Preparing General Mission Analysis Tool for Operational Maneuver Planning of the Advanced Composition Explorer Mission

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The General Mission Analysis Tool (GMAT) is an open-source space mission design, analysis and trajectory optimization tool. GMAT is developed by a team of NASA, private industry, public and private contributors. GMAT is designed to model, optimize and estimate spacecraft trajectories in flight regimes ranging from low Earth orbit to lunar applications, interplanetary trajectories and other deep space missions. GMAT has also been flight qualified to support operational maneuver planning for the Advanced Composition Explorer (ACE) mission. ACE was launched in August, 1997 and is orbiting the Sun-Earth L1 libration point. The primary science objective of ACE is to study the composition of both the solar wind and the galactic cosmic rays. Operational orbit determination, maneuver operations and product generation for ACE are conducted by NASA Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF). This paper discusses the entire engineering lifecycle and major operational certification milestones that GMAT successfully completed to obtain operational certification for the ACE mission. Operational certification milestones such as gathering of the requirements for ACE operational maneuver planning, gap analysis, test plans and procedures development, system design, pre-shadow operations, training to FDF ACE maneuver planners, shadow operations, Test Readiness Review (TRR) and finally Operational Readiness Review (ORR) are discussed. These efforts have demonstrated that GMAT is flight quality software ready to support ACE mission operations in the FDF.

INTRODUCTION

NASA GSFC's Navigation and Mission Design Branch (NMDB) is responsible for providing core expertise in navigation, trajectory design and mission analysis support for all missions at GSFC. NMDB also provides on-orbit flight dynamics operations services through the FDF. As the operational arm of the NMDB, FDF's operational services include orbit determination, acquisition and data generation for space and ground networks, tracking data evaluation and maneuver planning support. FDF has provided orbit maneuver services for unmanned NASA missions of nearly every kind of orbit including lunar, libration point, and deep space. Typically, FDF supports flight dynamics computations for more than twenty missions. One current example includes providing maneuver operational support for the ACE mission.

ACE is a Sun-Earth libration point mission. The ACE mission is the third NASA spacecraft to fly a libration point orbit, and like International Sun-Earth Explorer 3 (ISEE-3) and Solar and Heliospheric Observatory (SOHO) before it, it orbits the Sun-Earth L1 point [1]. Launched on August 25, 1997, the ACE mission is to study the composition of both the solar wind and the galactic cosmic rays. ACE is a spin-stabilized spacecraft with a required spin rate of 5.0 ± 0.1 revolutions per minute

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(rpm). With a dry mass of 785 kg, ACE at launch had 195 kg of hydrazine fuel and a delta-v capability of approximately 445 m/s [2]. As of mid-2013, ACE has 50.7 kg of fuel remaining. ACE is required at all times to have its spin axis (body +Z-axis) oriented such that the spin-axis-to-Sun angle is no fewer than 4 degrees and no more than 20 degrees. The ACE orbit is a Lissajous orbit of relatively small Rotating Libration Point (RLP) coordinate system X-axis and Y-axis amplitudes. Figure 1 shows the ACE mission orbit in RLP coordinate system as seen from the North Ecliptic Pole (NEP). RLP X-axis lies on the Sun to Earth-Moon Barycenter line, Y-axis points towards Earth's motion and Z-axis is parallel to the NEP axis. The design amplitudes chosen for the ACE Lissajous were as follows: AX = 81,755 km, AY = 264,071 km, and AZ = 157,406 km.[1] These amplitudes correspond to angular dimensions of approximately 6 degrees out-of-plane and 10 degrees in-plane (Y-axis).

