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NAVIGATION OF THE GRAIL SPACECRAFT PAIR THROUGH THE EXTENDED MISSION AT THE MOON

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The GRAIL extended mission (XM) dramatically expands the scope of GRAIL's gravity science investigation by flying the pair of spacecraft at the lowest orbit the flight team can safely support. From the perspective of the Navigation team, the low orbit altitude introduces new challenges. At this lower altitude, navigation is more sensitive to higher-order terms of the gravity field so that orbit determination solutions are more difficult and there is less certainty of achieving maneuver targets.

This paper reports on the strategy and performance of the Navigation system for GRAIL's XM. On a weekly basis, the Navigation team provided reference trajectory updates, designed three maneuvers, and reconstructed the execution of those maneuvers. In all, the XM involved 55 planned maneuvers; five were canceled. The results of the Navigation team's efforts, in terms of maintaining the reference-trajectory targets, satisfying requirements, and achieving desired separation distances, are assessed.

INTRODUCTION

NASA's Gravity Recovery And Interior Laboratory (GRAIL) mission was a Discovery-class mission to map the lunar gravity field to high accuracy and spatial resolution.[1] The GRAIL science payload consisted of the Lunar Gravity Ranging System (LGRS). The LGRS measured the gravity field via the Ka-band ranging data telecommunicated between the two nearly-identical spacecraft, GRAIL-A (Ebb) and GRAIL-B (Flow), in a low, near-circular, near-polar orbit. The primary activity of the nine month Prime Mission (PM) was the 82-day Science Phase. The mean orbit altitude during this phase was approximately 55 km. Navigation for the PM has been reported previously.[2]

The GRAIL Project was managed at the Jet Propulsion Laboratory in Pasadena, CA, while the spacecraft were built and operated by the Lockheed-Martin Corporation in Denver, CO. This paper discusses the navigation strategy and performance from the end of the Science (SCI) phase in May 2012 to decommissioning in December 2013.

The Extended Mission (XM) dramatically expanded the scope of GRAIL's gravity science investigation. By operating the pair of spacecraft in the lowest orbit the flight team could safely support, the project increased the resolution of the gravity field measurement, see Figure 1. For the three

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months of XM science, weekly maneuver cycles kept altitudes at a mean value of about 23 km, but always greater than 8 km above the local topography.

The sensitivity to the gravity field that so enamored the Science team, was also a great challenge for the Navigation team. Proper modeling of the gravity field required very detailed models. As the estimation of such models was *the* research effort of this mission, it was not appropriate for the Navigation team (NAV) to bear such work. Instead, the GRAIL Science Data System (SDS) Orbit Determination (OD) team estimated that model and NAV used it without any alteration. NAV undertook the challenge of estimating the other trajectory models in the presence of strong residual signatures due to gravity, the one model that NAV could not estimate. As a result, the Navigation process was sensitive to any difference between the model and tracking measurements.

Larger OD uncertainty became larger maneuver delivery errors and therefore, a more challenging problem in flight-path control. Part of the solution to that problem was to more fully integrate Trajectory analysts into the Navigation process. This meant that, for GRAIL, the Trajectory analysts were developing new reference trajectories on a weekly basis and constantly re-optimizing the design to reduce target errors.

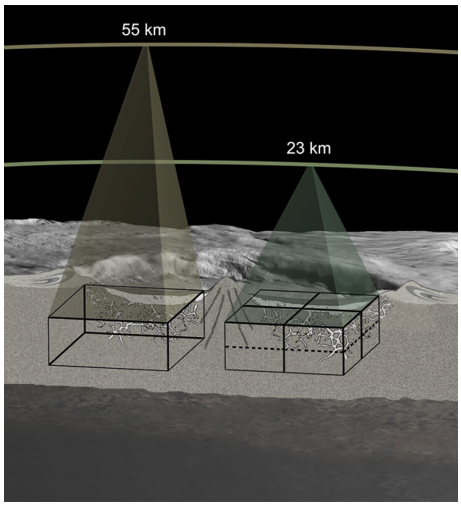


Figure 1. Improvement by changing altitude.

MISSION OVERVIEW

After performance of the flight systems was evaluated from 7 months of flight experience, the spacecraft team (SCT) at Lockheed Martin (LM) determined that the vehicles could survive the partial eclipse on June 4th, so the proposal to extend the mission until December 2012 was made. The GRAIL XM was chosen to map the lunar gravity at the even-closer mean altitude of 23 km for a three month science phase beginning in September 2012.

Between June and September 2012, the mission dealt with a lunar eclipse, more than two months of solar power too low for science, and then a series of maneuvers to transition to science formation. Once in the XM Science (SCI-XM) phase, three maneuvers were required each week from mid-August 2012 to December 2012 to keep the orbiters from impacting the Moon at this low altitude and maintain orbiter-to-orbiter separation close to 60 km. After the conclusion of the SCI-XM phase, the spacecraft would have too little fuel for another mission and would need to be decommissioned.

Mission Phase	GRAIL-XM ΔV Budget			
	Maneuver	GR-A ΔV (m/s)	GR-B ΔV (m/s)	Date (2012)
LEC	OCM-A1 / B1	15.7	15.5	31-May / 30-May
LBA	OTM-B3		0.05	20-Jun
TSF-XM	ECM-A1 / B1	30.0	29.9	21-Aug
SCI-XM	ECM-A2 / B2	7.3	7.4	30-Aug
SCI-XM	ECM-A3 / B3	4.2	4.2	06-Sep
SCI-XM	ECM-A4 / B4	11.0	10.9	13-Sep
SCI-XM	ECM-A5 / B5	11.7	11.7	20-Sep
SCI-XM	ECM-A6 / B6	8.0	8.0	27-Sep
SCI-XM	ECM-A7 / B7	4.1	4.0	04-Oct
SCI-XM	ECM-A8 / B8	10.9	11.0	11-Oct
SCI-XM	ECM-A9 / B9	11.5	11.6	18-Oct
SCI-XM	ECM-A10 / B10	7.9	8.0	25-Oct
SCI-XM	ECM-A11 / B11	4.1	4.0	01-Nov
SCI-XM	ECM-A12 / B12	12.0	11.0	08-Nov
SCI-XM	ECM-A13 / B13	11.5	11.1	15-Nov
SCI-XM	ECM-A14 / B14	8.1	8.2	22-Nov
SCI-XM	14 OTMs on GR-A	0.7		1 Day after ECMs
DCM				
GRAIL-XM ΔV Requirements		**158.5**	**156.4**	
ΔV Capability after PM		187.4	188.9	
Total ΔV Margin		**28.9**	**32.5**	

Legend:
LEC: Lunar Eclipse
LBA: Low Beta Angle
TSF: Transition to Science Formation
SCI: Science
DCM: Decommissioning
OCM: Orbit Circularization Maneuver
ECM: Eccentricity Correction Maneuver
OTM: Orbit Trim Maneuver

Note that this budget ends at ECM-A14,B14 so that it does not include decommissioning

Table 1. GRAIL XM ΔV Budget, Prior to Start of XM

An overview of the GRAIL XM mission design is given in Reference 3. The complex GRAIL mission owes its success to the systems engineering of the Mission Operations System.[4,5] OD results have been reported previously,[6] as have some results for flight path control.[7] The OD reference explains the OD filter strategy used during each phase and methods for mitigating the effects of the gravity errors in the solutions. The flight-path-control reference discusses maneuver $\Delta\mathbf{V}$ performance and execution-errors.

Science Objectives

The primary science objective was to determine the structure of lunar highland crust and maria, addressing processes that have shaped the near surface.[8] To address this objective, the mission undertook six investigations:

1. Structure of impact craters
2. Near-surface magmatism
3. Mechanisms and timing of deformation
4. Cause(s) of crustal magnetization
5. Estimation of upper-crustal density
6. Mass bounds on polar volatiles

These investigations were enabled by lowering the orbit altitude to approximately 23.5 km, com-

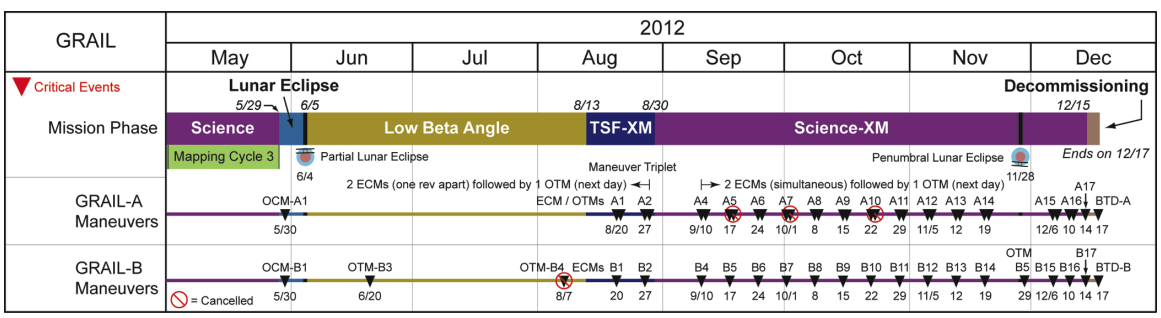
pared to 55 km in the prime mission. This increased both the spatial resolution and accuracy of the gravity measurement. With a spatial resolution of under 15 m at the lower altitude, the sensitivity of the gravity measurement was brought to a scale that was a fraction of the average thickness of the lunar crust.

In November 2012, the science objectives were enhanced, notably with a campaign over Mare Orientale, and associated with changes to the last weeks of the mission. The final maneuvers of the mission were retargeted to an even lower altitude for the last four days of data collection. Decommissioning, previously planned for 14 December, was delayed until 17 December which allowed time for engineering activities. Included in these activities were the Burn to Depletion (BTD) maneuvers to more precisely determine the remaining propellant and calibrate SCT's previous calculations tracking propellant usage.

