(Preprint) AAS 13-269

GRAIL ORBIT DETERMINATION FOR THE SCIENCE PHASE AND EXTENDED MISSION

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The Gravity Recovery and Interior Laboratory Mission (GRAIL) is the 11th mission of the NASA Discovery Program. Its objective is to help answer fundamental questions about the Moon's internal structure, thermal evolution, and collisional history. GRAIL employs twin spacecraft, which fly in formation in low altitude polar orbits around the Moon. An improved global lunar gravity field is derived from high-precision range-rate measurements of the distance between the two spacecraft. The purpose of this paper is to describe the strategies used by the GRAIL Orbit Determination Team to overcome challenges posed during on-orbit operations.

INTRODUCTION

The primary Science phase of the GRAIL mission began on March 6, 2012, after the two GRAIL spacecraft established a precision formation in polar, low altitude, near-coplanar orbits around the Moon[1]. Continuous Ka-Band spacecraft-to-spacecraft range-rate data were acquired in this orbit. The altitude varied between 20 and 90 km above a spherical model of the Moon with an average altitude of 55 km. The minimum elevation was 10 km with respect to the physical surface. A single maneuver was performed on March 30, 2012 to maintain the spacecraft-to-spacecraft separation distance required to be sensitive to long and short wavelength gravity harmonics. In accordance with the mission plan, the spacecraft relative range varied from 109 km at the beginning of the science phase, to 216 km at the time of March maneuver, then down to 84 km at the end of the science phase on May 29, 2012. The spacecraft were nominally expected to impact the lunar surface a few days later.

The project was granted funding for an additional seven months of operation known as the Extended Mission (XM)[2]. The XM began with a brief Lunar Eclipse phase (LEC), in which pop-up maneuvers were performed to prevent lunar impact and the spacecraft were configured to survive a partial lunar eclipse on June 4, 2012. The spacecraft then entered an extended period of minimal operations, known as the Low Beta Angle phase (LBA), with an average altitude of 85 km

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above the spherical lunar model. A loose formation was maintained, with a spacecraft-to-spacecraft separation of approximately 650 km. No gravity data could be acquired during the initial portion of the XM because the formation geometry precluded the generation of sufficient power for operations of the science instruments. The project finally entered the Transfer to Science XM phase (TSF-XM) on August 13, 2012. Six maneuvers were performed during this period, reestablishing the precision formation at a low lunar altitude.

Table 1. Key Dates in the GRAIL Mission

Event	Date	Solution ID
Primary Mission Science Phase (SCI)	March 6, 2012	od118
Lunar Eclipse Phase (LEC)	May 29, 2012	od202
Low Beta Angle Phase (LBA)	June 5, 2012	od210
XM Transfer to Science Formation Phase (TSF-XM)	August 13, 2012	od257
XM Science Phase (SCI-XM)	August 30 2012	od274
Decommissioning Phase (DEC)	December 14, 2012	od364
End of Mission	December 17, 2012	od370

The objective of the Science XM phase (SCI-XM) was to investigate the structure of the highland crust and maria, achieved by flying at the lowest altitude that could be safely maintained. The XM altitude varied between 15 and 35 km above a spherical model of the moon with an initial average altitude of 23.5 km. The minimum elevation was 3 km with respect to the physical surface. The desired relative range for the spacecraft was between 45 and 75 km. The average orbital lifetime in the XM was between 7 and 10 days. Consequently, many operational aspects of the SCI-XM were different from the SCI phase. The general plan for the entire XM phase called for a weekly cycle, which consisted of three maneuvers, as opposed to a single maneuver in the entire SCI phase. Each spacecraft would perform near-simultaneous orbit maintenance maneuvers, to prevent impact with the lunar surface. These would be followed by a GRAIL-A statistical cleanup maneuver, if needed, to refine the spacecraft-to-spacecraft relative range.