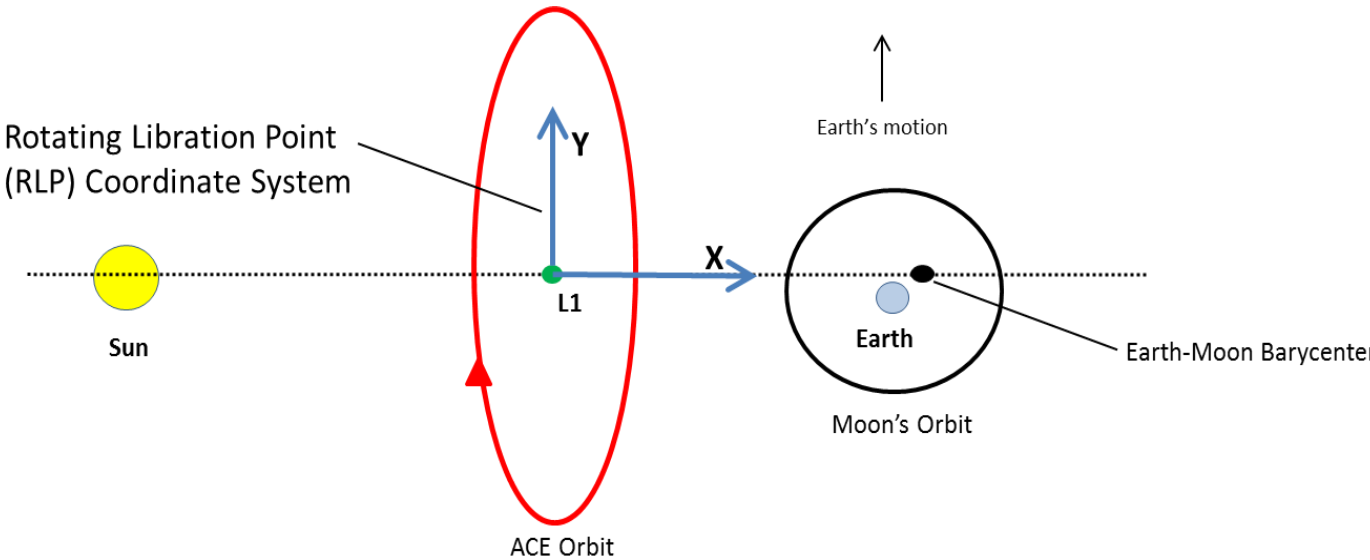


Figure 1. ACE mission orbit in Rotating Libration Point Coordinate System

The basic philosophy for ACE Lissajous station-keeping is to coast for as long as can be tolerated in order to minimize operational impact to science. Although there was no hard specification on the upper size limit for station-keeping burns, it was decided based on SOHO experience that 0.75 m/s is a reasonable guideline [1]. For ACE, there are two complicating factors to contend with regarding trajectory stability and maneuver design. First: weekly spin-axis attitude reorientation maneuvers cause regular perturbations to the ACE Lissajous mission orbit. Second: Lissajous Z-axis control maneuvers were required beginning about two years into the mission [1, 3]. The station-keeping maneuvers are typically three months apart but they can vary by a matter of weeks in either way. As of 23 September 2013, there have been 67 ACE station-keeping maneuvers starting from 15 January 1998 with nominal delta-Vs averaging 0.20 m/s and average intervals between burns of 103 days.

The FDF provides operational orbit determination, station-keeping maneuver planning and product generation for the ACE mission. Several tools are used in the workflow to support ACE operations. ACE mission operations are conducted with tools that have been developed inside Goddard as well as with private commercial-off-the-shelf (COTS) tools. Orbit determination is performed using the Goddard Trajectory Determination System (GTDS) tool. Impulsive maneuver targeting, trajectory propagation and product generation is performed using FreeFlyer which is a COTS tool. Attitude and finite-burn modeling is performed using Goddard's General Maneuver Program (GMAN) tool.

Due to the frequency of weekly attitude maneuvers and the resulting orbital perturbations, maneuver planning and prediction for ACE is an ongoing process. Using FreeFlyer, the ACE maneuver team monitors the orbital evolution by performing impulsive maneuver targeting as Orbit Determination (OD) updates are made available from GTDS via the TCOPS Vector Hold File (TVHF). Impulsive maneuver retargeting is performed via FreeFlyer to evaluate the efficiency of the last maneuver and to predict the time and magnitude of the next station-keeping maneuver. ACE maneuvers occur on the order of once every three months but there is significant variability. About two weeks prior to a maneuver, FDF begins finite maneuver planning using the impulsive maneuver delta-v approximation targeted in FreeFlyer from the most recent navigation solution provided from GTDS in a TVHF file. Several cycles of finite-burn planning and targeting occur depending on the frequency of propulsion and OD updates and the frequency of attitude, momentum management, and/or spin maneuvers.

Figure 2 shows the tools and workflow for current ACE maneuver operations in the FDF. Using FreeFlyer, initial impulsive maneuver targeting is performed in an ACE engineering coordinate system. FreeFlyer generates impulsive delta-v data and a Code 500 ephemeris. This Code 500 ephemeris contains ACE maneuver epoch and corresponding state. Impulsive delta-v data and ACE maneuver epoch from Code 500 ephemeris is read by GMAN. Attitude modeling for ACE is then performed using GMAN. After selection of final attitude parameters has been manually entered into FreeFlyer from GMAN, then final impulsive maneuver is re-targeted in FreeFlyer using a spacecraft-attitude based delta-v coordinate system. Once FreeFlyer performs final impulsive targeting, then FreeFlyer is also used to generate a 28 days long ACE ephemeris. This 28 days long ACE ephemeris is the primary product that is delivered to the National Oceanic and Atmospheric Administration (NOAA) by the ACE maneuver planning team. Final finite-burn planning and command generation is performed by GMAN during the maneuver pass and the maneuver command file is generated using GMAN. Finally this maneuver command file is sent to Mission Operations Center (MOC). The MOC uploads this maneuver command file to the spacecraft. Notice that in Figure 2, FreeFlyer is the primary maneuver planning and product generation tool used for impulsive maneuver delta-v computations and for NOAA product generation.