Mission Timeline

The Lunar Eclipse (LEC) phase, see Table 2 and Figure 2, replaced the decommissioning phase as the last phase in the PM. The orbiters would have impacted the Moon on June 4th, 2012. Instead, the project prepared the orbiters thermal and power management systems to give them the best conditions to survive the partial lunar eclipse, also June 4th, 2012. The XM effectively started with this phase when each orbiter simultaneously performed Orbit Correction Maneuvers (OCMs) on May 30, 2012 to raise the orbit periapsis and mean altitudes in order to avoid the aforementioned lunar impact. The XM continued until 17 December 2012.

Figure 2 depicts the phases of XM and the placement of maneuvers. The first set of four Eccentricity Correction Maneuvers (ECMs) were used to put the spacecraft into the science formation during the aptly named Transition to XM Science Formation (TSF-XM) phase. That phase ended in late August, making way for the SCI-XM phase. Table 3 lays out the maneuver schedule on a grid of weeks to emphasize the rhythm of the mission, particularly SCI-XM. At the end of the SCI-XM phase in December, that rhythm was broken in support of the Mare Orientale campaign and course adjustments that were necessary to obtain the desired decommissioning.



Decommissioning maneuvers are omitted. ECM-A3,B3 were not planned

Figure 2. Timeline of Activities.

Navigation Requirements

The science objectives placed requirements on the mission design and navigation of the orbiters. One of the key and driving mission design/navigation requirements was to ensure the orbits of the two satellites during SCI-XM were co-planar, such that they would have an inclination difference of

Table 2. GRAIL XM Phases

Phase	Begin
Lunar Eclipse (LEC)	May 29, 2012
Low Beta Angle (LBA)	June 5, 2012
Transition to XM Science Formation (TSF-XM)	August 13, 2012
XM Science (SCI-XM)	August 30 2012
Decommissioning (DCM)	December 14, 2012
End of Mission	December 17, 2012

Table 3. XM Maneuver Calendar

wk	Phase	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
22	LEC			OCM-A1,B1		
23						
24						
25	LBA		OTM-B3			
26						
27						
28						
29						
30						
31	LBA	~~OTM-B4~~				
32						
33						
34	TSF-XM	ECM-A1,B1	OTM-A1			
35	TSF-XM	ECM-A2,B2	OTM-A2			
36	SCI-XM		~~OTM-A3~~			
37	SCI-XM	ECM-A4,B4	OTM-A4			
38	SCI-XM	ECM-A5,B5	~~OTM-A5~~			
39	SCI-XM	ECM-A6,B6	OTM-A6			
40	SCI-XM	ECM-A7,B7	~~OTM-A7~~			
41	SCI-XM	ECM-A8,B8	OTM-A8			
42	SCI-XM	ECM-A9,B9	OTM-A9			
43	SCI-XM	ECM-A10,B10	~~OTM-A10~~			
44	SCI-XM	ECM-A11,B11	OTM-A11			
45	SCI-XM	ECM-A12,B12	OTM-A12			
46	SCI-XM	ECM-A13,B13	OTM-A13			
47	SCI-XM	ECM-A14,B14	OTM-A14			
48	SCI-XM				OTM-B5	
49	SCI-XM				ECM-A15,B15	OTM-A15
50	DEC	ECM-A16,B16	OTM-A16			ECM-A17,B17
51	DEC	BTD-A,B				

The left column is the 2012 week number

less than 0.1° and a difference in longitude of the ascending node less than 0.1°. Other requirements for SCI-XM, some of which were carried over from PM:

- the maximum orbital inclination of 89.72° ± 0.152°;
- the periapsis altitude of the orbits to be greater than 10 km, but not exceed 55 km;
- the separation distance between the spacecraft was to be maintained between 45-75 km for the SCI-XM phase;
- the orbiters to fly with GRAIL-A in the lead position;
- the onboard ephemerides were updated, in order to maintain GRAIL-A and GRAIL-B attitudes and relative positions, with ephemeris pointing errors smaller than 0.073° (1σ).
- The predicted trajectory event-timing error needed to be less than 120 seconds for the LEC, and LBA phases and less than 180 seconds for the TSF-XM, SCI-XM, and DCM phases (i.e., for occultation entry/exit events).

To ensure adequate power from the solar arrays which were aligned in the orbit plane, the solar beta angle (angle between orbit plane and the Sun direction) during the SCI phase was always greater than 49°. This last requirement was later ignored for the start of the SCI phase during operations when it was found that the solar panels were able to have adequate power starting with beta angle of 40°.

NAVIGATION SYSTEM

Tracking

Much the same as the primary mission, Navigation during XM was accomplished using the traditional navigation data types of 2-way S-band Doppler (primary) and range radio-metric data transmitted through the Deep Space Network (DSN) in Goldstone, CA; Canberra, Australia; and Madrid, Spain and transponded by 1 of 2 hemispherical Low-Gain Antennas (LGAs) (mounted on the ± X-axis panels). Doppler data was augmented occasionally with the 1-way X-band Doppler data which was transmitted by 1 of 2 Radio Science Beacon (RSB) antennas also mounted on the ± X panels. The S-band frequency spectrum of the tracking signal restricted the available tracking resources to the following S-band-capable 34m tracking stations: Deep Space Stations (DSSs) 24, 27, 34, 45, 54, 65. DSS-24 (Goldstone), 34 (Canberra), and 54 (Madrid) are Beam Wave Guide (BWG) antennas. DSS-27 (Goldstone) is a High Speed Beam Wave Guide and DSS-45 (Canberra) and 65 (Madrid) are High Efficiency antennas. More detail on tracking may be found in Reference 6.

Navigation Team

The NAV Team, which was led by the Team Chief and Deputy Team Chief, consisted of the following functional sub-teams: the Trajectory Design (TRAJ), OD, and Flight Path Control (FPC) Teams. The OD and FPC Teams were subdivided into separate GRAIL-A and GRAIL-B teams. Each GRAIL-A and GRAIL-B Team included 3 OD analysts and 2 FPC analysts. A fifth FPC member was considered a floater and worked on tracking performance and other longer-term tasks. TRAJ consisted of 2 analysts who were originally members of the Mission Design Team, one who doubled as a GRAIL-A FPC member. The TRAJ team was responsible for updating the reference

trajectories of both spacecraft during all phases of the mission to ensure the science requirements were met. They also computed any necessary updates or verifications of the Safe-Mode Conic ephemeris[2] and prepared the Project for contingencies in the case of missed maneuvers. The OD Team was responsible for predicting the trajectories of both orbiters based on the latest tracking data on a near-daily basis. They were also responsible for reconstructing all maneuver executions and delivering the latest predicted trajectories to the DSN in order to generate antenna pointing and frequency predicts, or to SCT to upload to the orbiters for maintaining accurate pointing for gravity science. The FPC Team was responsible for designing all maneuvers, monitoring real-time data during maneuver execution, tracking maneuver performance, and contributing to maneuver assessments. OD solution deliveries and final maneuver designs were always verified by backup analysts and peer reviewed by the 6-9 member Navigation Advisory Group (NAG) at JPL.

With GRAIL's SCI-XM phase, the reference trajectory was updated on a weekly cycle, effectively involving the trajectory team in the maneuver design process. This meant that the maneuver-design strategy had a human in the loop. In that situation, the FPC team was not equipped to perform a typical high-fidelity Monte Carlo simulation.

Maneuver Development

The maneuver development schedule during SCI-XM phase was notable for having interleaved three parallel processes:

- monitoring of the current ECMs (#*N*), design of current Orbit Trim Maneuver (OTM), and design of next-week's ECMs (#*N+1*)
- development of the reference trajectory to guide the ECMs for week after next (#*N+2*)
- maneuver assessment for the current ECMs and OTM (#*N*) and OD covariance studies to predict near-term performance

The typical schedule during SCI-XM, using ECM-A9/B9 as an example, began with a new OD delivery early Monday morning, around 6:30 AM local time, to support real-time monitoring of tracking and telemetry for the near-simultaneous ECM-A9/B9, around 8:30 AM. A preliminary status would be reported around 1:00 PM. In support of the next-day's OTM-A9, a new OD delivery including a reconstruction of the ECMs would be delivered about 1:30 PM. By 3:30 PM, the maneuver design was delivered and by 5:30 PM ephemeris predicts were delivered to DSN. This gave the other teams time for analysis to support the command conference at 8:00 PM.

Tuesday repeated the OD delivery and monitoring times, but for OTM-A9. The post-OTM OD delivery would be made by about 1:30 PM and followed by the design process for the next week's ECM-A10/B10. The designs were reviewed by the NAG at 4:00 PM and NAV delivered the designs by 5:30 PM. With a short timeline for developing presentation materials, the automation architecture used for Cassini-Huygens was adapted and expanded for GRAIL Navigation.[9]

The assessments of ECMs and the OTM were presented on Wednesday morning along with a summary of the next ECMs. That meeting was followed by development of the sequence of commands for ECM-A10/B10. Verification between NAV and SCT was performed and reported at an afternoon meeting, around 3:30 PM. Near the end of Wednesday, about 5:00 PM, the new reference trajectory was delivered to the project. That reference trajectory would provide targets for ECM-A11/B11.

On Thursday, preliminary designs for ECM-A11/B11 were delivered by the FPC team by noon. At 12:30 PM there would be a command conference for ECM-A10/B10. At 1:00 PM, the so-called Kickoff meeting described the preliminary ECM-A11/B11 designs to the project. This schedule left Friday and the weekend available as margin, for coping with any delays that arose during the week.

The near-simultaneous scheduling of the ECMs was a very noticeable trait of the SCI-XM phase. However, whether the maneuvers were simultaneous or hours apart, the staffing, scheduling, and work load of NAV, and many other teams, was nearly identical. This could be concluded by noting that the work for each maneuver spanned days before execution and hours to days after execution. The consideration that lead to near-simultaneous ECMs was the on-board approximation of the spacecraft ephemeris. Whenever ECMs were separated by hours, the spacecraft's trajectories were increasingly different, and the attitude profile for orbiter-to-orbiter pointing diverged from the routine. Having the maneuvers nearly simultaneous, therefore, regularized the attitude profile and simplified the process of producing the best-fit polynomials. Perhaps the most noticeable impact to operations was that both the GRAIL-A and GRAIL-B teams needed to report results on the voice-net at the same time. The reporting procedures were practiced in an Operational Readiness Test (ORT) and found to be manageable.

