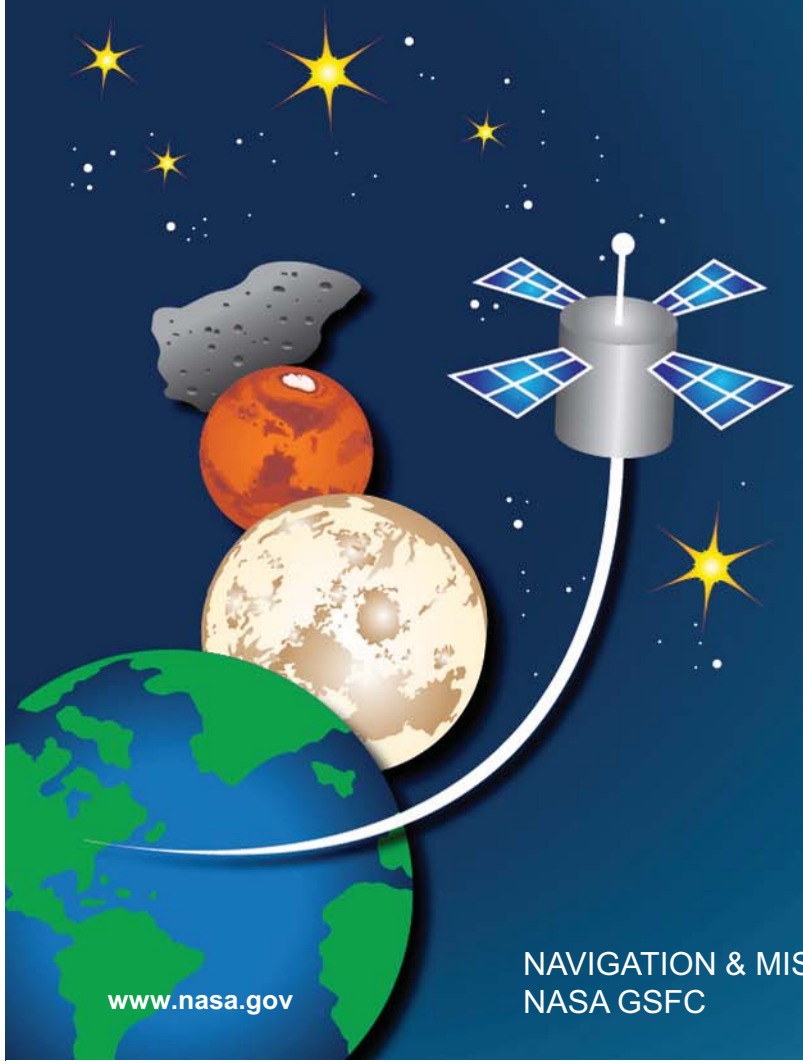
National Aeronautics and Space Administration

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



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NAVIGATION & MISSION DESIGN BRANCH Code 595
NASA GSFC

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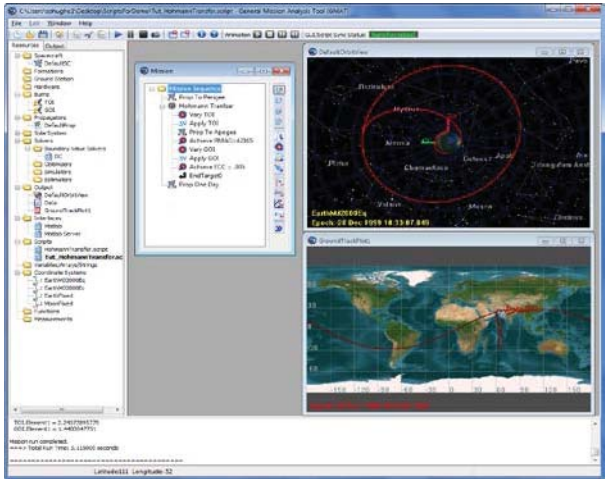
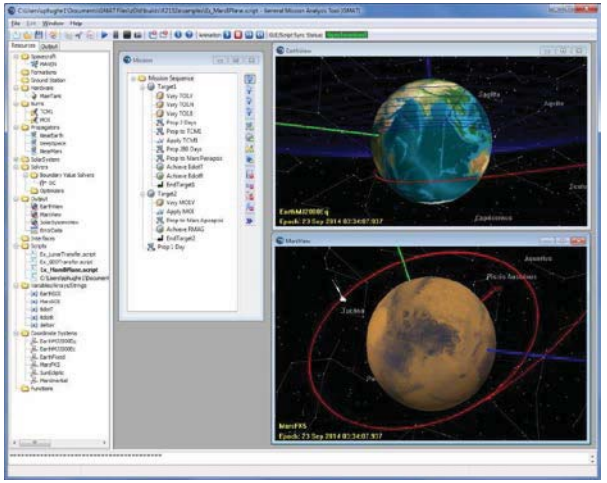
Outline

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

What is GMAT?

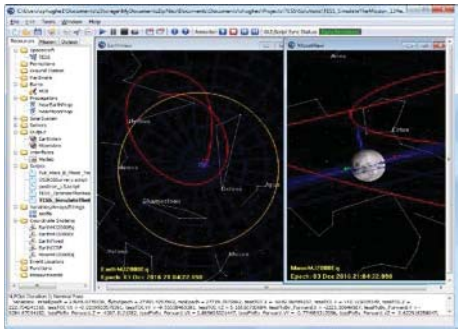
- GMAT is a mission design, analysis & trajectory optimization tool that is:
  - In-house
  - Open source
  - High fidelity
- GMAT R2013a
  - Released April, 2013
  - 6th public release
  - 1st major non-beta release
- GMAT R2013b
  - Released August, 2013
  - Certification candidate
  - Meets ACE requirements



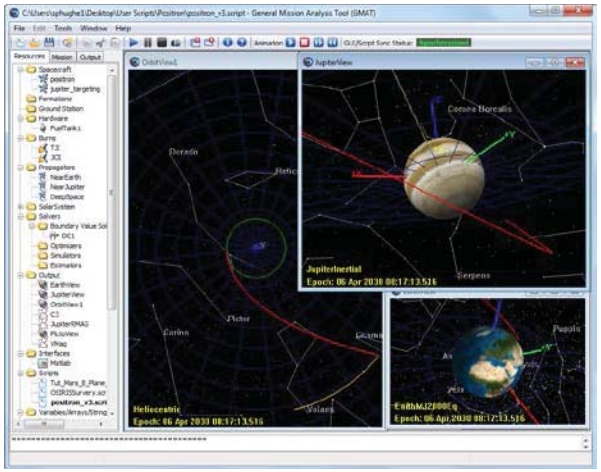


What is GMAT?… cont.

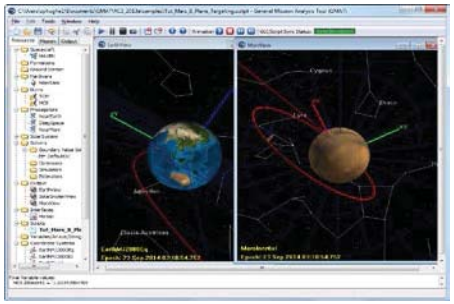
- **GMAT can support flight regimes ranging from:**
  - LEO
  - GEO
  - HEO
  - Libration
  - Lunar
  - Interplanetary & Deep space
- **GMAT has supported**
  - LCROSS
  - LRO
  - ARTEMIS
  - MAVEN
  - OSIRIS
  - TESS & more…