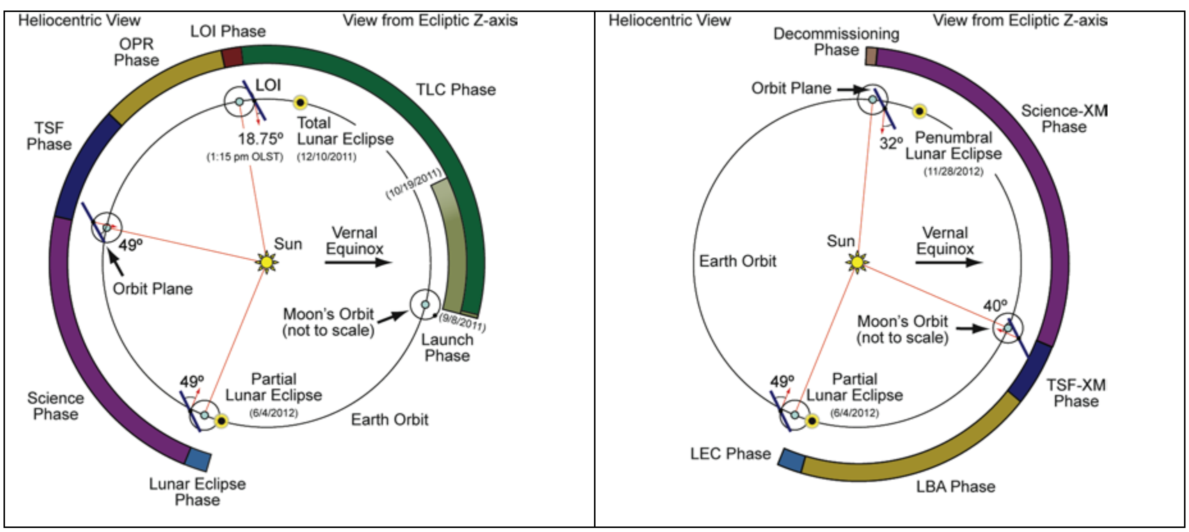


Figure 1. GRAIL Mission Phase and Geometry.

Continuous acquisition of gravity data resumed at the beginning of the SCI-XM phase on August 30, 2012. It continued until the start of the Decommissioning phase (DEC) on December 14, 2012, at which time the formation geometry again precluded the generation of sufficient power for operations of the science instruments. After surviving an annular lunar eclipse on November 28, 2012, the spacecraft performed deorbit maneuvers to achieve controlled lunar impacts, which avoided contamination of lunar heritage sites. Prior to impact, the spacecraft conducted a number of engineering demonstrations, including burn-to-depletion maneuvers to validate estimates of propellant usage. Key dates during the GRAIL mission are shown in Table 1, and the mission phases and heliocentric geometry are shown in Figure 1.

The purpose of this paper is to describe the strategies used by the GRAIL Orbit Determination Team to overcome challenges posed during spacecraft operations in low lunar orbit. This paper will discuss the orbit determination filter configuration, analysis, and results during the Primary Science and Extended Mission phases. It will summarize the requirements, major dynamic models, operational scenario, and challenges faced by the GRAIL Orbit Determination Team.

KEY NAVIGATION REQUIREMENTS AND CHALLENGES

GRAIL Navigation was required to satisfy stringent formation requirements for science data acquisition, such as spacecraft-to-spacecraft pointing within ±0.073 degrees, and orbit plane matching to within ±0.1 degree. The separation distance between the spacecraft was to be maintained between 50–250 km for the SCI phase, approximately 600 km for the LEC and LBA phases, and between 45–75 km for the SCI-XM phase. The predicted trajectory event-timing error needed to be less than 120 seconds for the SCI, LEC, and LBA phases and less than 180 seconds for the TSF-X, SCI-X, and DEC phases (i.e., for occultation entry/exit events). The Navigation Team was also required to perform navigation tasks, such as orbit determination, maneuver reconstruction and planning, in accordance with the mission operations timeline. No requirement for orbit reconstruction was levied on the Orbit Determination Team, as the GRAIL Science Team performed this analysis as part of their gravity field estimation process.

These specific requirements create two significant challenges for the GRAIL Orbit Determination Team: 1) the orbit determination and trajectory prediction accuracy must meet above requirements despite known, significant errors in the lunar gravity model, and 2) the orbit determination process must be optimized to meet timeline deadlines needed for sequence implementation, mission planning, maneuver design and monitoring, predicts generation and validation.