After both ECMs had executed, there was much interest in assessing the maneuver performance and providing a preliminary estimate of whether an OTM would be needed and, if so, how large it might be. NAV developed a tool to approximately estimate the post-ECM orbits. That estimate could be used to compute the corresponding estimate of spacecraft separation distance and, then, the OTM $\Delta\mathbf{V}$. These estimates were displayed graphically, a screenshot is given in Figure 5. Estimates computed by the tool were not used operationally, only to aid monitoring and assessment.

On the left side of Figure 5, the tool displayed Doppler tracking data residuals for both spacecraft, GRAIL-A above and GRAIL-B below. On the right side, at the bottom, was a plot of the predicted evolution of the separation distance. On this plot, the tool would indicate if the separation distance might exceed ± 15 km. Based on a rough estimate of uncertainty, the tool would also provide an estimate of the likelihood that the separation distance would exceed ± 15 km, requiring the OTM.

OPERATIONS

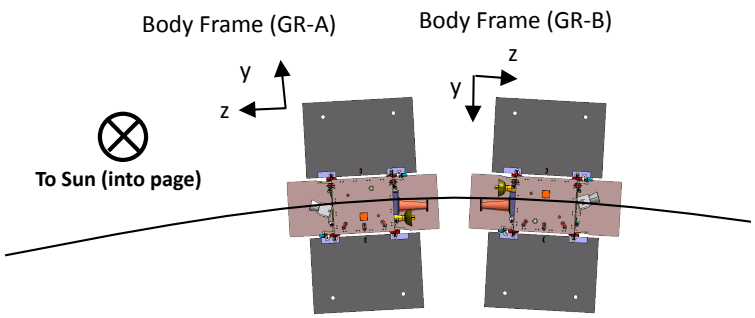
Lunar-Eclipse Phase

During any eclipse, the spacecraft would have to rely on batteries, which was deemed risky enough that the prime mission had been planned to occur entirely between eclipses. Based on flight experience and later analyses, the GRAIL spacecraft would be able to survive the eclipse following the prime mission on June 4, 2012. This, the LEC phase, included the activities to reduce power consumption and thermally prepare the spacecraft for passage through the eclipse.

The trajectory for the prime mission had been designed with a lunar impact one week after the end of the science phase. This impact was avoided by implementing OCMs on both spacecraft, OCM-A1 and OCM-B1. These maneuvers also changed the phasing of the spacecraft so that GRAIL-A would be in the lead position. This change was necessary because the the XM Science phase was on the other side of the Sun (roughly six months, or 180°, later). Each spacecraft would be turned roughly 180° for the solar arrays to track the Sun between the end of the prime science phase and the beginning of the XM science phase. For the Ka-band antennas to point at each other, GRAIL-A would need to be in the lead position. This is depicted in Figure 3.

During the LEC phase, NAV delivered new ephemerides to support onboard knowledge of Sun and Earth. The ephemerides that had been delivered and processed for the PM ran out at the end of the primary science phase.

On May 30, 2012, GRAIL-B executed OCM-B1, the day after a final Ka-band boresight calibration. The other maneuver, OCM-A1, was executed by GRAIL-A on May 31, 2012. Each maneuver needed roughly 16 m/s to raise the orbit altitude. Prior to these maneuvers, GRAIL-B had been in the lead position. Raising the orbit of GRAIL-B caused it to slow down and allow GRAIL-A to move into the lead position. The new arrangement was set once OCM-A1 was executed.



S/C are traveling to the left and GRAIL-A is in the lead position

Figure 3. XM Orbiter Configuration

Low-Beta-Angle Phase

The LBA phase was marked by low activity on the spacecraft. At low beta angles, there was not enough power to operate the LGRS for science. Post-launch analyses suggested that science data collection could be resumed at or above a beta angle of 40°. There was one maneuver, OTM-B3, executed on 20 June 2012 to manage the separation rate between the orbiters, targeted to the desired separation distance for the start of TSF-XM, 665 km.

OTM-B3 was a turn-and-burn style maneuver. It was small, with a $\Delta\mathbf{V}$ magnitude of 20.4 mm/s, see Table 7. The direction of the maneuver was parallel to the spacecraft's velocity vector – the separation distance at the targeted date was achieved by adjusting the orbital period.

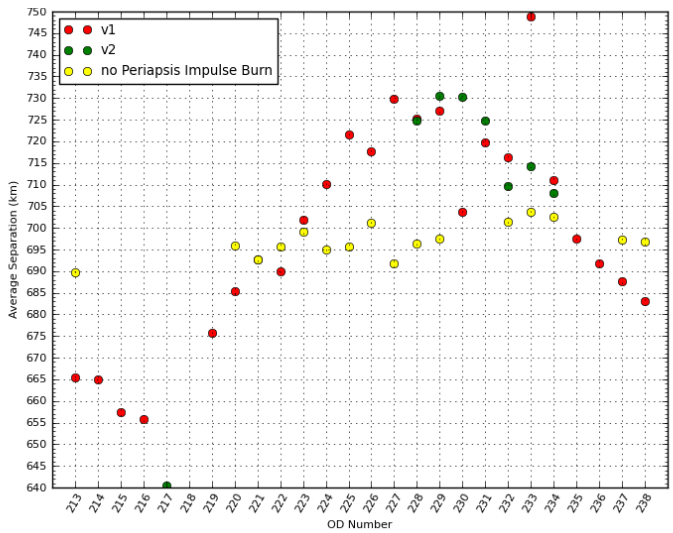
Beginning on June 5, 2012, these 10 weeks provided an opportunity for team training and ORTs that were necessary for XM. The training and ORTs were necessary because the maneuver schedule for XM was quite different than PM and procedures for the Navigation team, as well as for other teams, were changed significantly.

A maneuver, OTM-B4, was available during the first week of August 2012, near the end of the LBA phase. As long as the spacecraft-to-spacecraft separation distance for the start of the TSF-XM phase was within bounds, this maneuver would be canceled. However, the GRAIL navigation team observed a drift in the predicted separation distance following the execution of OTM-B3. The trend may be seen in Figure 4 with points plotted as "v1" and "v2". The relative range in that plot was evaluated for August 20, 2012 15:00 UTC and exhibited an increase of approximately 4.0 km/day. The secular nature of the drift was indicative of dynamic mis-modeling, which resulted in a semi-major axis (period) prediction error.

In the figure, separation distances are plotted for each OD delivery. OD deliveries were made nearly every day, but not at regular intervals. For the purpose of reading the plot, one may approximate the deliveries as daily. The delivery date of od213v1 was 11 Jun 2012 and the delivery date of od238v1 was 18 July 2012 giving an average of one delivery every 1.5 days.

The mis-modeling centered around the use of impulsive $\Delta\mathbf{V}$s at periapses during the data arc. The periapse $\Delta\mathbf{V}$s improved the tracking data residual errors during the data arc. However, because of the resultant mis-modeling, trajectory predictions were poor. The intent for these fictitious $\Delta\mathbf{V}$s was to capture deviations due to gravity modeling errors. The gravity modeling errors came from the lack of computer processing capability available to the Navigation team to estimate a full gravity model within the operations schedule. That schedule was not a constraint for the model estimation by the Science team.

The OD team examined simply removing the impulsive periapsis $\Delta\mathbf{V}$s from the filter strategy. The prior OD deliveries were recomputed with the new strategy and the result may be seen in Figure 4 with the label "no Periapsis Impulse Burn". The tracking data residuals were larger but the new strategy gave more consistent predictions. OD deliveries od239 and later used the new strategy.[6]



"v1" and "v2" refer to first and second deliveries, the second delivery with updated modeling

Figure 4. Comparison of Average Separation Distance at 15:00 UTC on 20 August 2012 Predicted by Various OD Deliveries (varying data cutoff)

Transition-to-XM-Science-Formation Phase

The primary purpose of the TSF-XM phase was to reduce each orbiter's semimajor axis and establish the conditions to begin collection of gravity science data. The first two weeks of ECMs were in the TSF-XM phase. The maneuver ECM-B1 was performed approximately two hours, roughly one orbit, before ECM-A1 and each imparted roughly 40 m/s $\Delta\mathbf{V}$. Performing the maneuver first, GRAIL-B was dropped to a lower, faster orbit to reduce the separation distance to 100 km so that the next week's maneuvers could drop it to 60 km for the science orbits.[3]

Also, in the first and second week, OTM-A1 and OTM-A2 provided a finer correction to the separation distance. Unlike the OTMs to come in the SCI-XM phase, the spacecraft's attitude

profile was inertially fixed during execution.

The following week saw the execution of ECM-B2 and ECM-A2, in that order, also with burn start times separated by nearly two hours. These ECMs used the same set of target parameters with values from the then-current reference trajectory, as developed by TRAJ. The lower target for separation distance, 60 km, was first used for OTM-A2, executed the day after ECM-B2,A2.

The Navigation team used lunar gravity models delivered by the Science team, which were of large degree and order spherical harmonics. The propagation time for maneuver targeting search iterations was prohibitively long as the maneuver start time and target event were separated by a week. For ECM-A2,B2 and OTM-A2, that duration was two weeks, in support of skipping ECM-A3,B3. The accepted compromise was to extrapolate trends in period and separation distance to the target epoch while other targeted parameters, such as eccentricity, were evaluated at the first periapsis after the $\Delta\mathbf{V}$ being designed.

