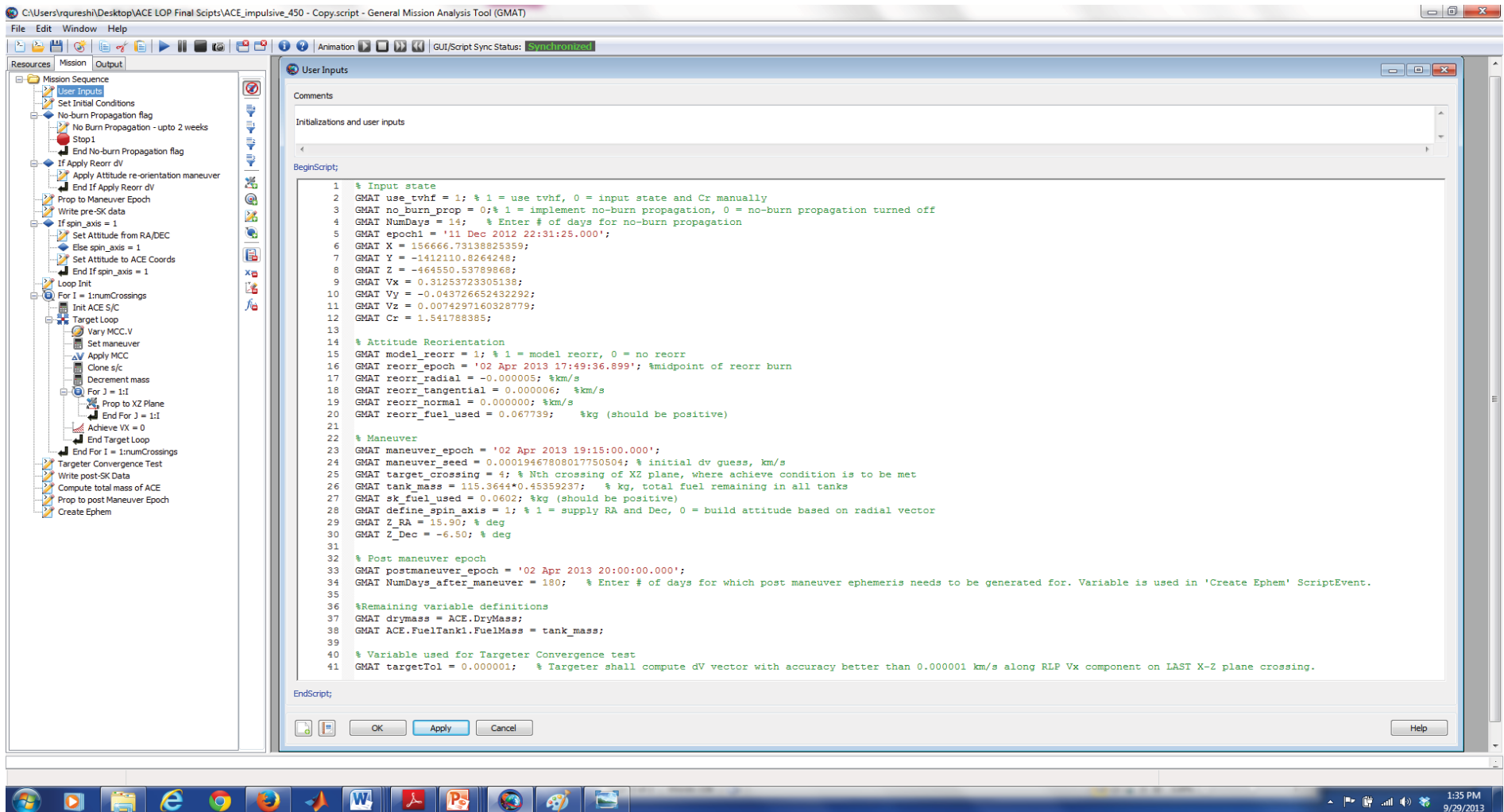
ACE Station-keeping & Attitude Maneuver Context

- **Initial** Maneuver targeting is performed in *ACE Engineering CS* defined as follows:
 - Z-axis: Defined by Earth center to ACE radial vector
 - X-axis: up orthogonal to z-axis, in plane formed by z-axis & North Ecliptic Pole (NEP)
 - Y-axis: Z cross X
- **Final** maneuver targeting is performed using *Spin-axis Attitude CS* once spin axis attitude is known prior to maneuver
 - Z-axis: Defined by spin-axis attitude expressed in mean J2000 RA/DEC
 - X-axis: Up orthogonal to z-axis, in plane formed by z-axis & NEP
 - Y-axis: Z cross X
- Weekly spin-axis attitude re-orientation maneuvers perturb ACE orbit & perturbations modeled using Local Vertical Local Horizontal (LVLH) CS



GMAT ACE_impulsive_vec###.script

“User Inputs” ScriptEvent



The screenshot displays the GMAT (General Mission Analysis Tool) interface. The main window shows a mission sequence tree on the left and a 'User Inputs' dialog box on the right. The dialog box contains a script with the following content:

```
BeginScript;
1 % Input state
2 GMAT use_tvhf = 1; % 1 = use tvhf, 0 = input state and Cr manually
3 GMAT no_burn_prop = 0; % 1 = implement no-burn propagation, 0 = no-burn propagation turned off
4 GMAT NumDays = 14; % Enter # of days for no-burn propagation
5 GMAT epoch1 = '11 Dec 2012 22:31:25.000';
6 GMAT X = 156666.73138825359;
7 GMAT Y = -1412110.82642469;
8 GMAT Z = -464550.53789866;
9 GMAT Vx = 0.31253723305138;
10 GMAT Vy = -0.043726652432292;
11 GMAT Vz = 0.0074297160328779;
12 GMAT Cr = 1.541788385;
13
14 % Attitude Reorientation
15 GMAT model_reorr = 1; % 1 = model reorr, 0 = no reorr
16 GMAT reorr_epoch = '02 Apr 2013 17:49:36.899'; %midpoint of reorr burn
17 GMAT reorr_radial = -0.0000005; %km/s
18 GMAT reorr_tangential = 0.0000006; %km/s
19 GMAT reorr_normal = 0.0000000; %km/s
20 GMAT reorr_fuel_used = 0.067739; %kg (should be positive)
21
22 % Maneuver
23 GMAT maneuver_epoch = '02 Apr 2013 19:15:00.000';
24 GMAT maneuver_seed = 0.00019467808017750504; % initial dv guess, km/s
25 GMAT target_crossing = 4; % Nth crossing of XZ plane, where achieve condition is to be met
26 GMAT tank_mass = 115.3644+0.45359237; % kg, total fuel remaining in all tanks
27 GMAT sk_fuel_used = 0.0602; %kg (should be positive)
28 GMAT define_spin_axis = 1; % 1 = supply RA and Dec, 0 = build attitude based on radial vector
29 GMAT Z_RA = 15.90; % deg
30 GMAT Z_Dec = -6.50; % deg
31
32 % Post maneuver epoch
33 GMAT postmaneuver_epoch = '02 Apr 2013 20:00:00.000';
34 GMAT NumDays_after_maneuver = 180; % Enter # of days for which post maneuver ephemeris needs to be generated for. Variable is used in 'Create Ephem' ScriptEvent.
35
36 %Remaining variable definitions
37 GMAT drymass = ACE.DryMass;
38 GMAT ACE.FuelTank1.FuelMass = tank_mass;
39
40 % Variable used for Targeter Convergence test
41 GMAT targetTol = 0.000001; % Targeter shall compute dv vector with accuracy better than 0.000001 km/s along RLP Vx component on LAST X-Z plane crossing.
EndScript;
```

GMAT Development Team
NASA GSFC



GMAT ACE Graphics

The screenshot displays the GMAT (General Mission Analysis Tool) interface. On the left is a mission sequence tree with steps like 'User Inputs', 'Set Initial Conditions', 'No Burn Propagation flag', 'Apply Attitude re-orientation maneuver', and 'Target Loop'. The main area contains four windows:

- EarthSunView:** A 3D star chart showing the Earth-Sun system with a red elliptical orbit. Constellations like Aries, Cetus, and Sculptor are visible. Epoch: 29 Sep 2013 20:00:00.000.
- EarthSunMoonView:** A 3D star chart showing the Earth-Sun-Moon system with a red elliptical orbit. Constellations like Caelum, Dorado, Reticulum, and Hydra are visible. Epoch: 29 Sep 2013 20:00:00.000.
- (dummySK.EarthSunMoonL1.V) vs (dummySK.EarthSunMoonL1.X):** A 2D plot of a red elliptical orbit. The y-axis ranges from -66000 to 66000, and the x-axis ranges from -251700 to 251700.
- (ACE.EarthSunMoonL1.V) vs (ACE.EarthSunMoonL1.X):** A 2D plot of a red elliptical orbit. The y-axis ranges from -52100 to 156300, and the x-axis ranges from -253200 to 253200.

The Windows taskbar at the bottom shows the system time as 1:08 PM on 9/29/2013.



GMAT ACE SK Maneuver Report

C:\Users\rqureshi\Desktop\ACE LOP Final Scripts\ACE_impulsive_450 - Copy.script - General Mission Analysis Tool (GMAT)

File Edit Window Help

Resources Mission Output

Reports

- rf
- skSummaryReport
- GMATphem
- ephem_GMAT_rb
- Ephemeris Files
- Orbit Views
- Ground Track Plots
- XY Plots

skSummaryReport

Reflectivity Coefficient read from IVHF: 1.5996296059131
Reflectivity Coefficient used for propagation: 1.613825474160093

State at SK Start

UTC Gregorian Epoch: 02 Apr 2013 19:15:00.000
L1 RLP Cartesian Position (km): 75325.2894203194 162875.8579983951 -135509.0684167426
L1 RLP Cartesian Velocity (km/s): 0.01670409463669048 -0.08418566133987783 0.01990107660935109
J2000 Cartesian Position (km): 1422692.838225372 198032.1339932948 -61500.77445109771
J2000 Cartesian Velocity (km/s): -0.04986075481545912 0.3259013584757251 0.1637968821020105
Greenwich Hour Angle (deg): 120.0422745661344
Magnitude of Radius Vector (km, Earth to ACE): 1437725.280882891
Magnitude of Velocity Vector (km/s, Relative to Earth): 0.3681402027943027
Sun-Earth-Vehicle Angle (deg): 8.604984962687371
RA and Dec of Position Vector in MJ2000 (deg): 7.924384911109343 -2.451657755050181
RA and Dec of Velocity Vector in MJ2000 (deg): 98.69842629415713 26.41890574846829
RA and Dec of Sun in MJ2000 (deg): 11.9770346115672 5.140744757780059

Impulsive SK Delta-v Components

Converged Delta-v (km/s): 0.0001946658900669525
Delta-v in MJ2000 (km/s): 0.0001860147622477548 5.298769890059078e-05 -2.203680436656905e-05
RA and Dec of Delta-v in MJ2000 (deg): 15.9 -6.499999999999999
Delta-v Radial Component (km/s): 0.000192311021691109
Angle between Delta-v and Radius Vector (deg): 8.921025841485331

PostBurn State

UTC Gregorian Epoch: 02 Apr 2013 20:00:00.000
J2000 Cartesian Position (km): 1422558.395401776 198912.3329896521 -61058.44446787286
J2000 Cartesian Velocity (km/s): -0.04991266694722112 0.326044856533996 0.1638769598506418
L1 RLP Cartesian Position (km): 75369.83457376427 162648.460063103 -135455.3598948916
L1 RLP Cartesian Velocity (km/s): 0.01648252495705635 -0.08426029708888595 0.01992432856722263
Greenwich Hour Angle (deg): 131.3230758766667
Magnitude of Radius Vector (km, Earth to ACE): 1437694.904416197
Magnitude of Velocity Vector (km/s, Relative to Earth): 0.3683098977273719
Sun-Earth-Vehicle Angle (deg): 8.59613126995845
RA and Dec of Position Vector in MJ2000 (deg): 7.959898817899592 -2.434065582920411
RA and Dec of Velocity Vector in MJ2000 (deg): 98.70357030611524 26.41970049665214
RA and Dec of Sun in MJ2000 (deg): 12.00553056985123 5.152732275125121

Close Help

1:18 PM 9/29/2013



Pre-Shadow Ops...Cont.

Basic Design methodology for GMAT's *ACE_impulsive_NOAA28day_vec###.script* :