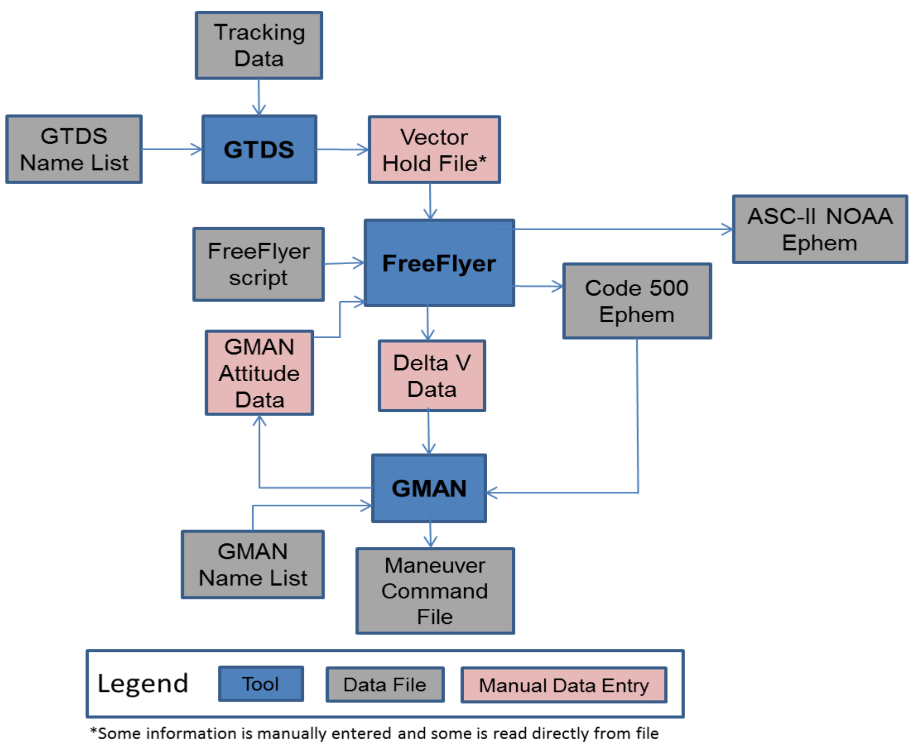


Figure 2. Tools and Workflow for ACE Maneuver planning using FreeFlyer

The NMDB creates and maintains state-of-the-art analysis tools for mission design, trajectory optimization and navigation support. One such tool is GMAT. GMAT is a desktop mission design, analysis and trajectory optimization tool developed collaboratively by NMDB and the private sector. GMAT runs primarily on Windows (Mac and Linux are alpha) and can be run via script files or a full featured Graphics User Interface (GUI). GMAT is a high fidelity system designed to support nearly all flight regimes utilized for NASA missions including LEO, GEO, HEO, Lunar, and deep space missions. GMAT is written in C++ and is currently about 580K (400K non-comment) source lines of code [4, 5]. The system has been used to optimize trajectories and maneuvers for the Lunar Crater Observation and Sensing Satellite (LCROSS), the Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) missions, the Lunar Reconnaissance Orbiter (LRO), and was used for formation design and analysis for the Magnetospheric Multiscale Mission (MMS).

Two versions of GMAT were released in 2013. The GMAT R2013a version was released in April, 2013. The GMAT R2013a version is the first public release since May 23, 2012, sixth public release and is the first major non-beta production release. GMAT R2013b was released in August, 2013. GMAT R2013b was a certification candidate to plan for and support ACE maneuver operations in the FDF. GMAT R2013b fully meets all of the requirements for ACE operational maneuver planning and product generation. The requirements for ACE operational maneuver planning were levied on the system by FDF’s ACE maneuver planners. The GMAT R2013b system has been certified for operational use for maneuver planning of the ACE mission by FDF’s Facility Review Board (FRB).

This paper focuses on major operational certification milestones and entire engineering lifecycle that GMAT went through in order to be deemed operationally certified to support ACE maneuver operations in the FDF. In this work, core phases from operational certification cycle that we discuss are:

- Gathering of all the ACE operational maneuver support requirements levied on GMAT.
- Verification and validation of the levied requirements.
- Gap analysis that analyzed and determined areas where GMAT could not meet levied requirements and required development of new ACE related features.
- Development, testing and documentation of new ACE related GMAT features.
- System design that explains how GMAT and other tools will be used to support ACE operations in the FDF.
- Pre-shadow operations phase in which GMAT scripts for ACE maneuver planning and product generation were written and output from GMAT was compared against FreeFlyer using several historical navigation solutions from GTDS.
- Development of test plans and procedures that the testers in FDF implemented to test and verify levied requirements on GMAT.
- Development of Local Operating Procedures (LOP) document that ACE maneuver planners use in the operations environment to support ACE operations using GMAT scripts.
- Training provided to the ACE maneuver planning team in how to utilize GMAT scripts to plan for and support ACE operations during a live Station-Keeping (SK) maneuver.
- Presented TRR to the FRB to verify that all tools and environment are ready to support shadow operations during an ACE SK maneuver.
- Non-interfering shadow operations held in FDF in which ACE maneuver team used both GMAT and FreeFlyer to support a live ACE SK maneuver and products from both tools were generated and compared against each other using latest OD solution from GTDS.
- Presented ORR to the FRB to share results from test plans implementation and non-interfering shadow operations. At the end of ORR, GMAT was deemed an operationally certified maneuver planning tool in the FDF for the ACE mission.