The TSF-XM ECMs $\Delta\mathbf{V}$ and start time were targeted to achieve the desired orbit period, eccentricity, argument of periapsis, and longitude of the ascending node. The target values for these were chosen by the Trajectory analysts to achieve the proper science orbit altitude and phasing. The target parameters eccentricity, argument of periapsis, and the longitude of the ascending node were defined as osculating at the first periapsis following the maneuver. The period target was selected so as to correct downtrack errors relative to the reference trajectory. In other words, the target value was selected to match the in-orbit phasing of the reference trajectory. The phasing was measured relative to a node crossing N orbits after the current maneuver. The node was between the spacecraft's orbit plane and the X-Y plane of EME2000. The relationship between node crossing time and period was modeled as in Equation 1.

$$t_N = t_{N,o} + N\left(P_f - P_o\right) \tag{1}$$

where t_N is the time of the Nth node crossing as affected by the maneuver $\Delta\mathbf{V}$ and P_f is the orbital period, also affected by the maneuver. The variables $t_{N,o}$ and P_o are the the corresponding quantities in the trajectory without the maneuver, viz. the OD estimate. This model would be fine if only the orbital period was changing. However, the maneuver also changes the time of the first post-maneuver node crossing. The time of that crossing is modeled as

$$t_1 = t_{1,o} + \left(P_f - P_o\right) \tag{2}$$

where t_1 and $t_{1,o}$ are the times of the first post-maneuver node crossing, with and without the maneuver $\Delta\mathbf{V}$, respectively. Differencing Equations 1 and 2 and solving for P_f produces

$$P_f = P_o + \frac{\Delta t_N - \Delta t_1}{N-1} \tag{3}$$

Now, P_f is the desired post-maneuver period, $\Delta t_N = t_N - t_{N,o}$ is the time between the Nth node crossing in the reference trajectory and the Nth node crossing in the OD trajectory, $\Delta t_1 = t_1 - t_{1,o}$ is the time between first post-burn node-crossing with the burn $\Delta\mathbf{V}$ modeled and as reported in the OD estimate.

Instead of implementing Equation 3 as written, we recall that P_f and Δt_1 are both affected by the maneuver. On the other hand, P_o and Δt_N are fixed values dependent only on the reference trajectory and the OD estimate. We then rearrange this to define a new time target function, as follows

$$P_{\text{bias}}(\Delta V) = P_f(\Delta V) + \frac{\Delta t_1(\Delta V)}{N-1} = P_o + \frac{\Delta t_N}{N-1} \tag{4}$$

The left-hand side of Equation 4 is a function of the maneuver $\Delta\mathbf{V}$ and the right-hand side is the desired value for that function. The function $P_{\text{bias}}(\Delta V)$ is referred to here as the biased period. This was the target parameter used for the ECMs in the TSF-XM and SCI-XM phases. Both period variables P_f and P_o were evaluated as averages of the orbital period over an 18-hour duration following the maneuver.

Each week, one day following the two initial ECMs, an OTM was performed to manage the separation distance between the two orbiters, see Table 3. The target separation distance of 60 km was repeated from OTM-A3 through OTM-A13 but was changed to 40 km at the end of the SCI-XM phase. OTM-A6 targeted a separation distance of 44 km.

Managing the separation distance ensured collision avoidance between the two orbiters and provided the desired configuration for science. OTMs were quite different from ECMs as they had only one target, the separation distance, and only one free parameter, the $\Delta\mathbf{V}$ magnitude. The $\Delta\mathbf{V}$ direction followed a prescribed pointing direction over time.

The $\Delta\mathbf{V}$ pointing for OTMs was an extension of the orbiter-point attitude definition. That definition used the on-board ephemeris to point the LGRS antenna at the other spacecraft. This was terminated at the start of an OTM. The attitude mode during the burn was defined as the start-of-burn orbiter-point attitude plus a constant-rate fixed-axis rotation designed to approximate orbiter-point. This rotation was performed about the same axis, defined in the spacecraft frame, for each OTM in the extended mission. Using the same axis each time simplified the process for all teams involved and did not significantly impact performance.

Propagation time was an issue for the OTM search iterations and a compromise similar to the ECMs was used. The separation distance at the target epoch was linearly extrapolated from the orbit period and the separation distance soon after the burn. In some cases, the linear extrapolation needed a fixed bias to reduce the prediction error. The extrapolation was computed according to Equations 5-8.

$$\delta(t_f) = \bar{\delta} + \gamma \cdot (t_f - \bar{t}) \tag{5}$$

$$\bar{\delta} = \frac{1}{N}\sum_{i=1}^{N} r(t_i) \tag{6}$$

$$\bar{t} = \frac{t_N - t_1}{2} \tag{7}$$

$$\gamma = \frac{2\pi\hat{a}}{\hat{P}^2}\frac{1}{N}\sum_{i=1}^{N}\left(P_b(t_i) - P_a(t_i)\right) \tag{8}$$

where quantities are being averaged with N points evenly spaced from t_1 to t_N; $\bar{t}$ is the midpoint of that interval. P_a and P_b are the osculating orbital periods for either spacecraft, GRAIL-A and GRAIL-B, respectively. GRAIL-A is in the lead so if $P_a > P_b$, then the spacecraft will get closer, and if $P_a < P_b$, they will drift further apart. The variable γ is an approximation of the relative separation rate with $\hat{a}$ and $\hat{P}$ approximate semimajor axis and period of the the science orbit, roughly

Table 4. OTM Cancellations

	OD	DCO	Target Epoch	Predicted Error
OTM-A3	od273v1	29-Aug	10 Sep	5.6 km
OTM-A5	od288v3	17-Sep	24 Sep	3.0 km
OTM-A7	od300v3	1-Oct	8 Oct	4.0 km
OTM-A10	od316v3	22-Oct	29 Oct	7.0 km

circular. Finally, $r(t_i)$ is the computed distance between the spacecraft at time t_i, $\bar{\delta}$ is the averaged separation distance, and $\delta(t_f)$ is the extrapolated separation distance at epoch t_f. In practice the FPC analysts chose t_1 to be an hour after the burn and t_N to be about 12 hours after t_1 with N large enough to get points every second.

XM-Science Phase

The primary objectives for the Navigation team during the SCI-XM phase were to manage the evolution of the eccentricity and argument of periapsis, maintain an orbital altitude near 23 km, and control the separation distance to 60 km. Additionally, TRAJ was still active in planning the decommissioning phase.

The SCI-XM phase was a repeating cycle of low-altitude orbits needing weekly adjustment so as to avoid lunar impact.[3] The orbital eccentricity, argument of periapsis, and phasing were adjusted by the pair of ECMs performed on Mondays. If perfect, those maneuvers, by virtue of the phasing target, would also achieve the desired separation distance. As that distance was important for the science investigation, it was corrected by an OTM one day after the ECMs. This is the same pattern and targeting previously used in the TSF-XM phase. The schedule of maneuvers is shown in Table 3. A notable difference is that, in TSF-XM, the ECMs were about 1 orbit apart but, in SCI-XM, they were only about 30 seconds apart.

In the event a maneuver was missed, the trajectory design provided a minimum of 10 days before impact with the surface. This would be enough time to recover using the next ECM or with additional maneuvers.

The mission design was able to afford one break in the maneuver schedule; week 36 of 2012 did not include any planned ECMs. Table 3, as a result, doesn't list any ECM-A3 or ECM-B3. However, an OTM-A3 might have been needed and was scheduled. Based on tracking data following OTM-A2, the prediction from the OD team of the spacecraft separation distance at the time of ECM-A4/B4 was approximately 71 km. The target had been 60 km. The criteria for needing an OTM was if the separation distance was below 45 km or above 75 km. Therefore, OTM-A3 was cancelled.*

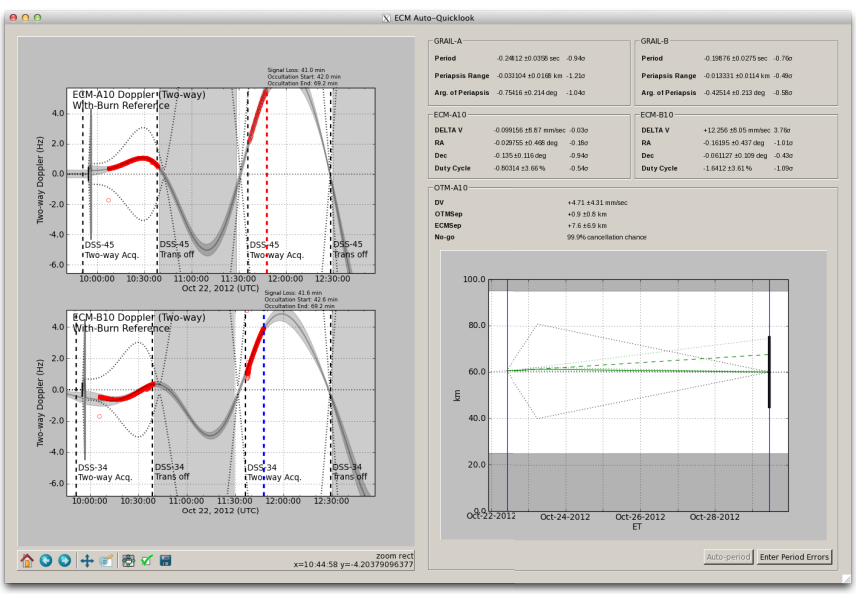
Three other OTMs were cancelled during SCI-XM: OTM-A5, OTM-A7, and OTM-A10. Each was cancelled because the predicted error in separation distance was too small compared to the criteria. All of the OTMs cancelled during the XM are listed in Table 4. OTM-A3 is notable for the longer duration between data cut-off (DCO) and the target epoch, about two weeks, as opposed to about 1 week for the others. OTM-A3 was cancelled based on results just after OTM-A2, a week ahead of the maneuver and, therefore, two weeks ahead of its target.

*Reference 6 neglected to mention the planning and cancellation of OTM-A3

Plans for the SCI-XM phase were updated well into August and beyond. Perhaps the largest change went into effect with refod289v1, used for the design of ECM-A7,B7 and the first reference trajectory to include up to and past ECM-A15,B15. The operations schedule changed significantly near the end of the SCI-XM phase, with week 47 of 2012 (19 November). That became the first week without an ECM pair the following Monday. The next ECMs, ECM-A15,B15 were in week 49, on Thursday, 6 December 2012. The maneuvers were moved from Monday to target a lower altitude for an overflight of the Mare Orientale basin. Along with this change, the post-ECM-A16,B16 orbit lifetime would end on 14 December. The final ECMs, ECM-A17,B17 were necessary to move the lunar impact for the desired decommissioning.

The changes rearranged operations schedules NAV and other teams. Ephemeris updates for the onboard pointing profiles and deliveries for DSN, etc., had to be shifted with appropriate changes to work schedules for the team members. After several weeks of an identical schedule, it would be a noticeable adjustment.

Another change came when the Science team requested that NAV lower the orbital altitude to improve the uniformity of topographic coverage, particularly in the region 0-60° W, 30-60° N. The changes were within the design constraints as the existing reference, although topographic altitudes were lowered throughout the 17 days between ECM-14 and -15. In fact, the topographic altitude dropped to 2 km immediately following ECM-14. If either ECM-A15,B15 were missed, the spacecraft would crash on December 10th. As for the maneuvers, the change resulted in an increase of 4.2 m/s in reference ECM-12 and 0.8 m/s in ECM-13, ECM-14 was reduced by 2.6 m/s. The first reference trajectory to reflect this change was refod312v3, used for the design of ECM-A11,B11.



Estimates not accurate, used for monitoring

Figure 5. Example of Graphical Display to Estimate an OTM in Real Time

Decommissioning Phase

The DCM phase ended with a destructive, targeted delivery of the GRAIL spacecraft onto the lunar surface. This phase started with ECM-A17,B17, which delayed lunar impact until 17 Decem-

ber 2012. These maneuvers first appeared in reference trajectory refod341v1, which was used for the design of ECM-A15,B15. The DCM trajectory had been redesigned to target the chosen surface feature and avoid lunar heritage sites.

With this end-game planned, the project allowed for some engineering experiments and, in particular, the final maneuvers were planned to burn to depletion. The so-called BTD maneuvers would not actually deplete *all* the fuel. Instead of implementing these burns with the usual $\Delta\mathbf{V}$ cutoff algorithm, SCT used an acceleration cutoff with a target acceleration designed to indicate that the tank was nearly empty. The BTD maneuvers and engineering activities were added as late as November 2012. Telemetry from the execution of these maneuvers indicated that SCT's estimates of fuel remaining had been accurate to about 0.5 kg. Table 7 shows the magnitude error of BTD-A was about 5 m/s and that translates to about 0.5 kg of fuel; likewise, BTD-B shows an error of 2.7 m/s that translates to about 0.3 kg of fuel.

The operations timeline did not allow time for an update to the BTD designs that would improve the targeting to the surface. Instead, NAV opted to set the burn direction for the BTD maneuvers as the nominal out-of-plane direction and execute them at a time so as to place the node of the new and old orbit planes as close as possible to the impact location. This minimized the influence of the BTD maneuvers on the impact target and was relatively insensitive to the $\Delta\mathbf{V}$ magnitude, which was important because the nature of these events placed a large uncertainty on $\Delta\mathbf{V}$ magnitude.

In order to minimize any telecommunications loss associated with multipath errors, both spacecraft's antennas were pointed directly to Earth after the BTD cutoff. There did not appear to be any loss of quality in the tracking data leading to impact.

To support real-time monitoring and help provide the latest information to other project members, NAV developed a tool to generate real-time, rough estimates of the BTD-A,B magnitudes and the impact location. The layout of this tool may be seen in Figure 8. The top left pane of the tool displayed a figure similar to Figure 6 - an overhead view of the spacecraft trajectories and their targets. The top right-hand pane display two graphs of real-time Doppler tracking data residuals. Each of those graphs displayed an extra axis, or ruler, for the user to visually inspect the residuals and be able to judge what the $\Delta\mathbf{V}$ magnitude of the BDT-A or BDT-B maneuver had been. The bottom left-hand pane displayed a disk of the Moon and the spacecraft's trajectory so a whole orbit around the Moon would be visible and the latitude of the impact site was marked. The bottom right-hand pane displayed a figure much like Figure 7, for as the moment of impact approached, this figure would show the spacecraft position relative to surface features and hazards, in particular, an intervening ridge and then the impact site. Estimates computed by the tool were not used operationally, only to aid monitoring and assessment.

Tables 5 and 6 compare the reconstructed impact locations of GRAIL-A and GRAIL-B to the nominal (designed) locations determined after the BTD-A,BTD-B timing updates. The times of impact are compared to the last 2-way Doppler data received at the Goldstone DSS-24 and DSS-27 stations and the open-loop 1-way X-band Doppler recording. Notice these times are after the reconstructed impact times. Figure 6 shows a close-up of the impact region. One thousand samples of the Monte Carlo analyses are shown as the blue and red scattered points and appeared as blurred regions in the figure. Note that the GRAIL-B data obscures much of the GRAIL-A samples. The reconstructed trajectories moved west of the nominal trajectories because of the longer BTD burn durations.

Figure 7 shows the reconstructed GRAIL-A and GRAIL-B trajectories in a sideways view, which

Table 5. Reconstruction of GRAIL-A's Impact Location

	Design	Estimate
Impact Event Time	22:28:46.6 $\pm$ 2 sec	22:28:46.96 $\pm$ 0.63 sec
East Longitude	$-26.4680°$	$-26.6432° \pm 0.0084°$
North Latitude	$75.6165°$	$75.613° \pm 0.035°$
Altitude	855.9 m	749.2 m

Table 6. Reconstruction of GRAIL-B's Impact Location

	Design	Estimate
Impact Event Time	22:29:14.8 $\pm$ 2 sec	22:29:15.56 $\pm$ 0.39 sec
East Longitude	$-26.7810°$	$-26.8992° \pm 0.0024°$
North Latitude	$75.6300°$	$75.654° \pm 0.022°$
Altitude	863.5 m	1035.3 m

shows the flight path over the topography before impact. The topography is from Lunar Reconnaissance Orbiter (LRO) data (LOLA). Each point plotted represents the nominal trajectory computed at the time-tag of a Doppler tracking measurement. There are clearly two points shown within the lunar surface. This artifact is due to two factors. The first is that plot of topography isn't in the correct frame for the LOLA data and this difference would bring one point outside the topography. The second factor is due to the way DSN Doppler measurements are taken. The DSN uses a phase-locked loop tuned to be robust to brief outages. As impact behaves, at first, like a brief outage, the loop does not fail immediately and will cause the DSN to report an extra data point. This is a *desired* feature in the DSN design, not a fault, and serves as a reminder that the Doppler data time-stamps are not intended to give an appropriate indication of impact. Post-processing of the Doppler data and data from the Radio Science Receiver at the DSN station do give a reliable indication of the impact timing and location..

NAVIGATION PERFORMANCE

The trajectories from OD reconstructions throughout the mission have been assembled into a final reconstructed trajectory for the mission. The trajectory is available from the Planetary Data System website, `http://pds.nasa.gov/`. The trajectory files are

- `grail_110910_120102_nav_v01.bsp`,
- `grail_120102_120301_nav_v01.bsp`,
- `grail_120301_120529_nav_v01.bsp`,
- `grail_120529_120830_nav_v01.bsp`,
- `grail_120830_121217_nav_v01.bsp`,
- `grail_121217_991231_crashsite_v01.bsp`.

By comparing these reconstructions to predictions made during the course of the mission, we may make some measurements of NAV's performance.

Orbiter-to-Orbiter Pointing Errors

The science investigation required each spacecraft to have accurate on-board pointing knowledge of the other spacecraft's location. This on-board pointing profile was computed from polynomial representations of both spacecraft's ephemerides. The ephemerides were supplied by NAV. NAV

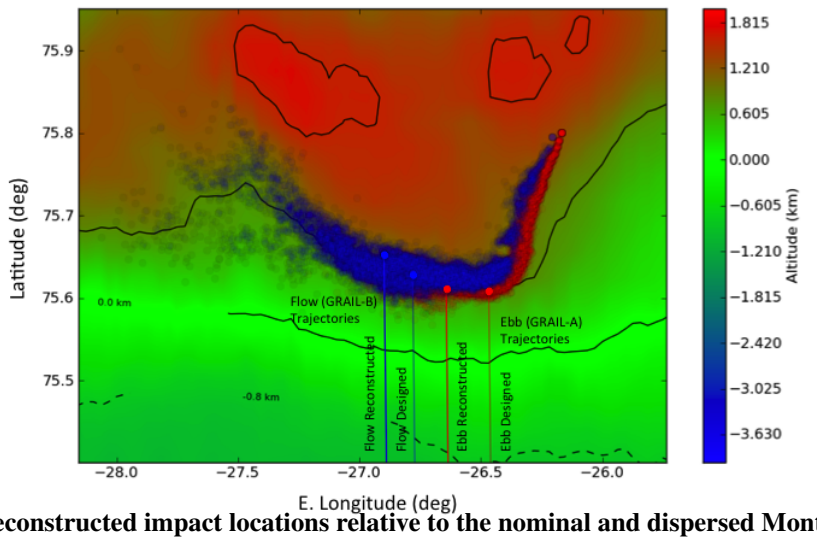


Figure 6. Reconstructed impact locations relative to the nominal and dispersed Monte Carlo cases

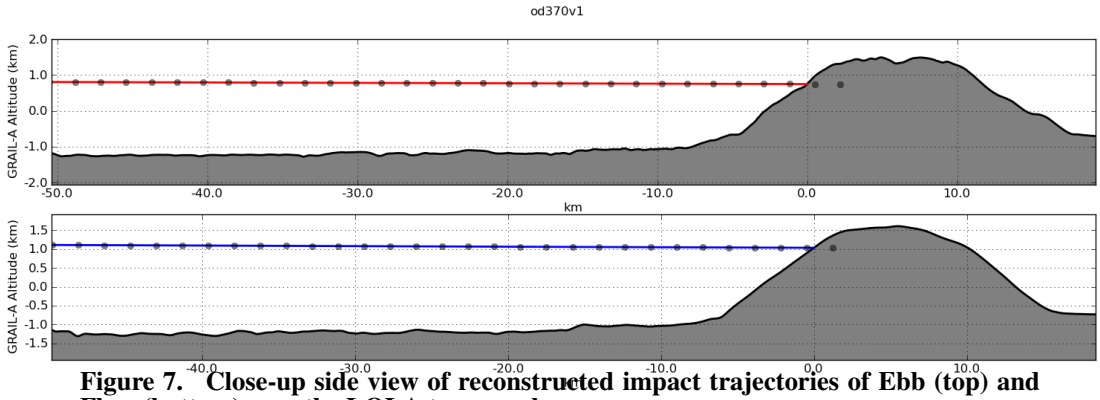
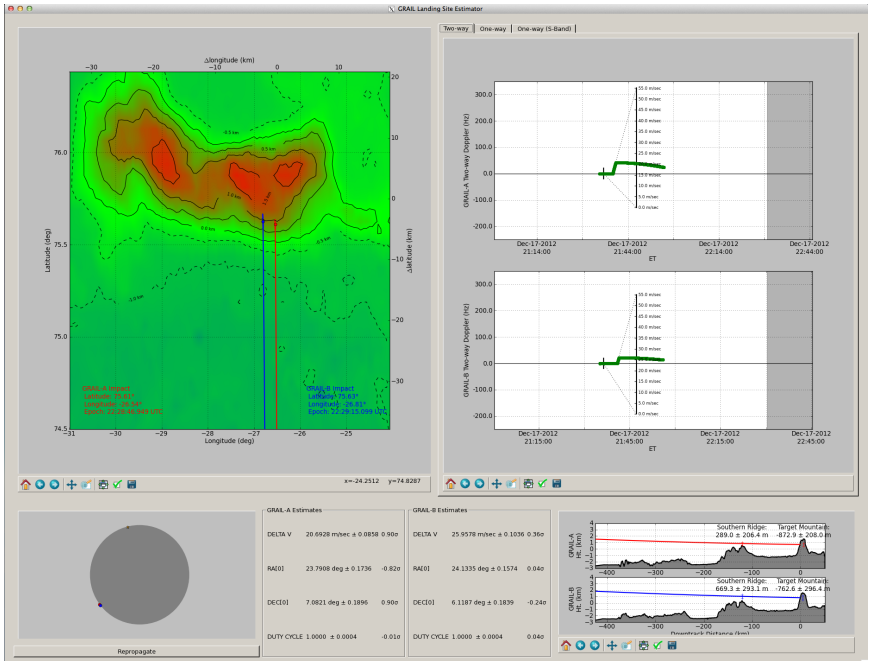


Figure 7. Close-up side view of reconstructed impact trajectories of Ebb (top) and Flow (bottom) over the LOLA topography



Estimates not accurate, used for monitoring

Figure 8. Example of Graphical Tool to Monitor BTD and Impact in Real Time

delivered these ephemeris updates with each maneuver design during XM; there was a delivery on Monday afternoon that was adjusted for the reconstruction of ECMs and the design of the OTM. On Tuesday, the delivery accounted for the reconstruction of the OTM and for the designs of the next week's ECMs. The polynomials were produced by SCT and delivered on Monday and Wednesday, respectively.

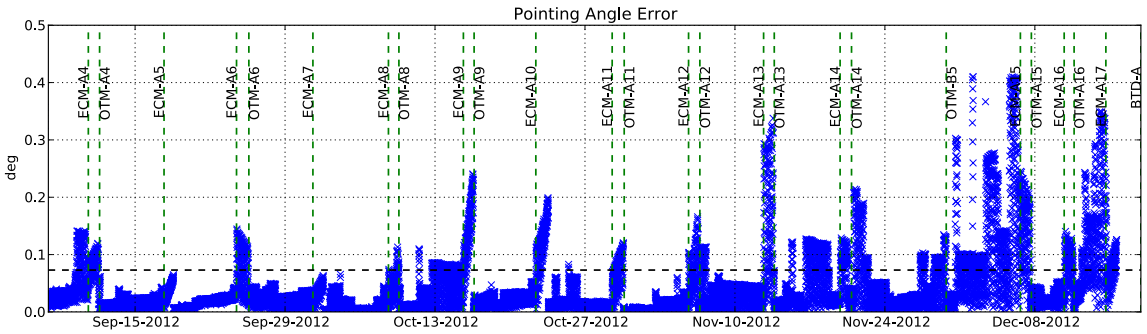
The angle between the predicted pointing vector, used for the ephemeris upload, and the reconstructed pointing vector, from the reconstruction trajectories, is plotted in Figure 9. Points are plotted every 12 hours for the duration of the SCI-XM phase, points before and after that phase are not included as the pointing error was not a concern. NAV generally expected the pointing error to be below about 0.073°; the figure shows that this was achieved for a great majority of the time during XM. The pointing error tended to increase quickly just after ECMs due to their larger execution errors.

Further aspects of OD performance are reported in Reference[6]

Flight-Path-Control Performance

The performance of FPC may be viewed from at least two different perspectives. On the one hand, there's a comparison to be made between the $\Delta\mathbf{V}$ budget and the actual $\Delta\mathbf{V}$ used. On the other hand, there's the question of how closely targeted parameters achieved the target values.

The budget of all of the deterministic maneuvers planned during the GRAIL XM is provided in Table 1. The budgeted numbers are based, in part, on experience from the primary mission and some limited NAV analysis. The limitations on that analysis stem from a lack of resources for performing a more complete FPC analysis. The table shows a $\Delta\mathbf{V}$ requirement for XM of 158.5



Onboard ephemerides updated with maneuvers, marked by vertical lines. Dashed horizontal lines shows the pointing requirement from the *prime* mission.

Figure 9. Angle Between On-board and OD Reconstruction of S/C-to-S/C Pointing Vectors

m/s (GRAIL-A) and 156.4 m/s (GRAIL-B).

Table 7 lists information about the maneuver designs and execution-errors as estimated by OD. All maneuvers in the XM are listed. The budget only included maneuvers through the nominal end of science, which was ECM-A14,B14. Comparing just those maneuvers reveals a total difference for GRAIL-A of 5.7 m/s with more $\Delta\mathbf{V}$ used than the budget. For GRAIL-B, the difference through ECM-B14 is 6.7 m/s, also more used than budgeted. In both cases, ECM-A1,B1 dominates the result with a difference of about 8 m/s for either spacecraft.

The 8 m/s is due to changes in the design after the budget was made, so it may not be fair to include it. If the 8 m/s is excluded, then GRAIL-A is under budget by 2.3 m/s and GRAIL-B is under budget by 1.3 m/s. It may be most appropriate to conclude that FPC performed better than expected, but that the $\Delta\mathbf{V}$ budget should have included some reserve to cover changes in design.

The next comparison for FPC is performance in achieving the trajectory targets. This information is shown graphically in Figures 10 through 14. As mentioned earlier, the targets for ECMs were eccentricity, argument of periapsis, longitude of the ascending node, and average period (biased period). In each plot, both the targeted value is shown along with the difference between the target and the reconstruction.

The OTM target was separation distance, plotted in Figure 10. This plot is a good example of why the target is plotted in addition to the error. The difference between the targets for OTM-A1 and OTM-A2 is quite large, meaning that OTM-A2 likely had larger errors to clean up. That means a larger maneuver and larger execution errors, which point to larger targeting errors and this is what the plot shows for OTM-A2.

The remaining OTMs are within ± 5 km of the their targets with most of them within ± 3 km of the the target. The requirement on performance for the separation distance was ± 15 m around the target. This is clearly met for all maneuvers except OTM-A2, which is slightly over 15 km error.

As described earlier and detailed in Equation 4, the biased period was targeted so as to recover phasing according to the reference trajectory, viz. correct downtrack errors. Figure 14 tracks the targeting errors in biased period. The target value was relatively constant for ECM-A2,B2 through ECM-A13,B13. When this target has noticeable variations, the spacecraft formation receives large changes. For example, the later ECMs need to reduce the period in order to lower the altitude for the Mare Orientale campaign. Errors in the biased period were all below 1.0 seconds except for

ECM-A1,B1 which were targeting the longest period.

The other targets are eccentricity, Figure 11, longitude of the ascending node, Figure 12, and argument of periapsis, Figure 13. Eccentricity errors are roughly $\pm 4 \times 10^{-5}$ around a target value on the order of 0.005, so that errors are about 1% of the target.

Longitude of the ascending node and argument of periapsis help determine the orbit geometry. Figure 12 shows that the targeted value for longitude of the ascending node has't changed much during XM, and NAV's performance remained within $\pm$ 0.003° throughout XM. The story for argument of periapsis is similar, but larger magnitude . The targeted value ranged from about 110° to 250°. The error in argument periapsis remained within $\pm 1.5°$

In general, there doesn't seem to be much of a correlation between the targeted value and the achieved error. There is, however, a correspondence between Figure 12 and Figure 15 as both show a general trend in longitude of the ascending node to drift from the nominal. Both plots show a drift down that appears to recover at the end of the trajectory.

