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

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

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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
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…

Download and find out more: gmatcentral.org

GMAT Development Team
NASA GSFC
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 $4^\circ$ & $20^\circ$ nominal

- **Station-keeping maneuvers:**
  - 2-3 months apart
  - Nominal delta-V’s averaging $0.33$ m/sec

- **Attitude Maneuvers:**
  - Performed weekly
  - Perturb ACE orbit

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GMAT Development Team
NASA GSFC
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
- Finite-burn modeling is performed using GMAN
- GMAN generates Maneuver Cmd. File
- FreeFlyer delivers 28 days long ephem to NOAA
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 ephem. delivered to NOAA

- GMAT scripts were written using similar design philosophy:
  - `ACE_impulsive_vec###.script`
  - `ACE_impulsive_NOAA28day_vec###.script`
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:

<table>
<thead>
<tr>
<th>REQID</th>
<th>Object Text</th>
<th>Test Plans</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT01</td>
<td>The ground system must be capable of ingesting the state vector from the TCOPS Vector Hold Files without user input.</td>
<td>Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.</td>
</tr>
<tr>
<td>MT02</td>
<td>The ground system must be capable of ingesting the epoch from the TCOPS Vector Hold Files without user input.</td>
<td>Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.</td>
</tr>
<tr>
<td>MT03</td>
<td>The ground system must be capable of ingesting $C_r$ from the TCOPS Vector Hold Files without user input.</td>
<td>Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.</td>
</tr>
<tr>
<td>MT04</td>
<td>The ground system shall use a user-input maneuver epoch for impulsive targeting.</td>
<td>Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.</td>
</tr>
<tr>
<td>MT05</td>
<td>The ground system shall support varying the delta-V along the spacecraft body Z-axis during differential correction of impulsive maneuver targeting.</td>
<td>Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.</td>
</tr>
<tr>
<td>MT06</td>
<td>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.</td>
<td>Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.</td>
</tr>
<tr>
<td>MT07</td>
<td>The differential corrector shall compute a delta-V vector which achieves an accuracy better than $0.00000 \pm 0.000001$ 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.</td>
<td>Follow procedure in FDSS-FORM-0015 Maneuver targeting Test Plan.docx and use ACE_impulsive_Burn_450.script GMAT script.</td>
</tr>
</tbody>
</table>
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):

<table>
<thead>
<tr>
<th>TVHF file</th>
<th>Maneuver Epoch [UTC-G]</th>
<th>GMAT SK ΔV [cm/sec]</th>
<th>ΔV diff. [mm/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vec424.txt</td>
<td>15 Jan 2013 17:30:00.000</td>
<td>15.01</td>
<td>0.024</td>
</tr>
<tr>
<td>Vec433.txt</td>
<td>15 Apr 2013 16:00:00.000</td>
<td>22.75</td>
<td>0.017</td>
</tr>
<tr>
<td>Vec440.txt</td>
<td>19 Mar 2013 16:00:00.000</td>
<td>12.53</td>
<td>0.018</td>
</tr>
<tr>
<td>Vec456.txt</td>
<td>25 Jun 2013 19:15:00.000</td>
<td>27.98</td>
<td>0.016</td>
</tr>
</tbody>
</table>

ΔV difference must be < 0.05 mm/sec
**ΔV Comparisons…Cont.**

ΔV diff. (perturbations from attitude maneuver modeled):

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vec420</td>
<td>19 Nov 2012 15:59:50.000</td>
<td>19 Nov 2012 17:30:00.000</td>
<td>29.65</td>
<td>0.021</td>
</tr>
<tr>
<td>Vec430</td>
<td>15 Jan 2013 16:03:08.000</td>
<td>15 Jan 2013 17:30:00.000</td>
<td>19.97</td>
<td>0.015</td>
</tr>
<tr>
<td>Vec450</td>
<td>02 Apr 2013 17:49:36.899</td>
<td>02 Apr 2013 19:15:00.000</td>
<td>19.47</td>
<td>0.018</td>
</tr>
<tr>
<td>Vec472</td>
<td>09 Jul 2013 16:42:37.000</td>
<td>09 Jul 2013 17:40:00.000</td>
<td>15.30</td>
<td>0.012</td>
</tr>
</tbody>
</table>

**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:

<table>
<thead>
<tr>
<th>TVHF file used</th>
<th>RSS position error after 28 days in EarthMJ2000Eq [mm]</th>
<th>RSS position error after 180 days in EarthMJ2000Eq [meters]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vec433.txt</td>
<td>0.50</td>
<td>2.72</td>
</tr>
<tr>
<td>Vec440.txt</td>
<td>2.9</td>
<td>3.04</td>
</tr>
<tr>
<td>Vec450.txt</td>
<td>6.1</td>
<td>2.62</td>
</tr>
<tr>
<td>Vec456.txt</td>
<td>1.6</td>
<td>4.73</td>
</tr>
</tbody>
</table>

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

\[\Delta V\] diff. (perturbations from attitude re-orientation maneuver modeled):

<table>
<thead>
<tr>
<th>TVHF file used</th>
<th>Initial State Epoch [UTC/G]</th>
<th>(\Delta V) diff. [mm/sec]</th>
<th>RSS position error after 28 days in EarthMJ2000Eq [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vec493.txt</td>
<td>23 Sep 2013 00:00:00.000</td>
<td>0.015</td>
<td>1.83</td>
</tr>
</tbody>
</table>

\(\Delta V\) 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
Basic Design methodology for GMAT's `ACE_impulsive_vec###.script`:

1. Set initializations & user input
2. Read data from TVHF
3. Generate 2 weeks long no-burn ephem if `no_burn_prop` flag on
4. Apply perturbations due to Att. Maneuver if `model_rearr` flag on
5. Prop. to maneuver epoch
7. Target Loop
8. Prop to post maneuver epoch & generate 6 months long ephem.
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*
Pre-Shadow Ops…Cont.

Basic Design methodology for GMAT’s `ACE_impulsive_NOAA28day_vec###.script`:

- **Initialization & user input in “User Inputs” ScriptEvent**
  - Read data from TVHF file in “Set Initial Conditions” ScriptEvent
  - ACE propagates to product start epoch in “Prop to Product_start epoch” ScriptEvent & generates 28 days long NOAA ephem via “Write NOAA Ephem” ScriptEvent