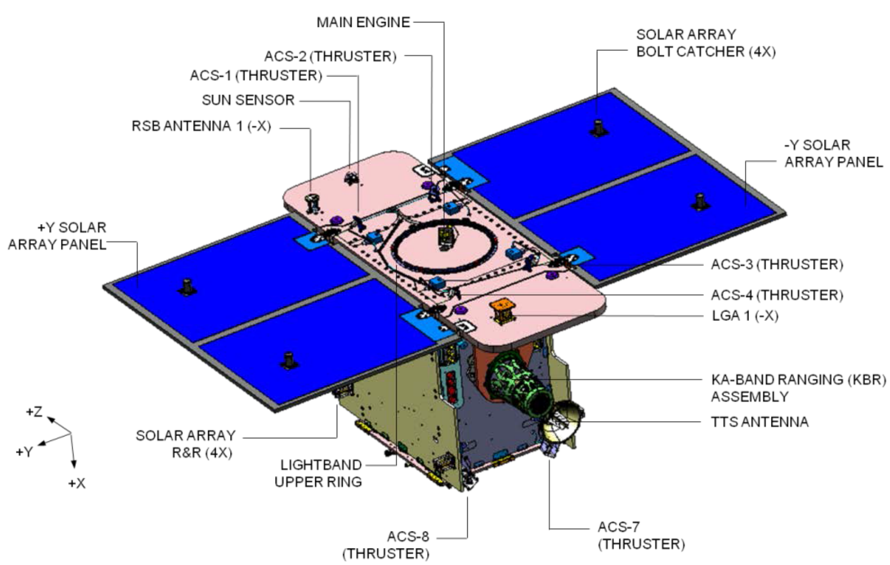


Figure 2. GRAIL Spacecraft On-Orbit Physical Configuration

SPACECRAFT DESCRIPTION

The GRAIL spacecraft shared exactly the same hardware with slightly different configurations. The solar array panel of the bus extended 70% wider than the bus body to shade the star tracker and radio science instruments. The spacecraft were powered by fixed solar panels with a total cell area of 2.8 m^2.

GRAIL employed a three-axis stabilized attitude control system. The Reaction Wheel Assembly consisted of a four-wheel pyramid design, with a 1.55 Nms momentum capacity. Large maneuvers were conducted with the 22 N Main Engine (ME). The ME was mounted on the spacecraft –X panel with a thrust direction along the spacecraft +X direction. The Attitude Control System thrusters (ACS) consisted of eight 0.9 N ACS thrusters which were mounted in four cluster pairs, and canted 15° from the spacecraft +X axis in the X-Z plane and 35° from the +X axis from the X-Z plane. The configuration and cant-angle design enabled use of the thrusters for small maneuvers by selecting thruster pairs that produced a net translational Δv along the spacecraft ±Z-axis, while canceling Δv along the other axis. The ACS thrusters were also employed in a balanced configuration to conduct momentum wheel desaturations (desats), which imparted a very small translational Δv (<0.2 mm/sec).

Two Low Gain Antennas (LGA) were mounted on the ±X panels of each spacecraft. The onboard S-band transponder was capable of generating two-way coherent S-band Doppler and range data. During the orbital phase, use of the antenna alternated between the two LGAs every two weeks as the orbit plane rotated with respect to the Earth. There were also two X-band Radio Science Beacons (RSB) mounted on the ±X panels of the spacecraft. These used an Ultra-Stable Oscillator (USO), capable of generating usable one-way X-band Doppler tracking data.

The primary science instrument carried by the GRAIL orbiters was the Ka-band Lunar Gravity Ranging System (LGRS), which measures the inter-satellite range-rate. The raw measurements consisted of dual one-way Ka-band range or phase counts, which was post-processed on the ground to produce the range-rate observables with respect to the spacecraft center of mass. Timing of the measurements between the orbiters was maintained through the S-band Time Transfer System (TTS), which was based on the USOs onboard both orbiters. These USOs were calibrated to the DSN clocks via the one-way X-band Doppler signal transmitted through the RSB antennas.

Each spacecraft also carried an education and public outreach imaging system call MoonKam, which consisted of five camera heads. This system allowed middle school students and teachers to participate in the mission by scheduling camera sequences to image specific areas of the lunar surface on a non-interference basis with the LGRS operation.

The mass of each spacecraft at launch was about 306 kg, of which 106 kg was propellant. The remaining propellant at the start of the SCI phase was approximately 20 kg on both spacecraft. Figure 2 shows the GRAIL on-orbit hardware configuration.