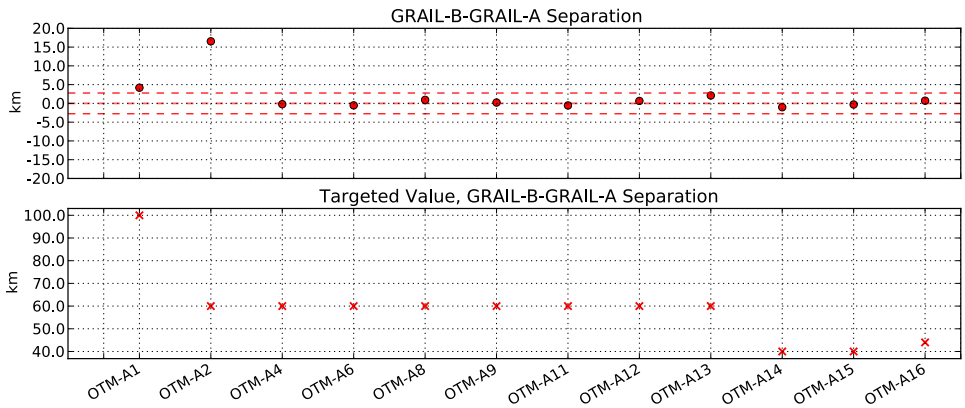


Figure 10. Errors in Achieving the Separation Distance (Reconstruction minus Target)

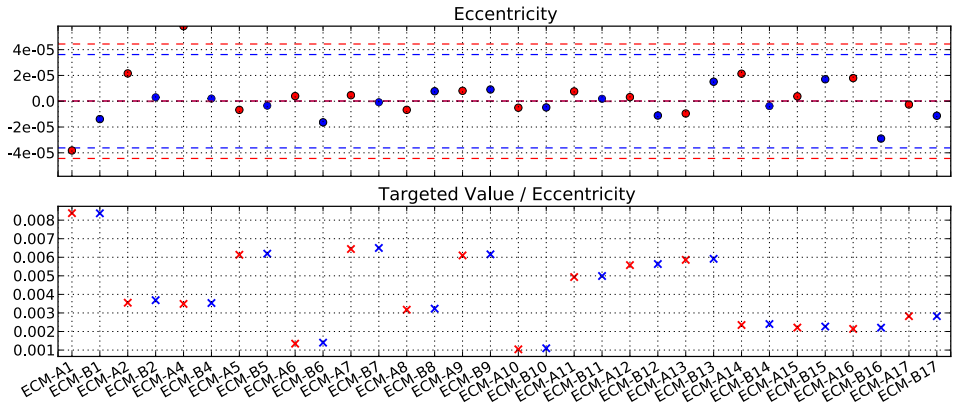


Figure 11. Errors in Achieving Eccentricity Target (Reconstruction minus Target)

All the sub-teams of NAV had a part to play in how well the spacecraft matched the reference trajectories. However, this is a particularly difficult aspect of performance to measure. The difficult chiefly comes from the routine updates and changes that were made to the reference trajectory.

Table 7. Designed ΔV and Execution Errors (OD Estimate)

Mnvr	Start UTC	OD Recon.	Design Mag m/s	Design Dur sec	Exe. Errs Mag mm/s	Exe. Errs Ptg mrad
OCM-A1	30-MAY-12 21:34:35.48	od203v3	15.550	180.627	−4.84	7.577e−01
ECM-A1	20-AUG-12 17:54:08.71	od263v3	38.341	451.439	3.78	1.191e+00
ECM-A2	27-AUG-12 18:12:34.32	od271v3	10.208	120.564	23.62	5.683e+00
ECM-A4	10-SEP-12 15:14:49.07	od283v3	10.056	119.343	−3.68	2.679e−01
ECM-A5	17-SEP-12 16:51:26.19	od288v3	9.909	117.865	−4.02	1.004e+00
ECM-A6	24-SEP-12 11:16:42.03	od294v3	9.779	116.217	−6.45	9.294e−01
ECM-A7	01-OCT-12 14:25:59.24	od300v3	8.028	95.603	2.25	8.573e−01
ECM-A8	08-OCT-12 15:40:54.36	od306v3	5.907	70.438	−6.16	2.469e+00
ECM-A9	15-OCT-12 15:35:32.68	od311v3	9.482	112.464	13.19	3.671e+00
ECM-A10	22-OCT-12 09:54:18.62	od316v3	8.529	98.662	−1.38	4.522e+00
ECM-A11	29-OCT-12 12:57:32.64	od322v3	9.028	106.214	1.59	5.380e+00
ECM-A12	05-NOV-12 16:06:55.73	od328v3	12.096	142.600	0.38	4.193e+00
ECM-A13	12-NOV-12 16:14:36.30	od334v3	10.954	131.189	−1.31	1.868e+00
ECM-A14	19-NOV-12 19:39:24.41	od340v3	5.815	69.930	1.90	3.178e+00
ECM-A15	06-DEC-12 15:34:38.82	od355v3	6.805	82.050	−5.19	8.929e−01
ECM-A16	10-DEC-12 17:42:29.20	od359v3	11.377	137.152	−1.93	1.530e+00
ECM-A17	14-DEC-12 15:07:16.96	od364v3	4.576	55.124	−4.79	5.143e+00
BTD-A	17-DEC-12 21:34:49.13	od370v1	15.600	180.156	5032.52	9.255e−01
OCM-B1	30-MAY-12 19:39:51.82	od203v3	15.511	182.336	2.64	1.618e+00
ECM-B1	20-AUG-12 16:04:44.54	od263v3	37.602	446.061	18.18	3.472e−01
ECM-B2	27-AUG-12 16:22:30.52	od271v4	10.537	125.752	−4.59	1.423e+00
ECM-B4	10-SEP-12 15:15:10.50	od283v3	9.684	115.939	−3.95	2.506e+00
ECM-B5	17-SEP-12 16:51:51.16	od288v3	10.059	120.925	−6.00	1.092e+00
ECM-B6	24-SEP-12 11:17:27.89	od294v3	9.781	117.580	−4.33	2.758e+00
ECM-B7	01-OCT-12 14:26:24.57	od300v3	8.048	97.046	−2.39	9.681e−01
ECM-B8	08-OCT-12 15:41:40.75	od306v3	5.939	71.533	1.80	3.614e+00
ECM-B9	15-OCT-12 15:36:24.10	od311v3	9.457	113.571	8.81	1.258e+00
ECM-B10	22-OCT-12 09:55:04.99	od316v3	8.510	99.096	−2.31	4.072e+00
ECM-B11	29-OCT-12 12:58:01.99	od322v3	9.113	108.136	5.54	3.285e−01
ECM-B12	05-NOV-12 16:07:22.70	od328v3	12.173	145.161	−4.20	2.652e+00
ECM-B13	12-NOV-12 16:15:25.76	od334v3	11.116	134.559	1.93	5.300e+00
ECM-B14	19-NOV-12 19:39:59.01	od340v3	5.675	68.873	1.23	5.845e+00
ECM-B15	06-DEC-12 15:35:08.37	od355v3	6.862	83.389	0.20	7.399e+00
ECM-B16	10-DEC-12 17:42:49.08	od359v3	11.376	138.252	−10.79	2.012e+00
ECM-B17	14-DEC-12 15:07:33.22	od364v3	4.519	54.880	−1.12	4.117e−01
BTD-B	17-DEC-12 21:35:15.63	od370v1	23.300	269.509	2721.82	1.774e+00
OTM-B3	20-JUN-12 17:33:00.00	od218v4	0.020	60.857	−1.79	5.249e+00
OTM-B5	29-NOV-12 17:25:50.52	od349v3	0.004	5.8	−0.36	2.907e+01
OTM-A1	21-AUG-12 15:03:33.50	od265v3	0.063	5.831	−0.71	1.413e+02
OTM-A2	28-AUG-12 16:18:19.90	od272v4	0.031	81.435	−3.67	7.376e+01
OTM-A4	11-SEP-12 16:27:41.16	od284v3	0.024	72.9	−0.12	2.451e+01
OTM-A6	25-SEP-12 14:54:42.91	od295v3	0.034	105.0	0.23	8.726e+01
OTM-A8	09-OCT-12 15:06:04.12	od307v3	0.026	79.2	0.87	1.350e+02
OTM-A9	16-OCT-12 15:36:15.53	od312v3	0.021	60.6	0.32	1.320e+02
OTM-A11	30-OCT-12 15:53:43.80	od323v3	0.020	58.9	0.37	2.063e+01
OTM-A12	06-NOV-12 17:25:42.34	od329v3	0.030	94.3	0.50	9.733e+00
OTM-A13	13-NOV-12 16:08:08.65	od335v3	0.088	293.1	1.13	3.355e+01
OTM-A14	20-NOV-12 21:14:48.19	od342v2	0.022	66.0	0.55	1.117e+02
OTM-A15	07-DEC-12 16:11:13.20	od356v3	0.029	92.4	1.50	1.394e+01
OTM-A16	11-DEC-12 15:56:49.17	od360v3	0.047	154.8	0.84	4.263e+01

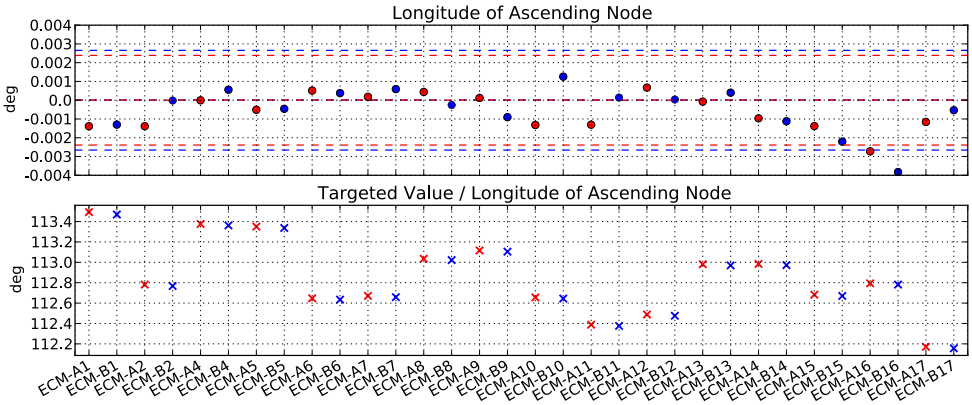


Figure 12. Errors in Achieving Longitude-of-Ascending-Node Target (Reconstruction minus Target)

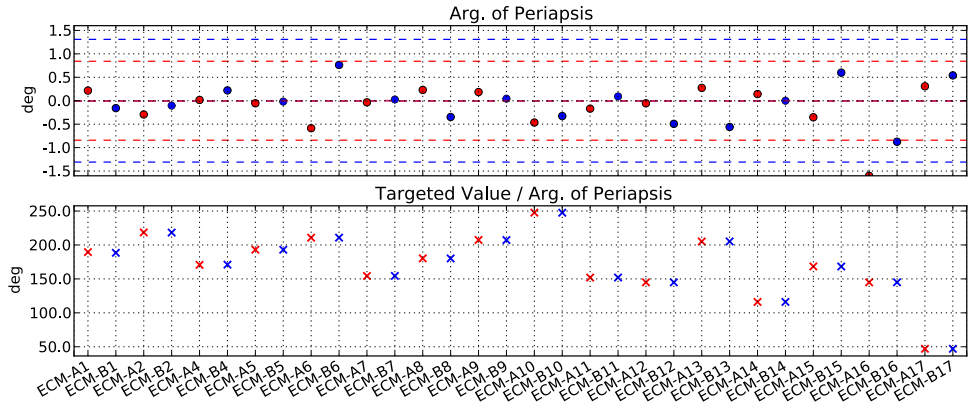


Figure 13. Errors in Achieving Argument-of-Periapsis Target (Reconstruction minus Target)

The plots in Figure 15 attempt the comparison, anyway, for two reference trajectories. The first is refod252v1, created before the start of the SCI-XM phase and was used for the design of ECM-A2,B2. The second is refod301v1, which was used about half-way through the SCI-XM phase, for the design of ECM-A9,B9. The reference refod301v1 included the changes for the DCM phase.

Figure 15 includes plots for some of the most import aspects of the trajectory. The error between the orbital planes of the two spacecraft is represented by two plots. Included is the difference in osculating inclination of GRAIL-A minus that of GRAIL-B, both relative to the "Libration Moon Pole" forced to be an inertial frame at each plotted point. Also shown is the difference in longitude of the ascending node of GRAIL-A minus GRAIL-B, in the same manner as inclination. The altitude of the spacecraft is represented by the plot of periapsis range (The Moon's radius is, on average, 1737 km). Finally, the separation distance is shown directly. Each plot has points for refod252v1, refod301v1, and "Recon", which is the concatenation of the aforementioned reconstruction trajectories.

It's clear from the plot of separation distance that changes were made during the course of the mission. The reference refod252v1 was designed for a separation distance of about 55 km but that target was changed to 60 km. The reference refod301v1 indicates the change to 40 km made for

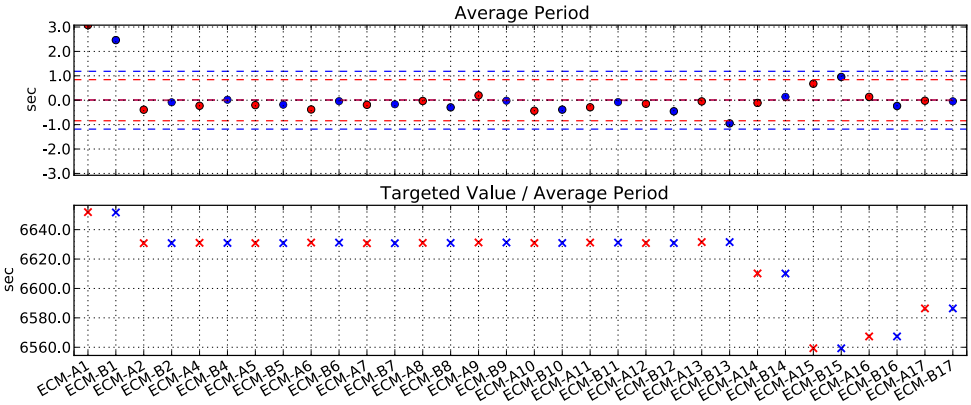


Figure 14. Errors in Achieving Biased-Period Target (Reconstruction minus Target)

the end of acSCI-XM. The reconstructed trajectory has some deviations, due to maneuver execution errors, but the OTMs clearly return the separation distance back to the reference reliably for the whole of SCI-XM.

The matching of GRAIL-A's and GRAIL-B's orbital planes was required to be with 0.1° of inclination and longitude of the ascending node. The comparisons in Figure 15 seem to indicate that there was some drift in the OD reconstructions but, as it starts out negative and ends positive, it fits pretty well between ±0.005° and almost entirely between ±0.01°. The longitude of the ascending node (LAN) did not fare quite as well. Even the refod252v1 reference trajectory showed some drift in this difference of angles. The offset of that drift increased in refod301v1 and the NAV performance seems to track that fairly well. The NAV performance for LAN does remain within ±0.02° which is still well under ±0.01°.

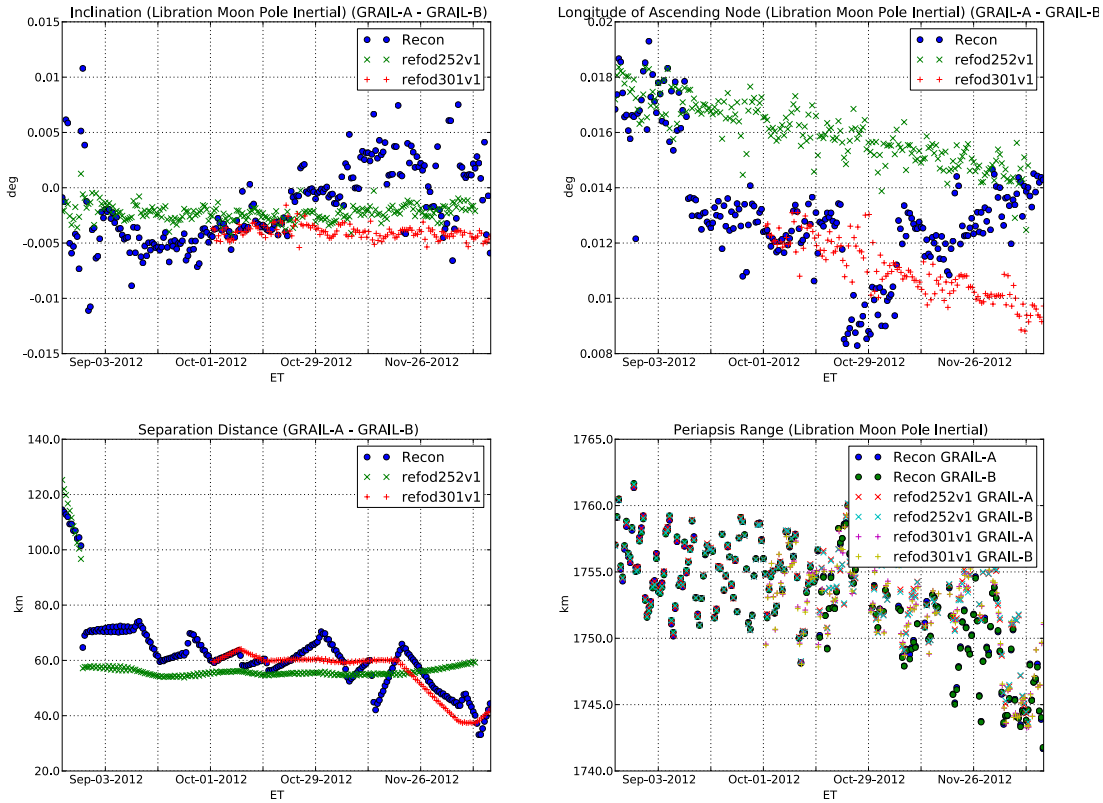
The performance for periapsis radius is the most difficult to judge. Around 26 November 2012, the periapsis radius of the reconstruction is below the reference trajectories but there are only a few points that appear to be below 1745 km, which is approximately an 8 km altitude. This performance is appropriate for the later portion of the SCI-XM phase the altitude was dropped for the Mare Orientale basin campaign.

LESSONS LEARNED

Reporting Occultation Times

NAV traditionally reports occultation times, and other geometrical information, in the Orbit Propagation, Timing, and Geometry (OPTG) file. The entries in this file for occultation events did not allow a way to account for occultation geometry relative to a topographic location, such as a DSN station. This became important, because the GRAIL spacecraft, when viewed from the DSN ground stations, are found to be occulted at different times than the geocentric DSN reported. The OPTG that had been used by GRAIL was geocentric, typical of JPL missions. However, analysis showed that occultation times when viewed from GDSCC/MDSCC/CDSCC (Goldstone/Madrid/Canberra) varied by up to 6 minutes compared to the geocentric view.

In addition, the geocentric OPTG did not report some occultations that were seen from the topocentric view. If not corrected, the discrepancies could contribute to potential loss of recorded



"Recon" is the reconstructed trajectory, "refod252v1" and "refod301v1" are reference trajectories. Points are plotted every 12 hours

Figure 15. Comparisons of Reconstructed Trajectories to Reference Trajectories

science or engineering data and potential difficulties for DSN stations during occultations that weren't predicted accurately or at all.

To avoid these difficulties, NAV delivered "pseudo-topocentric" OPTG files that provided the most conservative (earliest) occultation enter and the most conservative (latest) occultation exit time, taking into account topocentric occultation events as viewed from GDSCC, MDSCC, CDSCC, and Earth Center. No interface agreements or format specifications needed to changed, but the software changes required the usual oversight. Fortunately, JPL's navigation software, MONTE, has since gained a new file format that can address these issues.

OTM Slew Rate

In the extended mission, GRAIL-A led GRAIL-B, but this had been vice versa in the prime mission. A consequence that is perhaps not obvious, and that was not noticed right away, was a significant change to the slew rate that would be used for the OTMs. The slew rate was specified in spacecraft coordinates and when the lead position was switched, the two spacecraft's axes were rearranged causing a change in both the magnitude and polarity. The change in polarity made it very easy to the see the significance of this during an ORT; it could cause attitude errors of nearly 20°. That ORT showed the necessity of updating the on-board setting for the OTM slew rate. Likewise, the resolution of an issue like this reminds us of the importance of participating in ORTs.

CONCLUDING REMARKS

GRAIL's Extended Mission presented many challenges for navigation in regards to planning, analysis, and operations. In response, the navigation team increased the involvement of the Mission Design team and improved robustness in OD and FPC strategies.

The Mission Design team adjusted reference trajectories in response to changes in planning and to correct any long-term errors. The FPC maneuver targeting strategy used averaging and extrapolation to reduce trajectory propagation time while recovering essential performance for following the reference trajectory. The OD strategy, and artful adjustment of data weights, successfully forced unmodeled gravity into tracking residuals instead of affecting estimates of filter parameters.

GRAIL NAV contributed to 50 successfully executed maneuvers, maintained orbital altitudes less than 10 kilometers, and successfully targeted impact locations for both spacecraft. We expect this experience and successful navigation to be a significant contribution to the scientific benefit of GRAIL to future navigation.

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