The major focus of this effort was to demonstrate that GMAT is a mature, flight quality system that has been operationally certified to support real-time spacecraft mission operations. The work that we present is unique because prior to this effort, GMAT had never gone through an operational certification cycle in order to be deemed qualified to support mission operations in the FDF. In addition to being certified for ACE operations, this work has laid core groundwork for GMAT to target operational certification for other present and future Goddard missions. GMAT has been installed in FDF MOR and now in addition to FreeFlyer, GMAT is ready to serve as the primary maneuver planning tool to support ACE maneuver operations in the FDF.

MAJOR OPERATIONAL CERTIFICATION MILESTONES

Requirements Gathering

Requirements for operational maneuver planning and support for the ACE mission were gathered by working closely with the ACE maneuver planning team located in the FDF. The FDF is responsible for compiling mission operations requirements for any tool that may be used in an operations environment. 97 requirements were gathered and levied on GMAT to support and plan for ACE maneuver operations and product generation. Throughout the requirements gathering phase, one of the most important tasks was to monitor that requirements that were being levied on GMAT make sense and are clearly defined, and to assure that any unnecessary requirements that do not reflect current ACE mission operations be removed from the list of final set of requirements.

Several draft versions of ACE requirements were exchanged between the ACE maneuver planning and GMAT team. After approximately 3.5 months of intense reviews, proper clarification and internal validation of all requirements, a final list of requirements was agreed upon between the ACE maneuver planning and the GMAT team. The final list of requirements went through a System Requirements Review (SRR) which was conducted by FDF FRB.

A complete list of requirements for ACE maneuver planning and support will be shown in the Appendix section. The ACE Requirements Traceability Matrix will show all 97 requirements in a matrix form.

The requirements are sub-divided into 6 requirements areas or categories shown in Table 1.

Table 1. Six Requirements Areas within ACE Requirements for maneuver planning

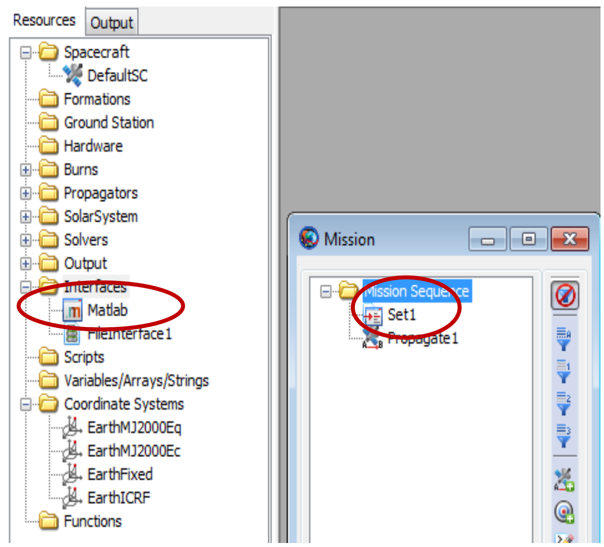
ACE Requirements Areas	# of Requirements in each Requirements Area
Coordinate System	13
Force Model	15
Maneuver Targeting	27
Orbit Propagation	10
Product Output	22
Spacecraft Model	10

Gaps Analysis

After the final set of requirements for ACE operational maneuver planning were formalized at the end of the Requirements Gathering phase, all requirements were analyzed by conducting a gaps analysis. Gaps analysis led us to determine areas where GMAT could not meet the levied requirements and therefore required development of new ACE related features.

1. Detailed discussion about specific requirements that GMAT could not meet is discussed in this section.

2. Discussion on new ACE related features which were developed, tested and documented to successfully support ACE maneuver operations. Figure 3 will be referenced in the detailed discussion on new ACE related GMAT features which were developed and released under GMAT R2103b version.



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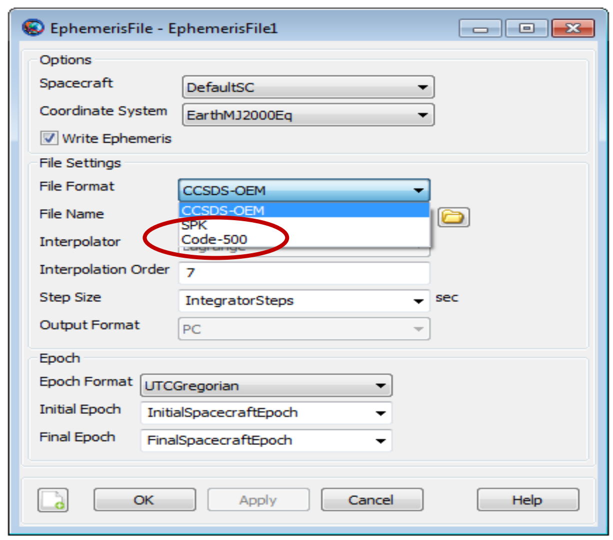
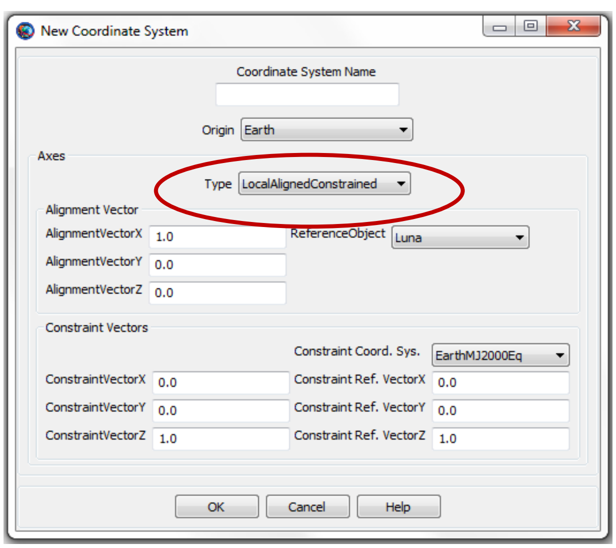


Code 500 ephemeris



LocalAlignedConstrained Coord. Axis Type

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

Spacecraft acceleration parameters

Figure 3. New ACE related Features developed in GMAT to support ACE Operations

System Design

Once GMAT R2013b was released that is intended to support ACE mission operations in the FDF, a new tools and workflow block diagram for ACE maneuver operations was designed. This new ACE mission operations block diagram now shows GMAT being the primary maneuver planning and product generation tool used for ACE maneuver planning and product generation support.

Detailed discussion that references Figure 4 is discussed in this section which explains how in addition to FreeFlyer, now GMAT can be used to support ACE maneuver operations in the FDF.

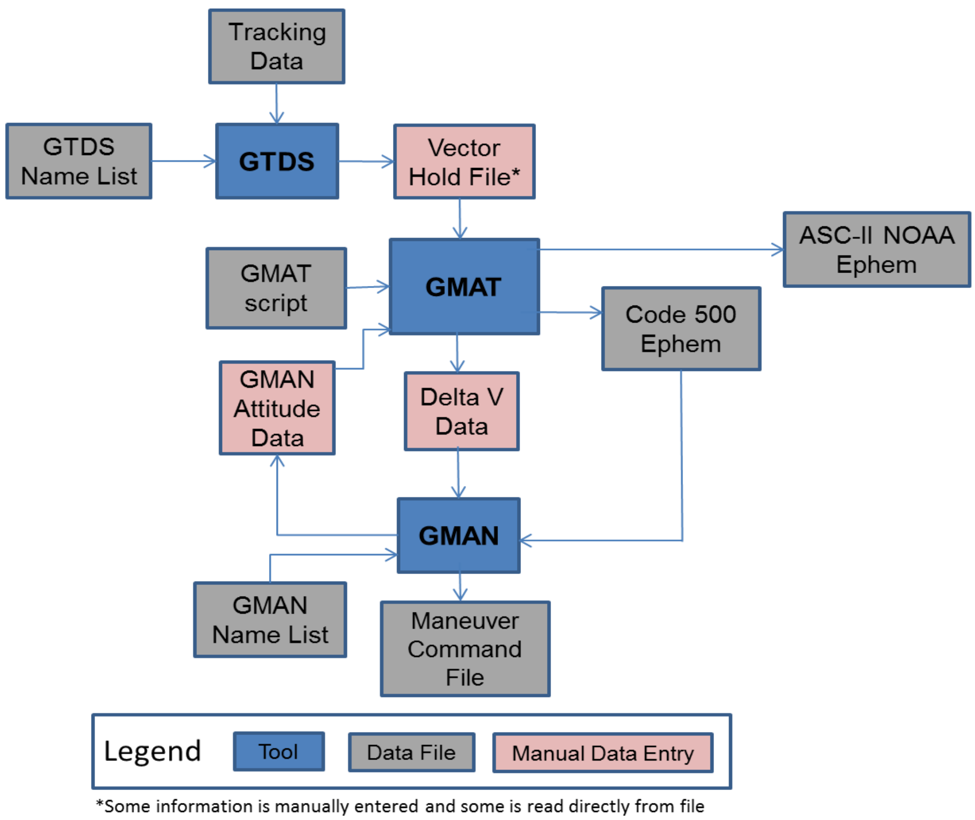


Figure 4. Tools and Workflow for ACE Maneuver Planning and Support using GMAT

Pre-Shadow Operations

The ACE maneuver planning team uses two FreeFlyer scripts for maneuver operations support: FreeFlyer's ACE_impulsive_###.MissionPlan & ACE_impulsive_NOAA28day_vec###.MissionPlan scripts. Every week, the latest OD solution for ACE is delivered to the maneuver team through a TVHF file (vec###.txt) and both of these scripts are ran using the updated OD state.

First FreeFlyer script (ACE_impulsive_###.MissionPlan) serves two purposes: Firstly, weekly initial impulsive burn targeting is done using an engineering based coordinate system to generate weekly delta-v necessary for future station-keeping maneuver by running latest OD solution from GTDS. This OD solution is found in TVHF file that FreeFlyer parses through or a user manually entered the updated navigation solution into FreeFlyer. Secondly, after selection of final attitude parameters, final impulsive maneuver is re-targeted using a spacecraft attitude based delta-v coordinate system.

Second FreeFlyer script (ACE_impulsive_NOAA28day_vec###.MissionPlan) is used to simply generate 28 days long ACE ephemeris for a given TVHF file. This 28 days long ACE ephemeris is the main product from FreeFlyer that is delivered to NOAA.

The design methodology behind GMAT scripts needed to support ACE maneuver operations and product generation was very similar to that of FreeFlyer scripts. Two GMAT scripts: ACE_impulsive_###.script & ACE_impulsive_NOAA28day_vec###.script were written. Both of these scripts serve exactly the same purpose as described above for FreeFlyer ACE scripts. The first GMAT script (ACE_impulsive_###.script) is used to target both initial and final impulsive delta-v necessary for station-keeping and second GMAT script (ACE_impulsive_NOAA28day_vec###.script) generates 28 days long ACE ephemeris which is delivered to NOAA.

Detailed discussion on design methodology of first GMAT script (ACE_impulsive_###.script) takes place in this section and it references Figure 5.

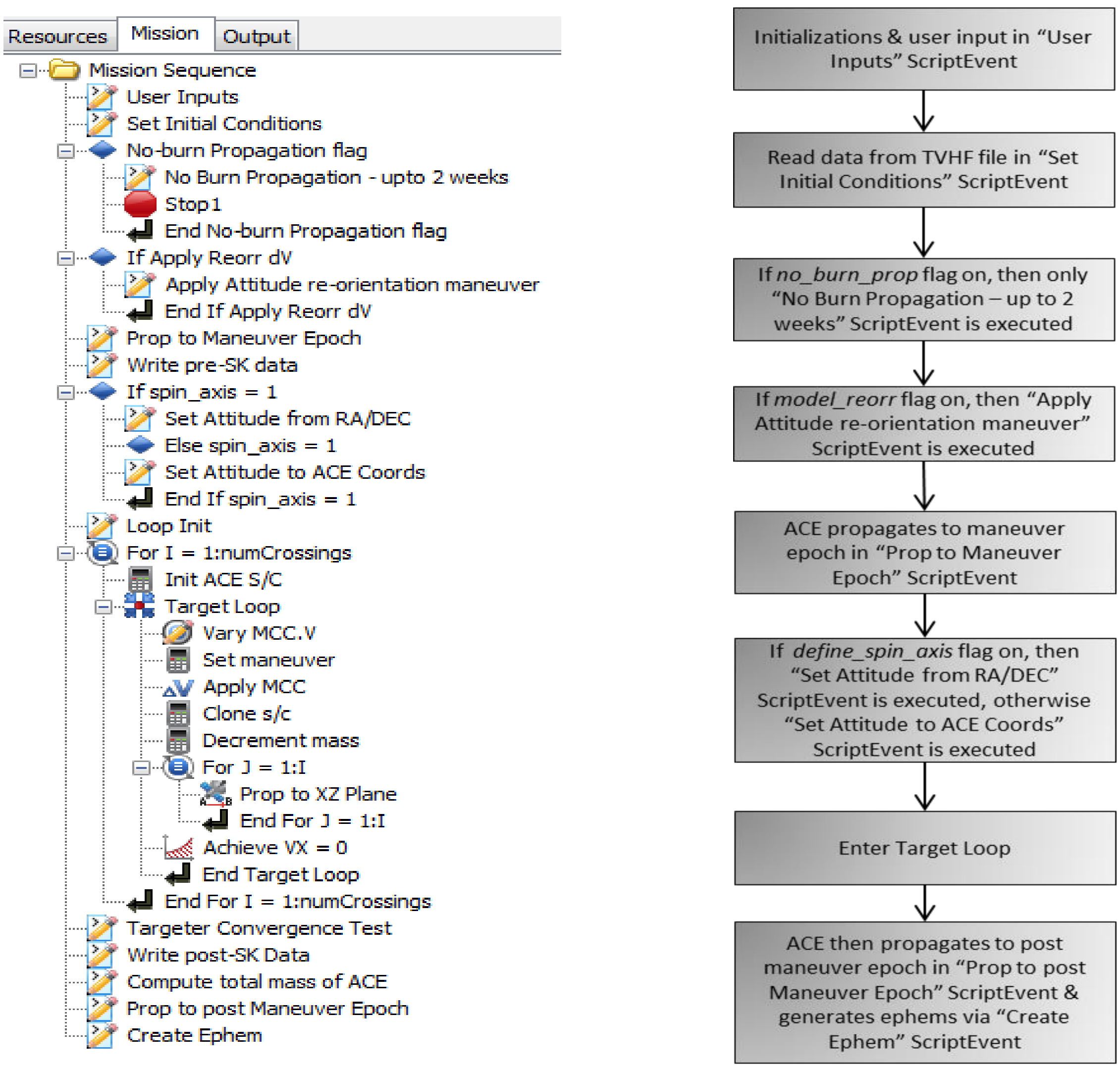


Figure 5. Design methodology for GMAT's ACE_impulsive_###.script

Detailed discussion on ACE station-keeping targeting strategy is also discussed in this section and it references Figure 6:

1. ACE mission orbit is shown in RLP coordinate system. Point 1 on ACE mission orbit is where an updated navigation solution is provided for ACE via a TVHF file that GTDS generates.
2. ACE then propagates to point 2 on the ACE orbit. This point 2 corresponds to attitude re-orientation epoch where perturbations due to spin axis attitude re-orientation maneuver are applied to ACE mission orbit.
3. After applies attitude perturbations, ACE then propagates to maneuver epoch where it enters the targeting loop which performs ACE station-keeping.

ACE SK targeting strategy is a simple one in which single control is varied to meet a single constraint. GMAT varies Z component of delta-v vector in order to make sure that X-component of ACE velocity in RLP coordinate frame is 0 at the 4th RLP XZ plane crossing.

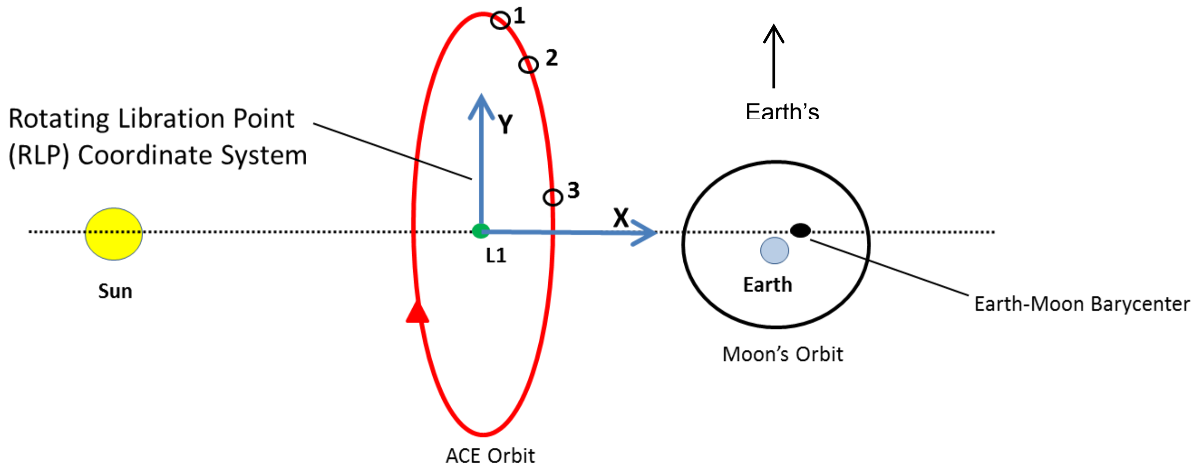


Figure 6. Targeting Strategy for ACE Station-Keeping

Detailed discussion on design methodology of second GMAT script (ACE_impulsive_NOAA28day_vec###.script) follows and this discussion references Figure 7:

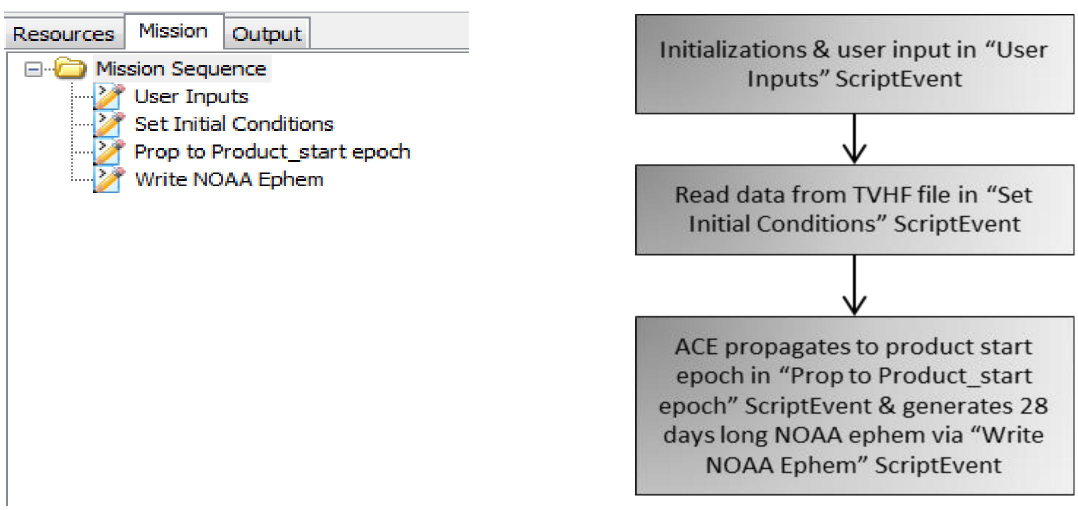


Figure 7. Design methodology for GMAT's ACE_impulsive_NOAA28day_vec###.script

Development of Local Operating Procedures and Test Plans

1. Detailed discussion on development of Local Operating Procedures (LOP) document is presented in this section. This LOP document served as a complete training manual for ACE maneuver planning team and contains detailed procedures on how to use GMAT scripts to support complete ACE maneuver operations in the FDF. Some of the sample procedures from this LOP document will be shown in the Appendix section.

2. Detailed discussion on development of test plans and procedures is also presented. These test plans were written and sent to FDF so that testers would implement these test plans in order to verify all the ACE maneuver planning requirements levied on GMAT. The test plans were written for 8 requirements areas which covered total of 97 requirements. The results that came after implementation of the test plans will also be discussed in this section and it references Figure 8.

   Few sample test plans which were written will also be shown in the Appendix section.

Requirements Areas	Test Plans	Status
Coodinate Systems	**FDSS-FORM-0015 Set up of RA Dec of Spin Axis and different Coordinate Systems Test Plan.docx** and use ACE_impulsive_Burn_XXX.script GMAT script. **FDSS-FORM-0015 Coordinate TransformationsTest Plan.docx** and use ACE_impulsive_Burn_Coordinate Transformations.script GMAT script	**Pass**
Force Model	Follow procedure in **FDSS-FORM-0015 Force Model Parameters Test Plan.docx** and use ACE_impulsive_Burn_XXX.script GMAT	**Pass**
Internet Connectivity & Operating System	Follow procedure in **FDSS-FORM-0015 Internet connectivity & Operating SystemTest Plan.docx** and use ACE_impulsive_Burn_XXX.script GMAT script	**Pass**
Maneuver Targeting	Follow procedure in **FDSS-FORM-0015 Maneuver targeting Test Plan.docx** and use ACE_impulsive_Burn_450.script GMAT script.	**Pass**
Orbit Propagation	Follow procedure in **FDSS-FORM-0015 Orbit Propagation Test Plan.docx** and use ACE_impulsive_Burn_XXX.script GMAT script.	**Pass**
Product Output	Follow procedure in **FDSS-FORM-0015 Product Output Test Plan.docx** and use ACE_impulsive_NOAA28day_vec450.script	**Pass**
Spacecraft model	Follow procedure in **FDSS-FORM-0015 Spacecraft ParametersTest Plan.docx** and use ACE_impulsive_Burn_XXX.script GMAT script.	**Pass**
Output Compares from historical OD solutions	Follow procedure in **FDSS-FORM-0015 Historical Impulsive Delta-V Test Plan.docx** and **FDSS-FORM-0015 Historical NOAA ephem Test Plan.docx** use ACE_impulsive_Burn_XXX.script GMAT script & ACE_impulsive_NOAA28day_vec450.script	**Pass**

Figure 8. Requirements to Test Traceability Matrix

RESULTS

ACE Station-Keeping Delta-V and Propagation Comparisons

1. Table listing station-keeping impulsive delta-v comparisons between FreeFlyer and GMAT will be shown in this section. Initial impulsive delta-v targeting was done using ACE Engineering coordinate system and perturbations due to attitude maneuver were not modeled into ACE mission orbit. Four historical navigation solutions were used to compare four delta-v comparisons from following TVHF files: Vec424.txt. Vec433.txt, Vec440.txt, and Vec456.txt

2. Another table showing station-Keeping impulsive delta-v comparisons between FreeFlyer and GMAT will be shown. This time final impulsive delta-v targeting is performed using attitude based delta-v coordinate system and perturbations due to attitude maneuver were modeled into ACE mission orbit. Four different historical navigation solutions were used to compare four delta-v comparisons from following TVHF files: Vec420.txt. Vec430.txt, Vec450.txt, and Vec472.txt

3. Third table showing short and long term propagation comparisons between FreeFlyer and GMAT will be shown. Short and long term propagation compares are 28 and 180 days respectively. Four propagation compares were done by using four different historical navigation solutions from GTDS. Four TVHF files used for propagation comparison were: Vec.433.txt, Vec440.txt, Vec450.txt, and Vec456.txt.

4. Results that will be shown in above tables are discussed in detail.

Test Readiness Review

Detailed discussion on test readiness review which was presented to FDF's FRB is discussed in this section. The outcomes of TRR and how did GMAT do at the end of TRR is discussed.

FDF Training and Shadow Operations

Discussion on training which was provided to FDF ACE maneuver planning team in how to use GMAT scripts to support ACE maneuver operations is presented in this section.

Discussion on non-interfering shadow operations which were held during a live ACE SK maneuver in FDF MOR is also presented in this section. ACE maneuver planning team used both FreeFlyer and GMAT to support ACE maneuver operations. At the end of the maneuver, products from both maneuver planning tools were produced and compared against each other.

Table showing impulsive delta-v and propagation comparisons between FreeFlyer and GMAT is presented. Impulsive SK delta-v and propagation compares were done using latest OD solution from vec493.txt TVHF. Vec493.txt file contained latest OD solution that was used to target ACE SK maneuver planned on Sep. 23rd, 2013.

Operational Readiness Review

Detailed discussion on operational readiness review is presented in this section. ORR was presented to the FRB committee. Results from test plans implementation and outcome of non-interfering shadow operations were presented. The outcome of ORR and how did GMAT do at the end of ORR is also presented in this section.

CONCLUSION

Summary

Big table of major GMAT ACE operational certification milestones, their delivery status and a very brief summary is shown.

APPENDIX

1. ACE Requirements Traceability Matrix that shows all 97 requirements will be shown in this section.

2. Sample Procedures from GMAT ACE LOP document will be shown in this section.

3. Sample of some of the test plans which were written to verify ACE requirements will be shown in this section.

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