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

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Rizwan H. Qureshi and Steven P. Hughes

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NAVIGATION & MISSION DESIGN BRANCH Code 595
NASA GSFC
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
  - 6\textsuperscript{th} 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…

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 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
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

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

ACM 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
GMAT Development Team
NASA GSFC

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
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
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 <a href="#">FDSS-FORM-0015 Maneuver targeting Test Plan.docx</a> and use ACE_impulsive_Burn_450 scripted 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 <a href="#">FDSS-FORM-0015 Maneuver targeting Test Plan.docx</a> and use ACE_impulsive_Burn_450 scripted 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 <a href="#">FDSS-FORM-0015 Maneuver targeting Test Plan.docx</a> and use ACE_impulsive_Burn_450 scripted 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 <a href="#">FDSS-FORM-0015 Maneuver targeting Test Plan.docx</a> and use ACE_impulsive_Burn_450 scripted 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 <a href="#">FDSS-FORM-0015 Maneuver targeting Test Plan.docx</a> and use ACE_impulsive_Burn_450 scripted 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 <a href="#">FDSS-FORM-0015 Maneuver targeting Test Plan.docx</a> and use ACE_impulsive_Burn_450 scripted 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 ± 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 <a href="#">FDSS-FORM-0015 Maneuver targeting Test Plan.docx</a> and use ACE_impulsive_Burn_450 scripted 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!
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]</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

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

<table>
<thead>
<tr>
<th>TVHF file used</th>
<th>Initial State Epoch [UTCG]</th>
<th>( \Delta V \text{ 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>

\( \Delta V \text{ difference must be } < 0.05 \text{ mm/s} \)
RSS pos. error (28 Days) must be < 10 mm
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:

- Set initializations & user input
- Read data from TVHF
- Generate 2 weeks long no-burn ephem if no_burn_prop flag on
- Apply perturbations due to Att. Maneuver if model_rearr flag On
- Prop. to maneuver epoch
- Perform initial targeting in ACE Eng. Coordinate Sys. If define_spin_axis flag on, final targeting done in Att. Coord. System
- Target Loop
- 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*
GMAT ACE_impulsive_vec###.script

"User Inputs" ScriptEvent
Basic Design methodology for GMAT’s ACE_impulsive_NOAA28day_vec###.script:

Initializations & 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