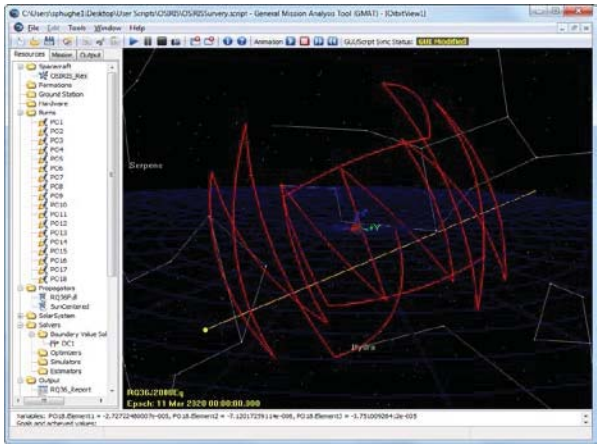
Optimal Lunar Flyby



Outer Planet Transfers



Optimal Mars Trajectories



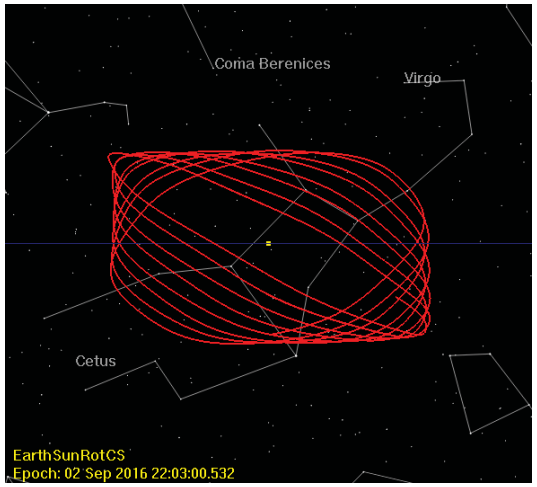
Asteroid (RQ36) Survey

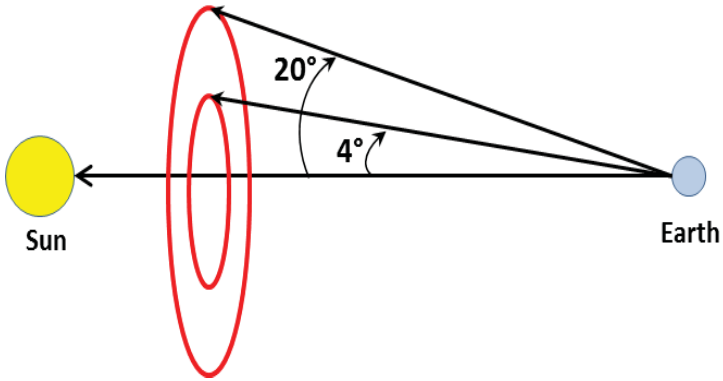
Download and find out more: gmatcentral.org

ACE Mission Overview

- Sun-Earth L1 Orbiter (Lissajous orbit)
  - Spin stabilized & launched in August, 1997
  - Design amplitudes are:
    - Ax = 81,755 km
    - Ay = 264,071 km
    - Az = 157,406 km
  - Sun-Earth-Vehicle (SEV) angle must be between 4º & 20º 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





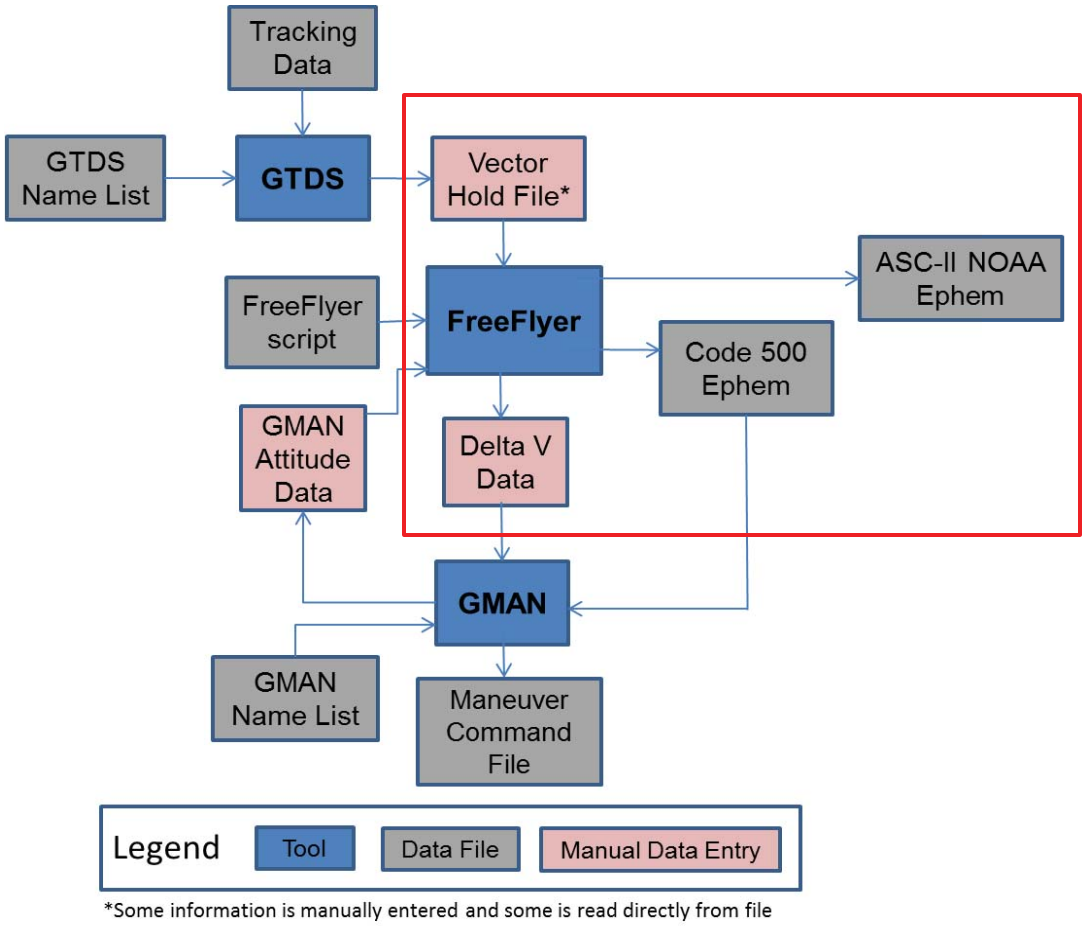
Sun-Earth-Vehicle Angle

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 ephem to NOAA



We focused on tools/interfaces in red box

ACE Maneuver Targeting Strategy:

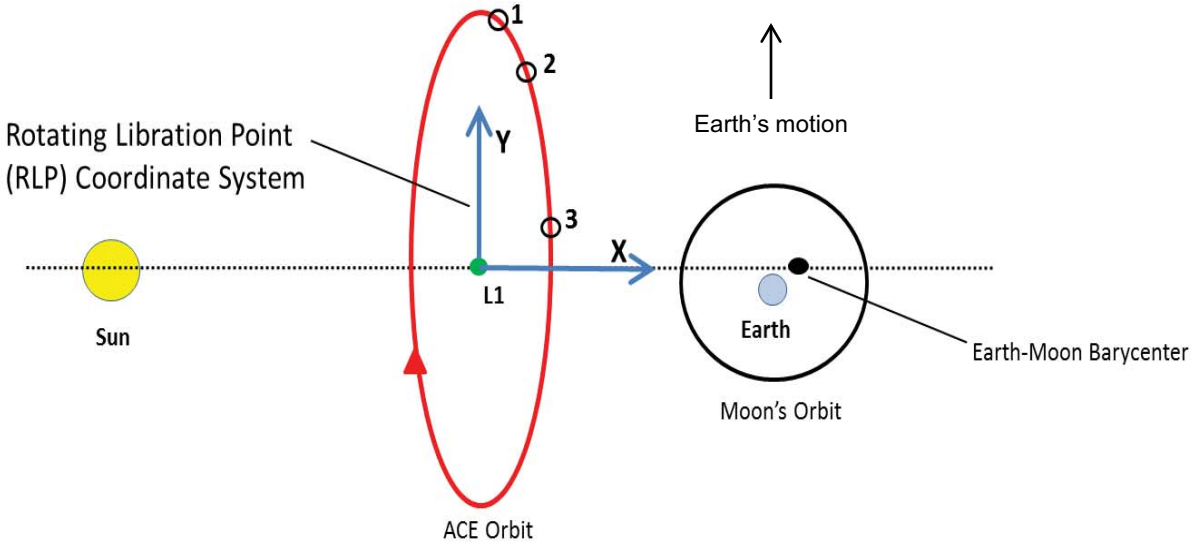
1. Get an updated OD state

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 Vx = 0 @ RLP XZ plane crossing (i.e. When RLP Y = 0)



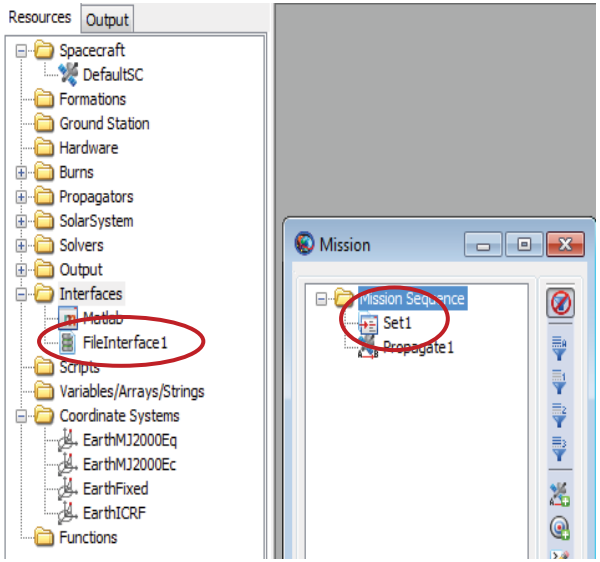
Requirements Gathering

- 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

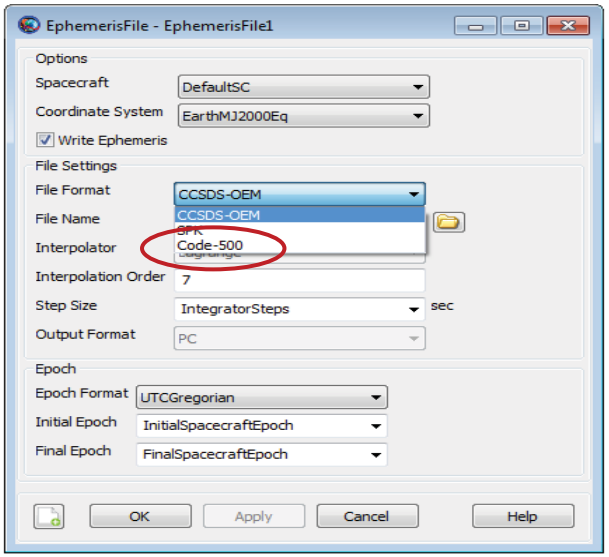
Gaps Analysis

- 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

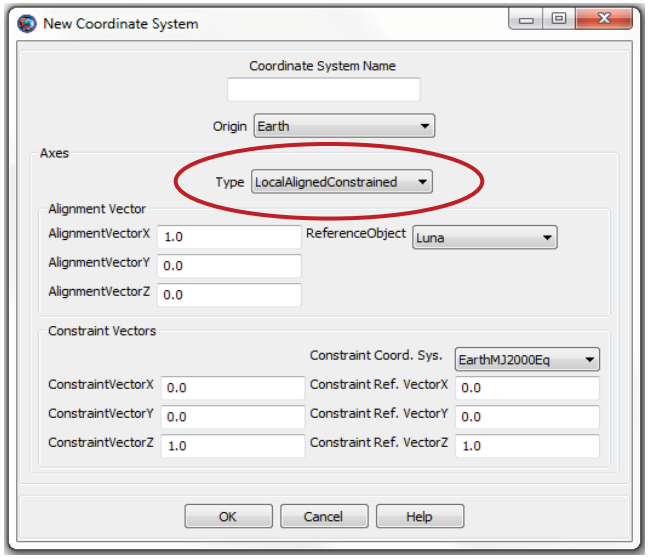
Gaps Analysis…Cont.



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 ephem. 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 201217:30:00.000	29.65	0.021
Vec430	15 Jan 2013 16:03:08.000	15 Jan 201317:30:00.000	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

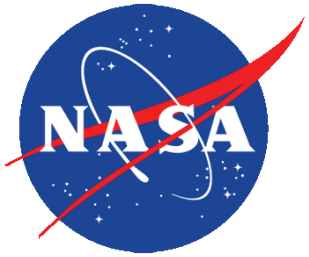
ΔV difference must be < 0.05 mm/s
RSS pos. error (28 Days) must be < 10 mm

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



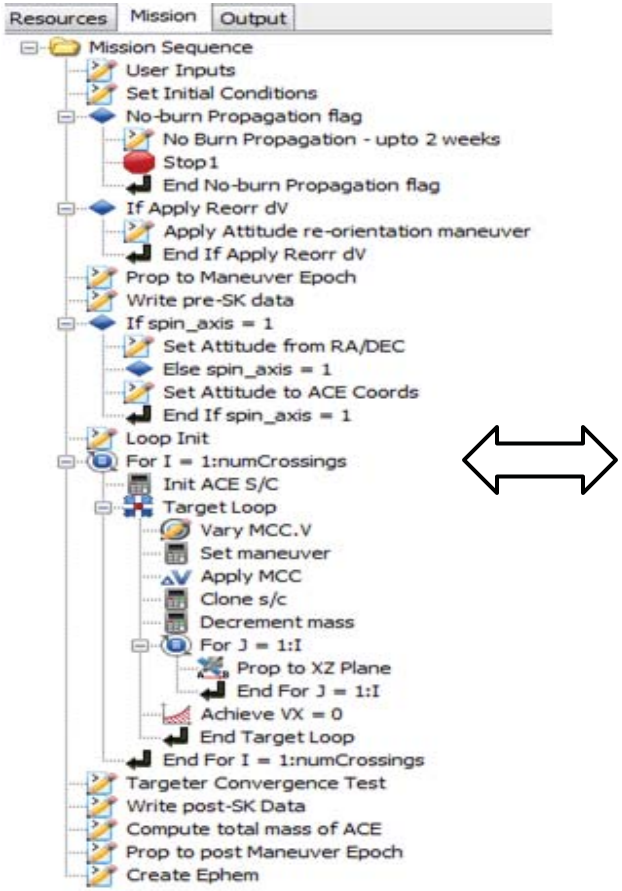
Backup Slides

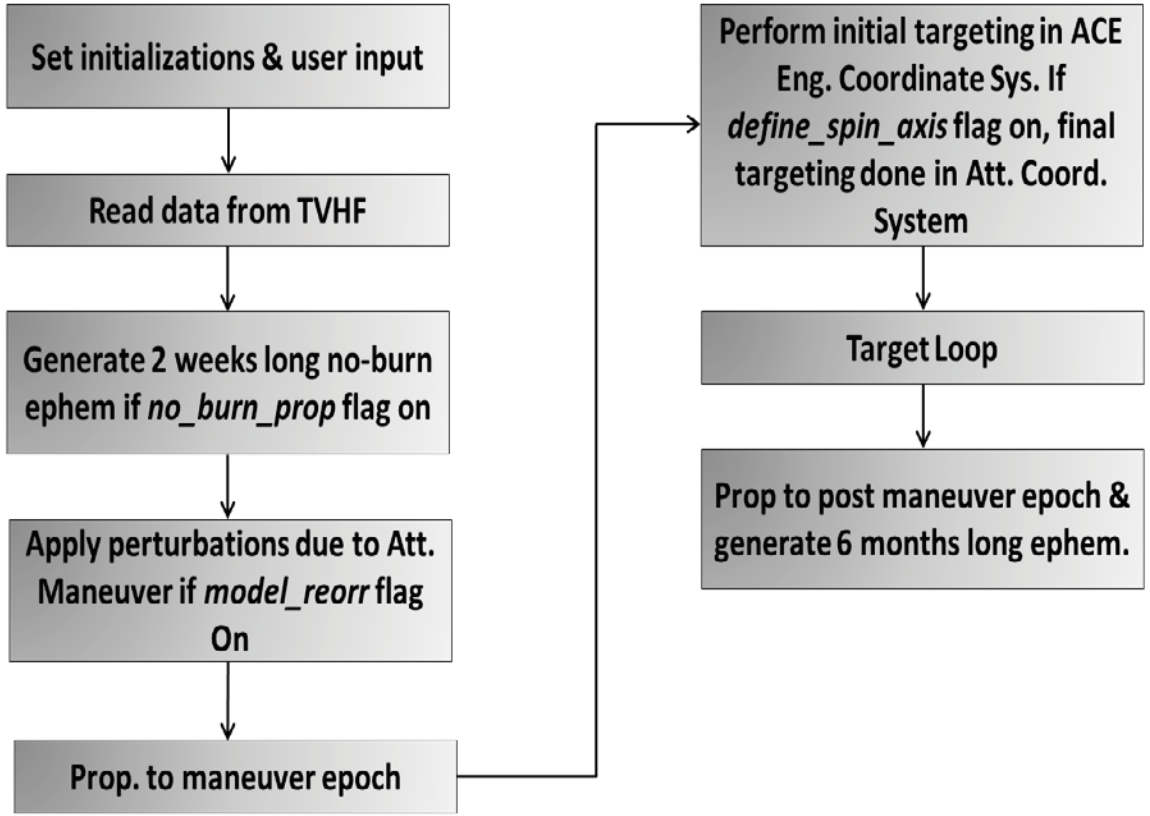
Software Development History/Status

- 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* :

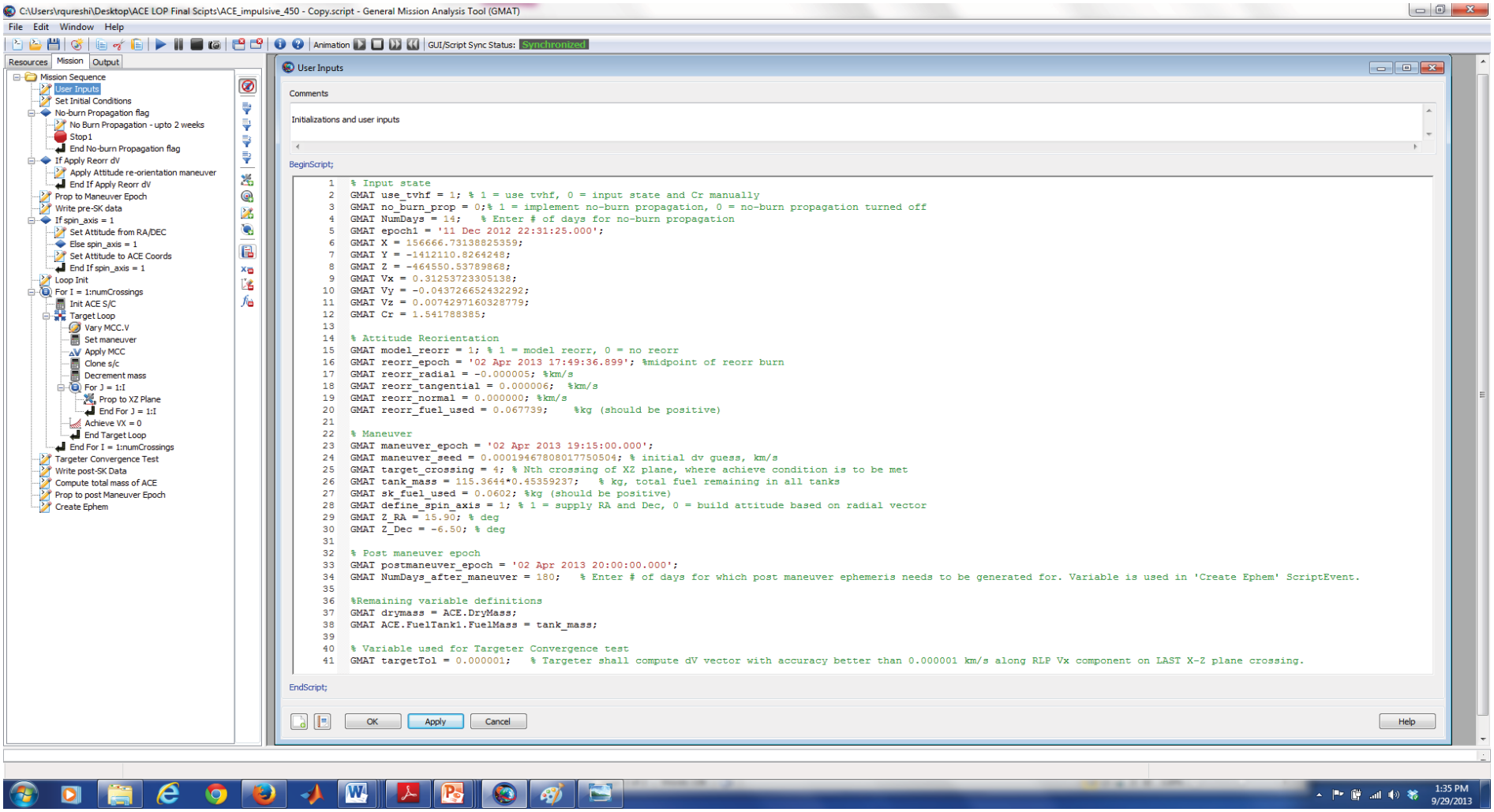




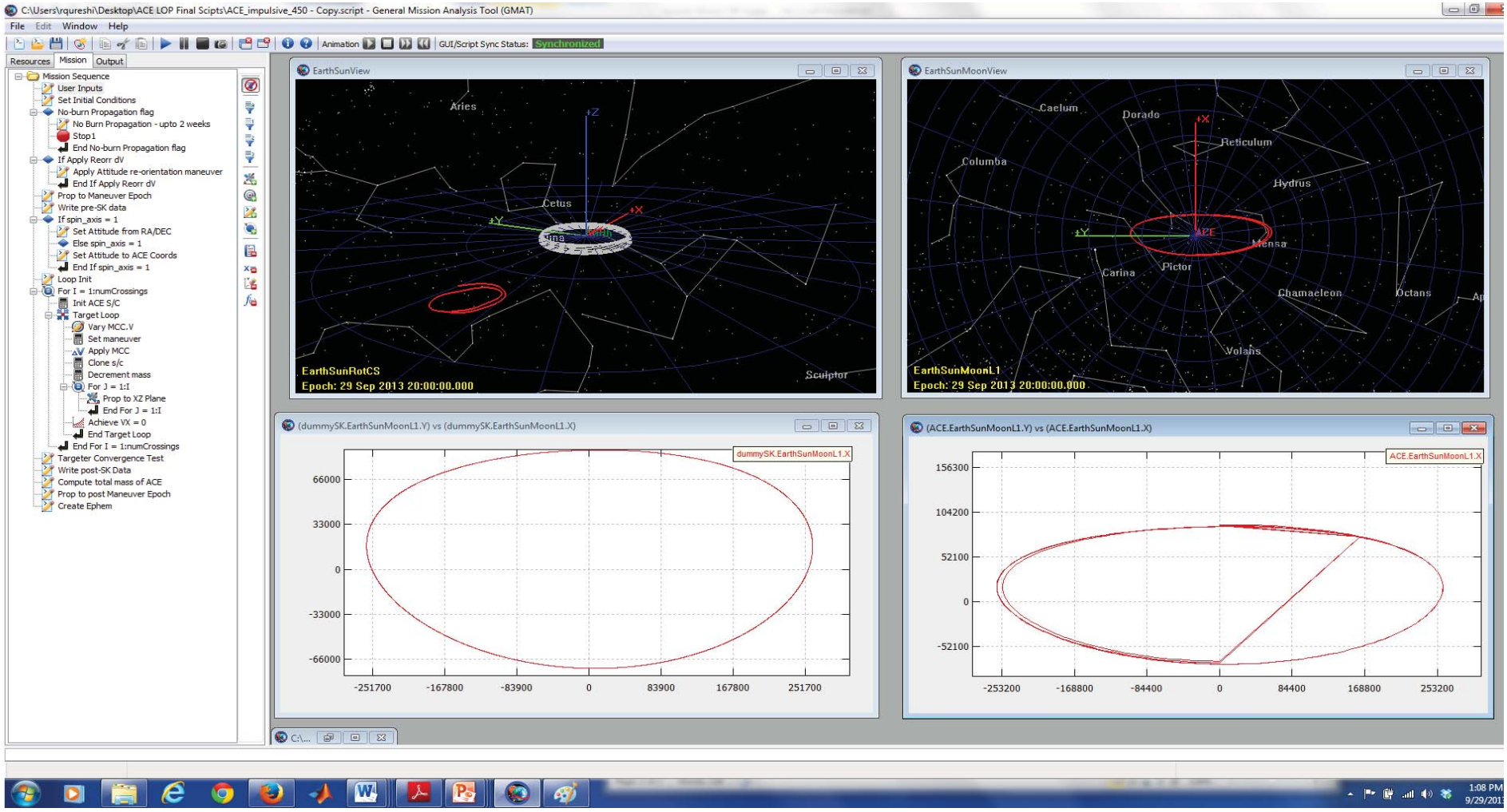
ACE Station-keeping & Attitude Maneuver Context

- **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

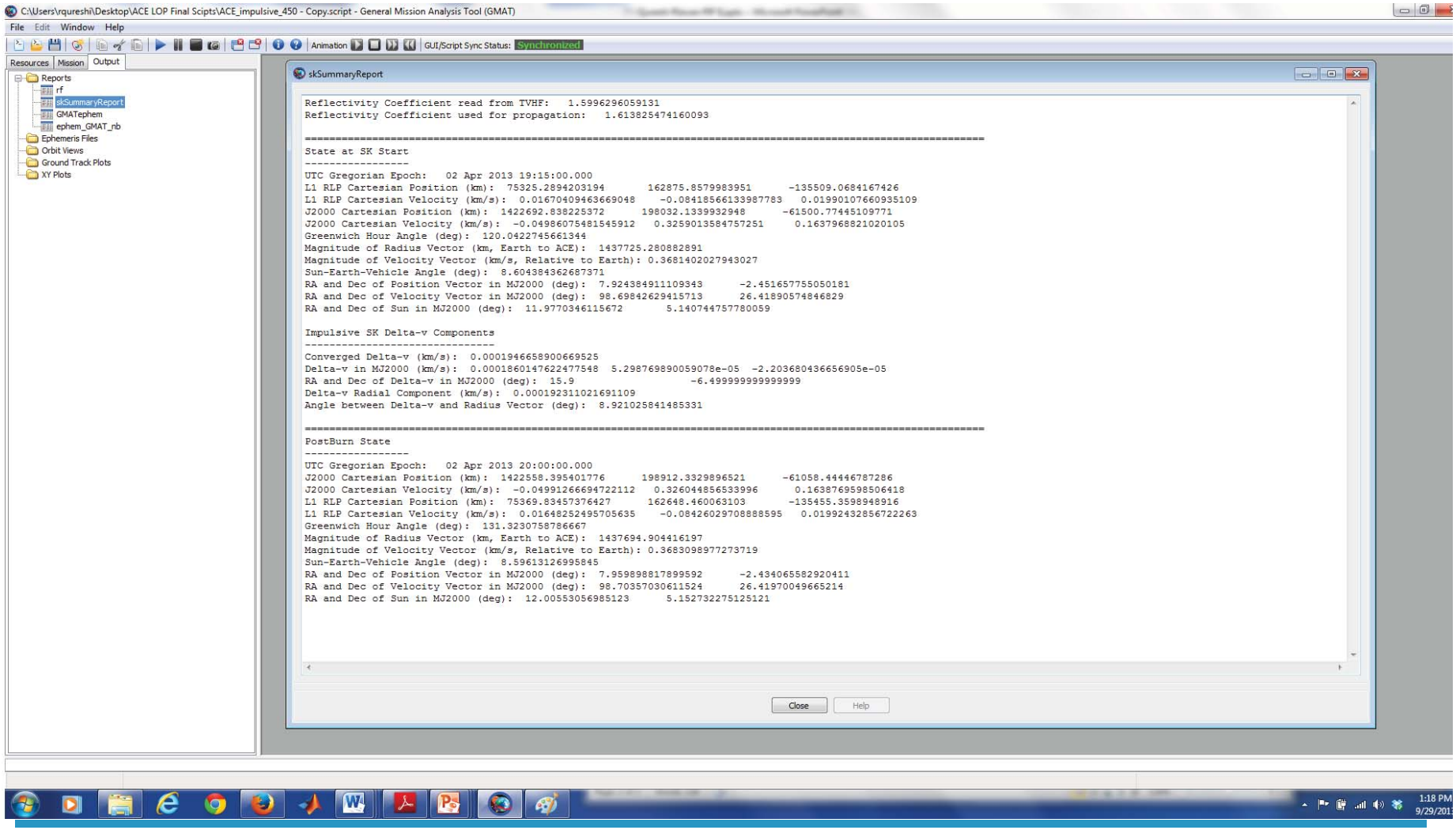
GMAT *ACE_impulsive_vec###.script*
"User Inputs" ScriptEvent



GMAT ACE Graphics



GMAT ACE SK Maneuver Report



Pre-Shadow Ops…Cont.

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