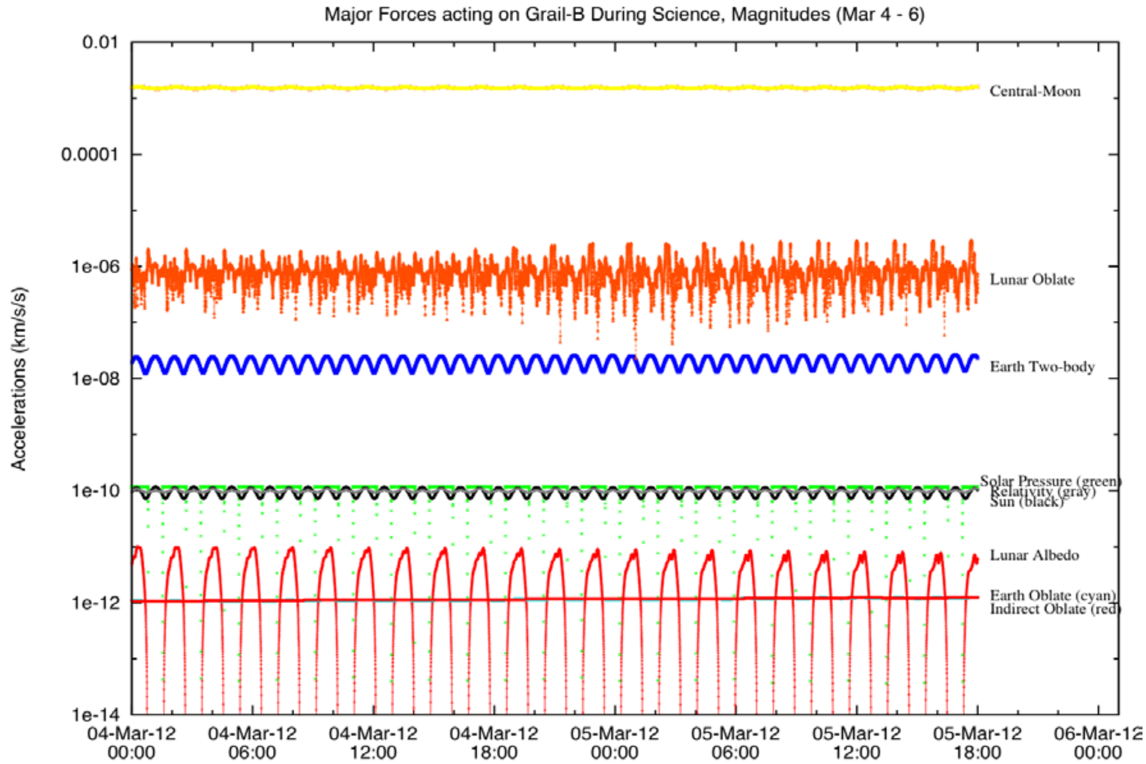


Figure 3. Major Forces Acting on GRAIL in Lunar Orbit

SPACECRAFT DYNAMICS

Major forces influencing the GRAIL flight path were gravity, solar radiation pressure and thruster events. Figure 3 illustrates a pre-launch analysis of the major forces acting on GRAIL in lunar orbit. Lunar gravity uncertainty was the dominant error source in the lunar orbital phases. Other forces, such as lunar albedo and the Earth oblate gravity field were insignificant compared with the other forces.

Solar Radiation Pressure

In order to model the solar radiation pressure force, the physical structure of the spacecraft was decomposed into a seven-component model. One flat-plate component represented the combined GRAIL –X panel and –X face of the solar array, and a second plate representing the backside of the solar arrays. The remaining five plates corresponded to the remaining spacecraft bus faces. The component orientations were fixed with respect to the spacecraft structure. Each plate was assigned specular and diffuse coefficients initially derived from the component properties and associated reflectivity and then updated in flight following a two-week solar pressure calibration campaign performed prior to arrival at the Moon[3]. The solar array diffusivity coefficients were also adjusted to account for the backside radiator thermal imbalance effect, as was seen the MRO cruise to Mars[4].

The wider spacecraft –X panel can put the spacecraft ±Z faces in shadow under certain conditions. When the aspect angle of the Sun and the spacecraft –X-axis was less than 32°, the spacecraft ±Z panels were completely in shadow. When the aspect angle was greater than 32° the area of the spacecraft ±Z panels illuminated by the Sun changes as a function of the aspect angle. A time-varying Z-area table was implemented to account for this effect based on the spacecraft attitude profile.

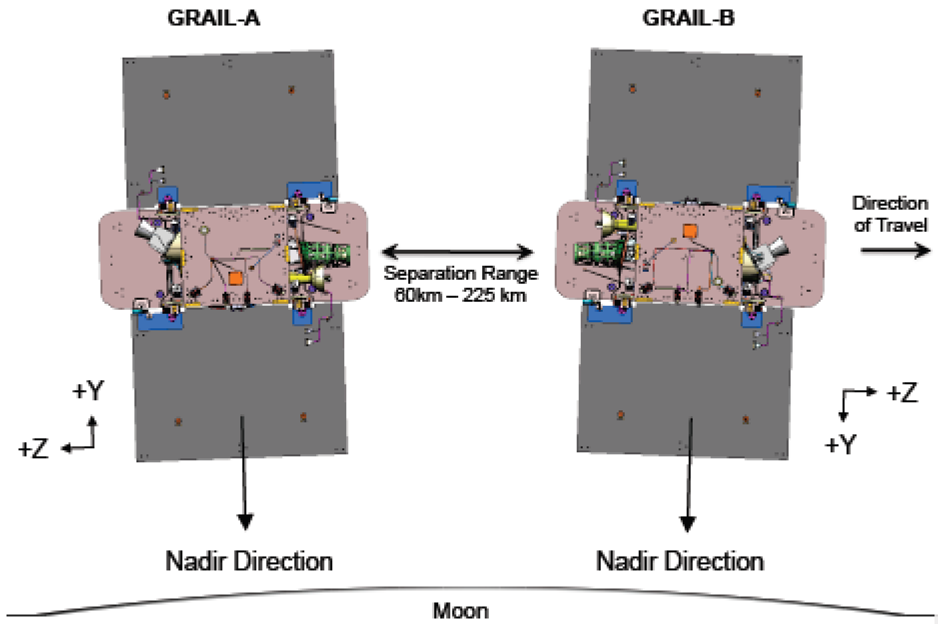


Figure 4. Orbit Attitude during Science Acquisition

Spacecraft Orientation

The attitude profile during the SCI Phase is shown in Figure 4. The orbiter-to-orbiter vector was aligned with the Ka-band antenna horn boresights, with GRAIL-B leading GRAIL-A. The orbiter –X-axis points in the orbit normal direction such that the solar arrays remained parallel to the orbit plane. The attitude during the SCI-XM was the opposite of the SCI phase, with GRAIL-A leading GRAIL-B. For the LBA, TSF-XM and DEC phases, the orbiters maintained a constant 40° bias off sun-point. This attitude reduced effect of thermal re-radiation from the lunar surface and positioned the –Y panel radiators away from the Moon. A Sun-point attitude, with the solar panels normal to Sun, was employed during the LEC phase and the annular lunar eclipse to maximize the battery state-of charge during these events. During the entire time in low lunar orbit, the GRAIL spacecraft would perform autonomous 180° slews about the X-axis when the orbit plane crossed the Earth-Sun line, to keep the star trackers' field-of-view positioned away from the Earth. This occurred approximately every 13.7 days as the Moon orbited around the Earth.

Propulsive Events

A total of 56 maneuvers were planned while in low circular lunar orbit. Table 2 shows the maneuver timeline. Maneuvers to establish the target science acquisition orbit or prevent lunar impact due to natural orbit evolution were executed in pairs (one by each spacecraft). During the SCI and LBA phases, GRAIL-B performed cleanup maneuvers to achieve the precision science acquisition formation or desired relative separation rate. GRAIL-A executed the cleanup maneuvers during the TSF-XM and SCI-XM phases. GRAIL-A performed 31 maneuvers and GRAIL-B performed 21. As indicated in Table 3, four cleanup maneuvers were not needed (OTM-B4, OTM-A5, OTM-A7 and OTM-A10).

Table 2. Planned Maneuvers Executed (GRAIL-A: 31, GRAIL-B: 21, Total: 52).

Maneuver Date	GRAIL-A	GRAIL-B	Phase
March 30, 2012	-	OTM-B2	SCI
May 30, 2012	OCM-A1	OCM-B1	LEC
June 20, 2012	-	OTM-B3	LBA
August 20, 2012	ECM/OTM-A1	ECM-B1	TSF-XM
August 27, 2012	ECM/OTM-A2	ECM-B2	TSF-XM
September10-11, 2012	ECM/OTM-A4	ECM-B4	SCI-XM
September 17, 2012	ECM-A5	ECM-B5	SCI-XM
September 24-25, 2012	ECM/OTM-A6	ECM-B6	SCI-XM
October1, 2012	ECM-A7	ECM-B7	SCI-XM
October 8-9, 2012	ECM/OTM-A8	ECM-B8	SCI-XM
October 15-16, 2012	ECM/OTM-A9	ECM-B9	SCI-XM
October 22, 2012	ECM-A10	ECM-B10	SCI-XM
October 29-30, 2012	ECM/OTM-A11	ECM-B11	SCI-XM
November 5-6, 2012	ECM/OTM-A12	ECM-B12	SCI-XM
November 12-13, 2012	ECM/OTM-A13	ECM-B13	SCI-XM
November 19-20, 2012	ECM/OTM-A14	ECM-B14	SCI-XM
November 29, 2012	-	OTM-B5	SCI-XM
December 6-7, 2012	ECM/OTM-A15	ECM-B15	SCI-XM
December 10-11, 2012	ECM/OTM-A16	ECM-B16	SCI-XM
December 14-15, 2012	ECM/OTM-A17	ECM-B17	DEC
December 17, 2012	BTD-A	BTD-B	DEC

Table 3. Planned Maneuvers Not Executed (GRAIL-A: 3, GRAIL-B: 1, Total: 4).

Maneuver Date	GRAIL-A	GRAIL-B	Phase
August 7, 2012	-	OTM-B4	LBA
September 18, 2012	OTM-A5	-	SCIXM
October 2, 2012	OTM-A7	-	SC-XM
October 23, 2012	OTM-A10	-	SCI-XM

Four different types of maneuvers were implemented for the low lunar orbit operation based on magnitude, development cycle and implementation. There were two primary types of ME burns: Orbit Correction Maneuver (OCM) and Eccentricity Correction Maneuvers (ECM). These maneuvers all employed slews to and from the burn attitude, fixed inertial attitudes during the burn, and were preceded by momentum wheel desaturations (approximately 4 minutes prior to the maneuver). These maneuvers had magnitudes between 4.5 m/s and 15 m/s. The ME used a blowdown hydrazine system, and the thrust output was reduced to roughly 50% of its peak level at the beginning of the SCI phase[3]. Consequently, the thrust output level varied during maneuver execution and was described by a 6-degree thrust level polynomial for each burn.

The Orbit Trim Maneuvers (OTM) were used to cleanup ME burns and were performed by the ACS thrusters. The GRAIL spacecraft remained in orbiter-to-orbiter point at the start of the burn, which was implemented as a pitch-over maneuver with the pitch rate about the X-axis equal to the mean motion of the orbit. This would keep the Ka-horns of the two orbiters pointed at each other during the burn, maintaining the LGRS link. These maneuvers were scheduled near the lunar poles where redundant LGRS data could be acquired, so that it would not disrupt the collection of science data (except for OTM-B3 which occurred during the LBA phase). These maneuvers had magnitudes between 20 mm/s and 90 mm/s.

The Burn to Depletion (BTD) were ME burns performed as engineering demonstrations to validate models of in-flight propellant consumption. The maneuvers were executed approximately 50 minutes prior to lunar impact and were implemented as cross-track burns to minimize the change to the down-track location of the impact point. Modifications to the maneuver sequence were added to detect the onset of the depletion event and halt the maneuver, retaining a small reserve of propellant in case attitude rates exceed the control authority of the reactions wheels. The nominal magnitudes for these maneuvers were 15.6 m/s and 23.3 m/s for GRAIL-A and GRAIL-B respectively. Extended thrust level polynomials to 55 m/s were used for these maneuvers to give accurate modeling in case large over-burns occurred.

The other on-orbit propulsive events were angular momentum wheel desaturations. These managed wheel speed within acceptable levels and were implemented by firing coupled ACS thruster pairs, designed to impart no net translational Δv to the system. Momentum wheel desaturations were generally commanded from the background sequence and had a frequency of one every two to four days (with a maximum interval of ten days). A calibration campaign was conducted prior to lunar arrival, which indicated a Δv on the order of 0.2 mm/s with no noticeable thruster misalignment problems.

Gravity Modeling

The gravitational acceleration for the Sun and other planets were modeled as Newtonian point masses, and relativistic corrections for the Sun, Jupiter, Earth and Moon. The JPL DE421[5] was used for the planetary ephemeris and constants. A version of the GGM02c Earth spherical harmonic model, based on GRACE mission results and truncated to a 20x20 field, was used in lunar phase.

GRAIL Navigation employed the best lunar gravity model available for the early SCI phase. This was the LP150Q field spherical harmonic representation to degree and order 150[6], developed using primarily two-way, S-band Doppler radiometric tracking data from the Lunar Prospector mission (LP). Like most other gravity field determinations prior to GRAIL, it was developed using two-way Doppler measurements of LP from Earth-based ground stations and there were no direct measurements of the gravity acceleration on the lunar far side. Consequently, that region of the lunar gravity field could only be inferred from the long-term effects on the spacecraft orbit

Table 4. Gravity Models.

Date of First Use	Field ID	Truncation	Phase	Solution ID	Lockfile
March 7, 2012	lp150q	150x150	SCI	od118	4.4
April 13, 2012	grail270a9a	200x200	SCI, LEC, LBA	od156	5.0
June 7, 2012	grail360b6a	200x200	LBA	od211	6.1
August 3, 2012	grail420c1a	200x200	LBA, TSF-X, SCI-X	od249	7.1
September 1, 2012	grail420c1a	300x300	SCI-X	od276	7.2
October 26, 2012	grail540c3a	320x320	SCI-X	od320	8.1
December 6, 2012	grail660c5a	400x400	SCI-X, DEC	od355	9.2

and was poorly determined. Starting from the second half of the SCI phase, a succession of global high-resolution gravity models were used. It was generated using only GRAIL LGRS data processed by the JPL GRAIL Lunar Gravity team. Several additional internal versions were released to the GRAIL Navigation Team to improve orbit determination and trajectory prediction. These fields incorporated more of the LGRS data and used significantly larger spherical harmonic expansions. Operational considerations precluded the use of the internal fields at their full expansions. Truncations of the harmonic field were selected that were a compromise between computational throughput and residual gravity errors. Details of the gravity models employed are shown in Table 4.

TRACKING DATA

Orbit determination for GRAIL in lunar orbit was accomplished using ground based radiometric tracking. The primary data type was S-band two-way Doppler data. The standard deviation of the in-flight two-way Doppler data was between 0.002 Hz and 0.0008 Hz. X-band one-way Doppler data was often available but was found to be of limited value because the USO response to shadow entry/exit imparted a large thermal cycle on the data (±0.02 Hz).

The Deep Space Network (DSN) request for the Science and XM phases of the mission was one tracking pass per day per orbiter with no gaps longer than 16 hours. The allocated tracking schedule generally satisfied the request for the Science phase but could not be entirely accommodated during the XM. This was due to conflicts with other missions' tracking requests, particularly during the Mars Science Laboratory landing and when GRAIL and Mars were in the same part of the sky. Starting in late November 2012, GRAIL became increasingly reliant on the Multiple Spacecraft Per Aperture (MSPA) technique, in which a single antenna would simultaneously acquire a downlink from both spacecraft. This allowed for the acquisition of telemetry and science data but degraded orbit determination performance because only one spacecraft could uplink.

Table 5. DSN Tracking Stations Supporting GRAIL.

Primary Stations	**Complex**	**Station Type**	**GRAIL Bands**
DSS-24	Goldstone	34m Beam Wave Guide	S-up, S-down, X-down
DSS-27	Goldstone	34m Beam Wave Guide	S-up, S-down
DSS-34	Canberra	34m Beam Wave Guide	S-up, S-down, X-down
DSS-45	Canberra	34m High Efficiency	S-up, S-down, X-down
DSS-54	Madrid	34m Beam Wave Guide	S-up, S-down, X-down
DSS-65	Madrid	34m High Efficiency	S-up, S-down, X-down
Secondary Stations	**Complex**	**Station Type**	**GRAIL Bands**
DSS-15	Goldstone	34m High Efficiency	X-down
DSS-25	Goldstone	34m Beam Wave Guide	X-down
DSS-26	Goldstone	34m Beam Wave Guide	X-down
DSS-27	Goldstone	34m High Speed Beam Wave Guide	X-down
DSS-43	Canberra	70m	S-down, X-down
DSS-55	Madrid	34m Beam Wave Guide	X-down
DSS-63	Madrid	70m	S-down, X-down

Primary support for GRAIL by the DSN was provided by six 34m tracking stations. These were the only DSN assets capable of acquisition of the S-band two-way Doppler data and telemetry. Five of these stations were also able to support the simultaneous acquisition of the X-band one-way Doppler and science data. Occasionally, when the primary stations could not be allocated, five other DSN tracking stations would be employed for receipt of X-band telemetry data and one-way Doppler, without S-band uplink. Contention with other projects for tracking time increased dramatically starting in September, 2012, when DSS-54 in Madrid was taken off-line due to hardware problems. Details of DSN tracking assets supporting GRAIL are shown in Table 5.

ORBIT DETERMINATION AND THE SPACECRAFT OPERATIONAL SCENARIO

Orbit Determination was carried out by two semi-independent teams: one for GRAIL-A and one for GRAIL-B. The GRAIL operational scenario in the SCI and early XM phases was driven by a one-week cycle of sequence generation, uplink and on-board execution. The GRAIL Orbit Determination Team initiated this cycle every Monday. The OD process would typically take about four hours to complete. The initial step involved gathering the latest tracking data, media and clock calibrations, reconstructed and planned thruster events and spacecraft orientation changes. Updating these inputs usually took about one hour of preparation time. Performing the orbit determination typically took about two hours, including validating and editing tracking data, refining the filter strategy, and verifying the results in the context of previous solutions. The generation of deliverable products would generally take another one hour. This would include trajectory predictions in a variety of formats and tables of geometric events and light times. These products were used by a number of GRAIL operations teams: the Mission Design Team to monitor mission progress and plan future mission activities, the Navigation Maneuver Design Team to plan future maneuvers necessary to achieve the desired mission trajectory, the Mission Planning and Sequence Team to write on-board sequences to perform mission tasks, the Spacecraft Team to monitor and operate the spacecraft, the DSN for generation of tracking products and long term planning, and the Science Team to operate the LGRS and analyze data returned from that instrument.

A second cycle of orbit determination and product generation would be performed on Thursday. This data would be employed by the project if the solution showed a large difference with respect to the current on-board background sequence. Solutions were also performed on all other weekdays and for the previous weekend for internal use by the Navigation team to asses the consistency of solutions, verify if changes to the trajectories were not compatible with the mission plan and look for tracking anomalies. Other tasks included support for the four maneuvers, which occurred during this time.

The operational tempo of the project increased dramatically during the final five months of the mission, starting with the TSF-XM phase. In addition to the previously mentioned activities, the operations teams had to support as many as three maneuvers per week (as opposed to four maneuvers during the previous six months). Again the Orbit Determination Team initiated the weekly cycle each Monday by preparing “fresh” reference trajectories needed to monitor the ECM maneuvers in real-time, starting two hours before their execution. This was followed by a five-hour time allotment to complete an assessment of the maneuver performance and generate post maneuver trajectory predictions. These solutions were used to design the potential cleanup OTM maneuver to be performed on Tuesday morning. At eight hours following the maneuvers, the Orbit Determination Team would then deliver OTM burn and no-burn trajectory predictions to the DSN for the generation and validation of the Tuesday tracking products. Late Monday was also spent pre-configuring the real-time tracking data monitoring system for the next day’s OTM.

<table>
<tr><th colspan="2">Orbit Determination
Activities in Blue</th><th colspan="3">All Activities for Two Spacecraft
Except for OTM Support (GRAIL-A only)</th></tr>
<tr><th>Monday</th><th>Tuesday</th><th>Wednesday</th><th>Thrusday</th><th>Friday</th></tr>
<tr><td>OD for Maneuver
R/T Monitoring</td><td>OD for Maneuver
R/T Monitoring</td><td rowspan="2">ECM Design
Project Approval</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Maneuver R/T Setup</td><td>Maneuver R/T Setup</td></tr>
<tr><td rowspan="2">ECM Maneuver

R/T Monitoring
Quick Assessment
OD Reconstruction
Product Delivery

Weekly OD</td><td rowspan="2">OTM Maneuver

R/T Monitoring
Quick Assessment
OD Reconstruction
Product Delivery

Weekly OD</td><td>Daily OD</td><td>Daily OD</td><td>Daily OD</td></tr>
<tr><td rowspan="2">Develop Staffing Plan, Tracking Data Delivery Schedule and OD Delivery Schedule for Next Week</td><td rowspan="2">ECM Co-Variance Analysis</td><td></td></tr>
<tr><td>OTM Design</td><td>ECM Design</td><td>ECM R/T
Monitoring Prep</td></tr>
<tr><td>Trajectory
Prediction
with/without OTM</td><td>ECM Design
Navigation Internal
Approval</td><td>ECM Design
Validation</td><td>Trajectory
Prediction
with/without ECM</td><td rowspan="2"></td></tr>
<tr><td>ECM R/T
Monitoring Prep</td><td></td><td></td><td></td></tr>
</table>

Note – Activity Times are Approximate

Figure 5. