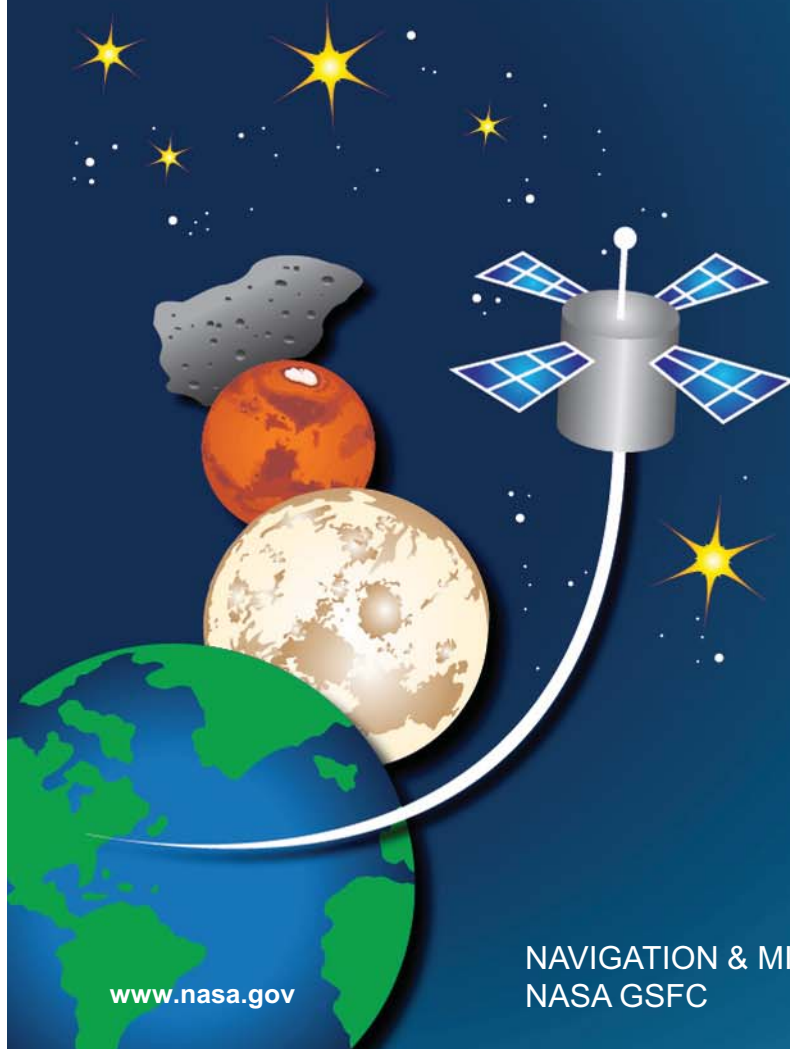


National Aeronautics and Space Administration

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

NAVIGATION & MISSION DESIGN BRANCH Code 543.2
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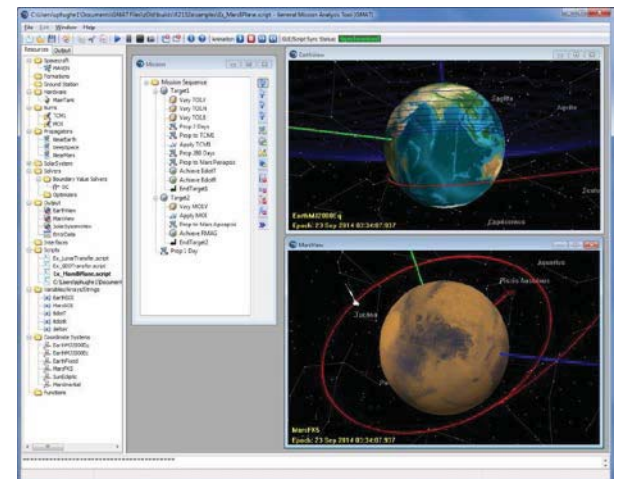
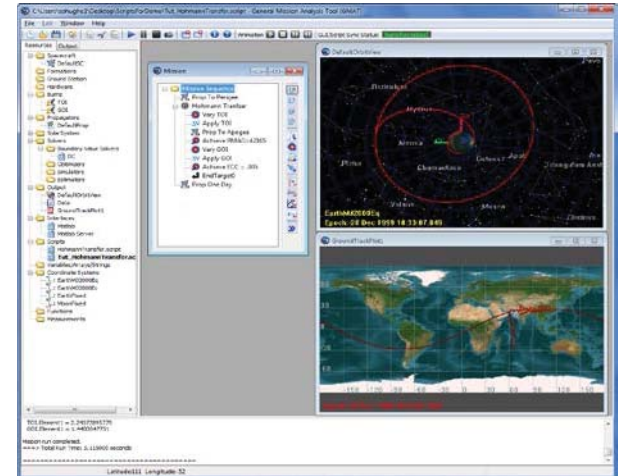
Outline

- 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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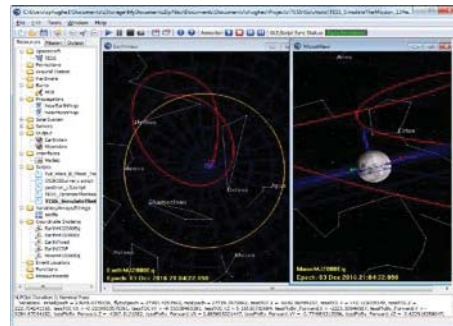
What is GMAT?... cont.

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

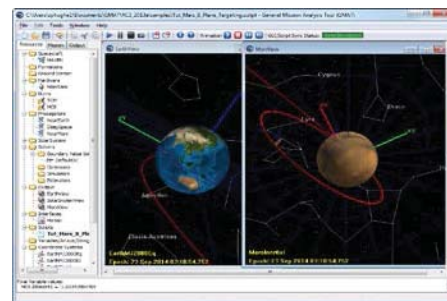
- LEO
- GEO
- HEO
- Libration
- Lunar
- Interplanetary & Deep space

- **GMAT has supported**

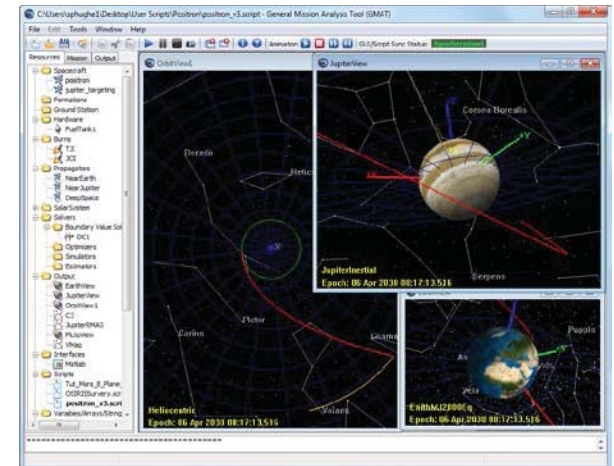
- LCROSS
- LRO
- ARTEMIS
- MAVEN
- OSIRIS
- TESS & more...



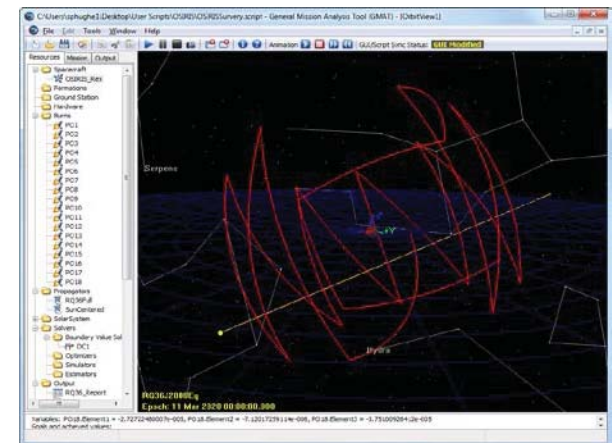
Optimal Lunar Flyby



Optimal Mars Trajectories



Outer Planet Transfers



Asteroid (RQ36) Survey

Download and find out more: gmatcentral.org

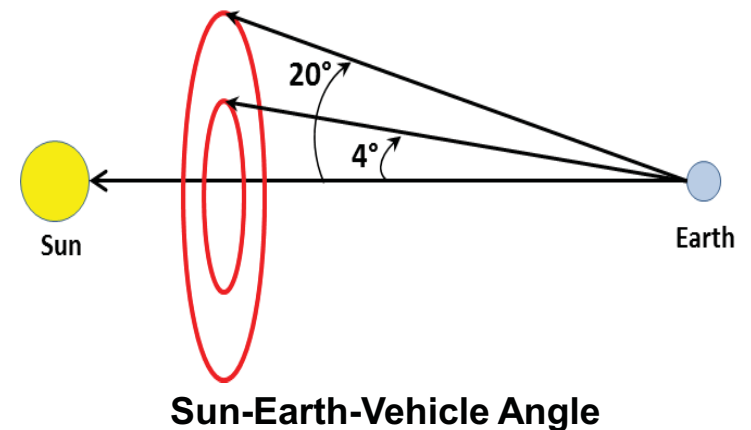
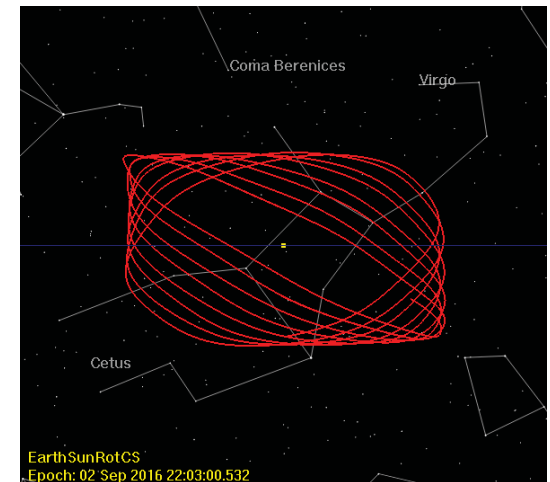
GMAT Development Team
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ACE Mission Overview

- 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



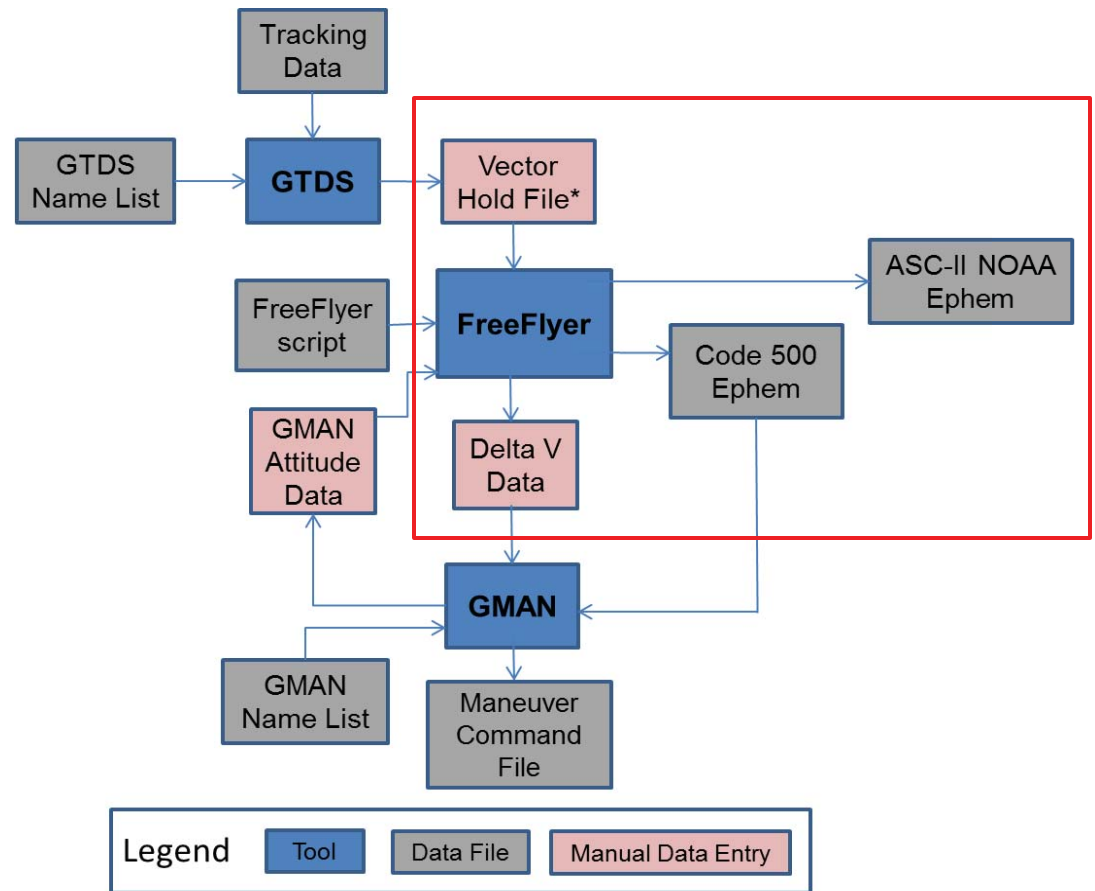
Flight Operational Certification Cycle

- 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

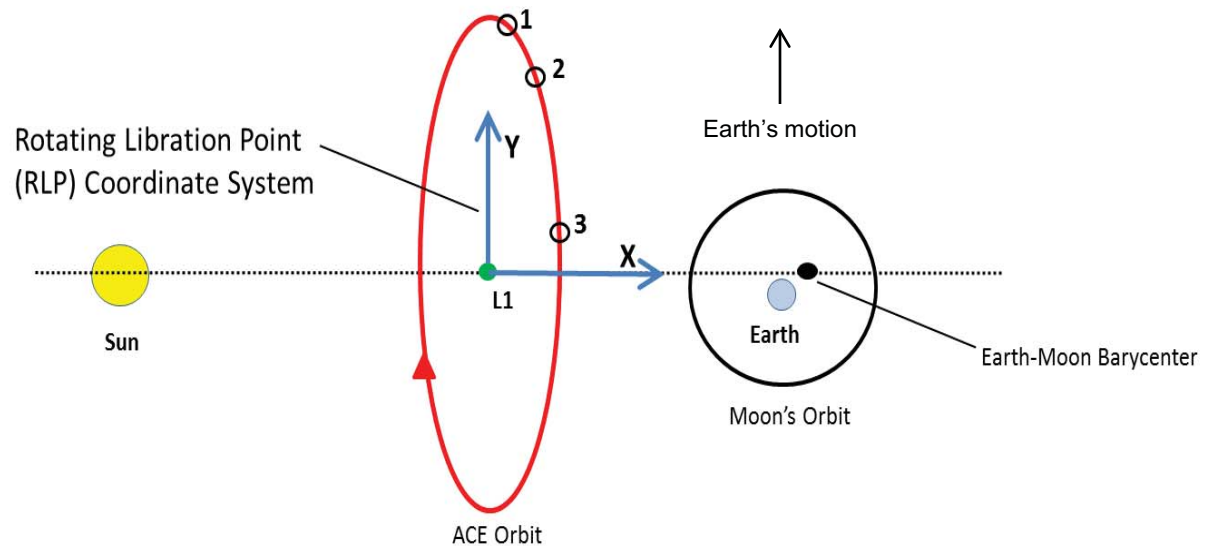


ACE Maneuver Targeting Strategy:

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

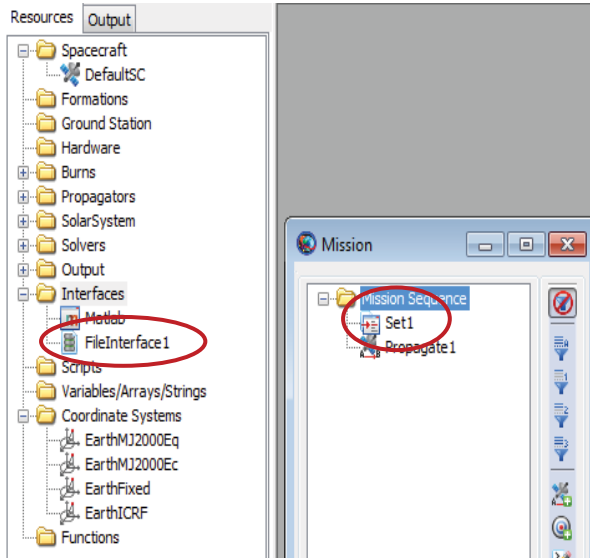


Gaps Analysis

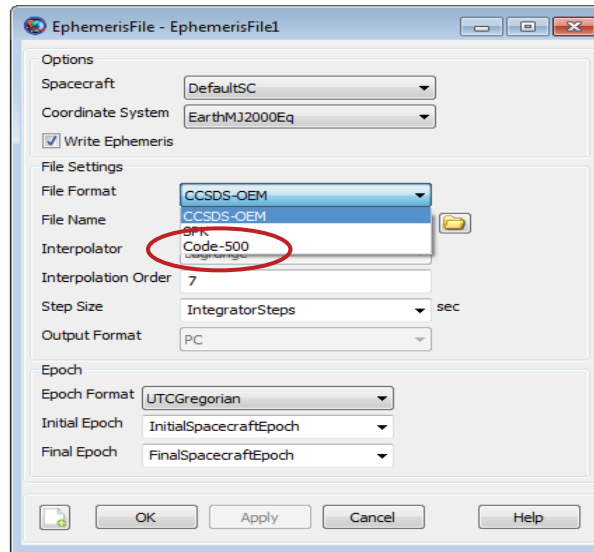
- Missing features:
 1. Parse through a vector hold file
 2. Write code-500 ephemeris file
 3. Develop new ACE Coordinate Sys. for maneuver targeting
 4. Report spacecraft acceleration
- 3 months of Development, Testing & Documentation efforts led to release of GMAT version R2013b (August, 2013)!
- R2013b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



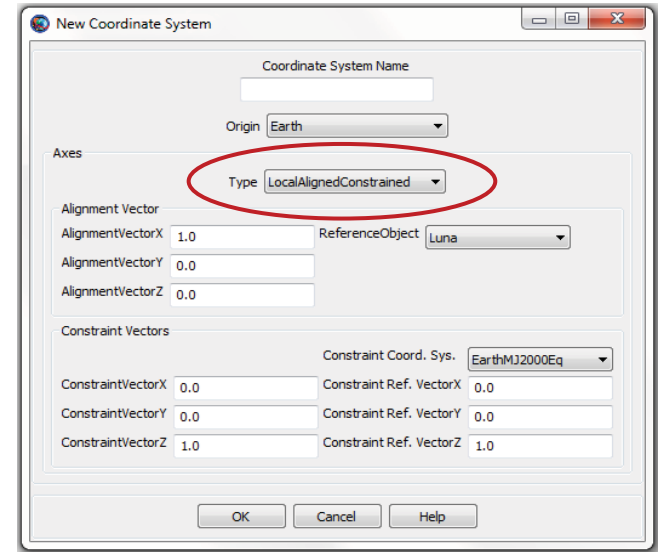
Gaps Analysis...Cont.



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)

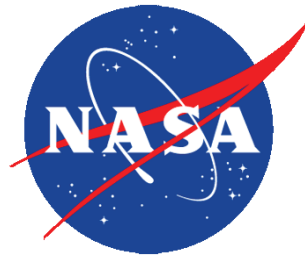
- On 11/19/2013: Presented ORR to ACE Maneuver Team
- Presented results from shadow Ops & test plans:
 - GMAT meets all requirements & passes all tests for ACE Maneuver Planning
- GMAT was deemed Flight Certified to support operational maneuver planning for ACE!



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



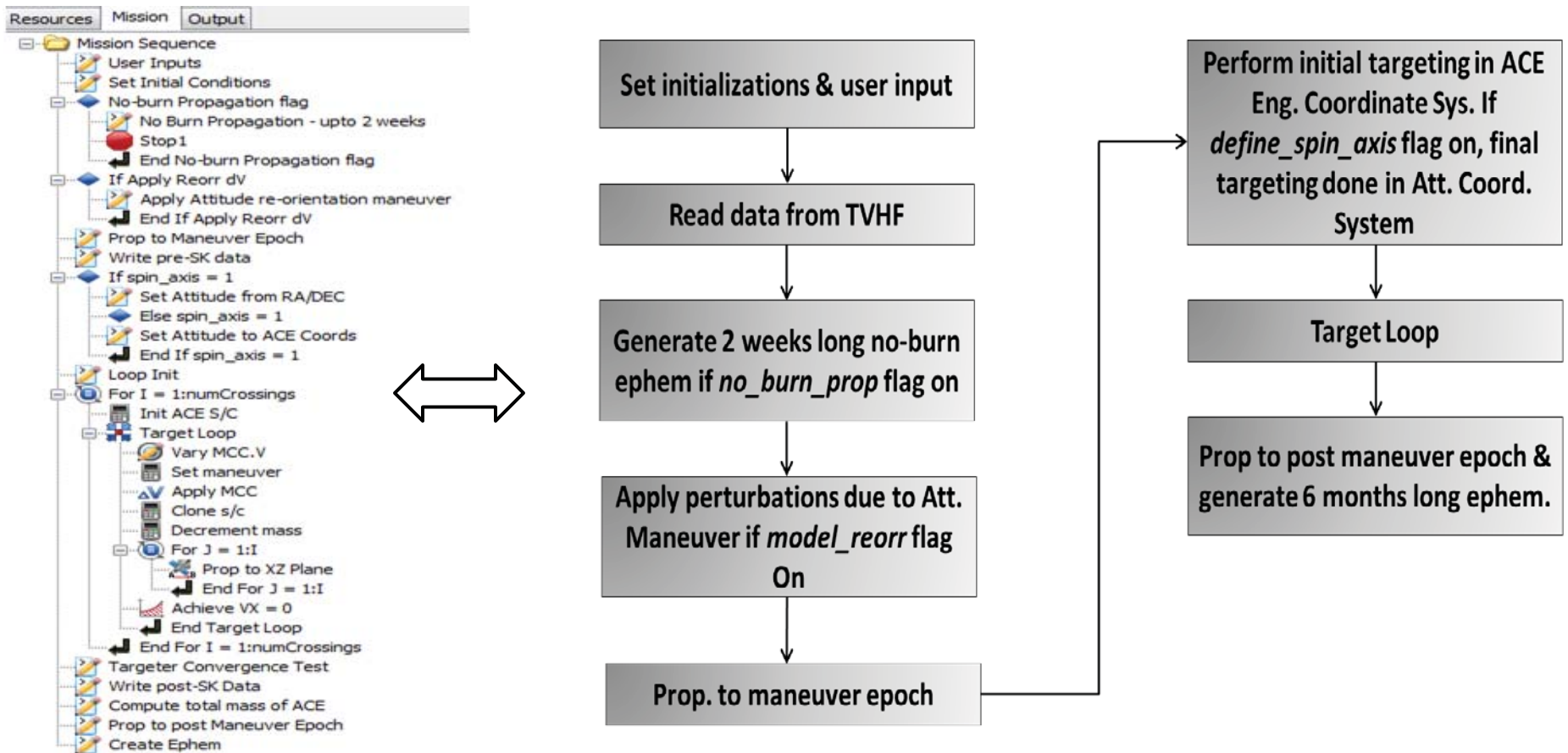
Software Development History/Status

- 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* :



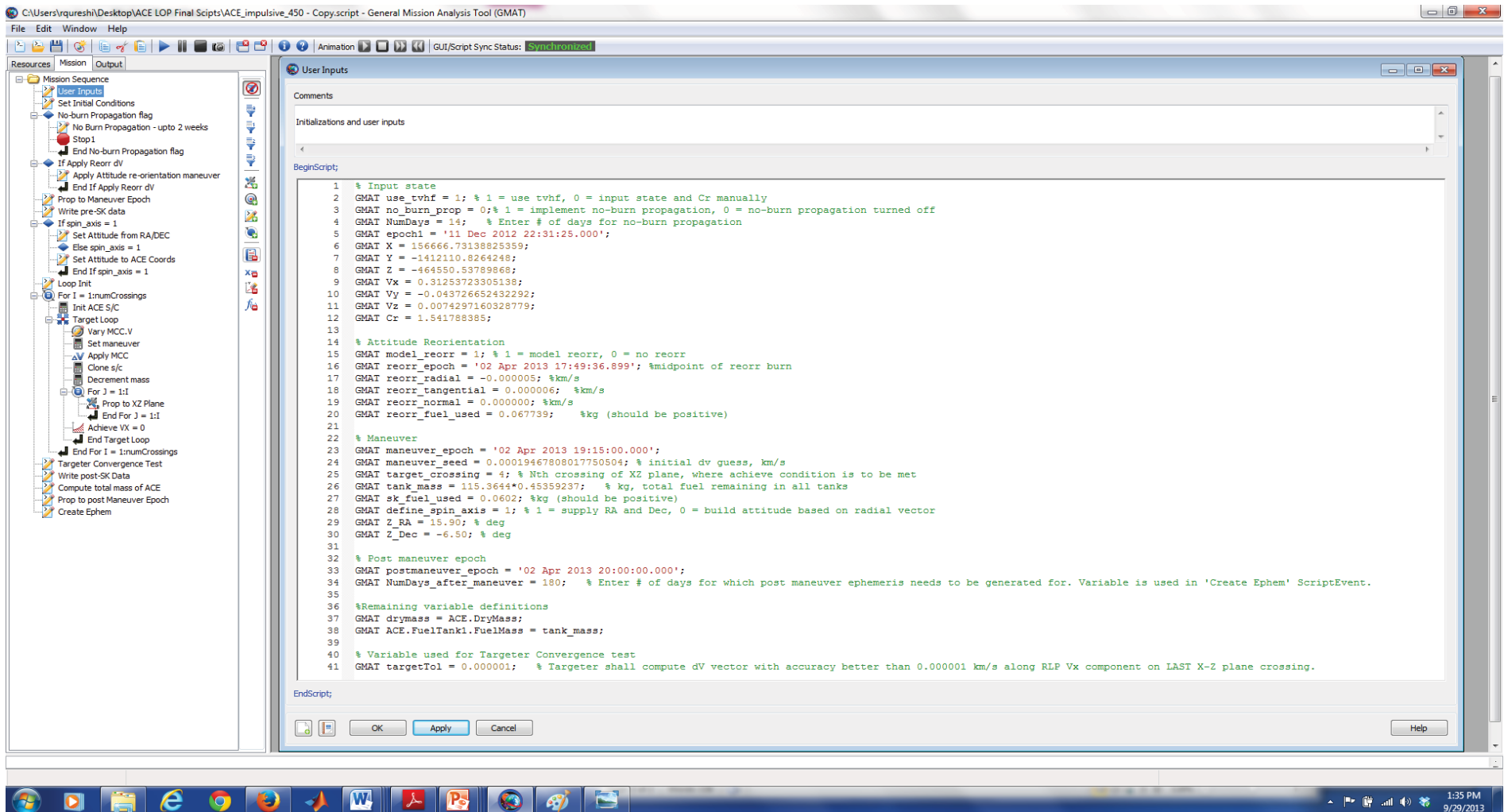
ACE Station-keeping & Attitude Maneuver Context

- **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) software 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 software interface with the following components:

- Mission Sequence (Left Panel):** A tree view showing mission steps such as "User Inputs", "Set Initial Conditions", "No Burn Propagation flag", "Apply Attitude re-orientation maneuver", and "Create Ephem".
- EarthSunRetCS (Top Left Plot):** A 3D plot showing the Earth's orbit around the Sun (labeled "Sun") in the ecliptic plane. The axes are labeled X, Y, and Z. Constellations like Aries, Cetus, and Sculptor are visible. The plot title is "EarthSunRetCS" and the epoch is "29 Sep 2013 20:00:00.000".
- EarthSunMoonL1 (Top Right Plot):** A 3D plot showing the Earth's orbit around the Sun and the Moon's orbit around Earth. The Earth is labeled "ACE". Constellations like Caelum, Dorado, Reticulum, Hydrus, Mensa, Carina, Pictor, Chamaeleon, Octans, and Volans are visible. The plot title is "EarthSunMoonL1" and the epoch is "29 Sep 2013 20:00:00.000".
- (dummySK.EarthSunMoonL1.Y) vs (dummySK.EarthSunMoonL1.X) (Bottom Left Plot):** A 2D plot showing the Earth's orbit in the X-Y plane. The X-axis ranges from -251700 to 251700, and the Y-axis ranges from -66000 to 66000. The plot title is "(dummySK.EarthSunMoonL1.Y) vs (dummySK.EarthSunMoonL1.X)".
- (ACE.EarthSunMoonL1.Y) vs (ACE.EarthSunMoonL1.X) (Bottom Right Plot):** A 2D plot showing the actual ACE orbit in the X-Y plane. The X-axis ranges from -253200 to 253200, and the Y-axis ranges from -52100 to 156300. The plot title is "(ACE.EarthSunMoonL1.Y) vs (ACE.EarthSunMoonL1.X)".



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* :

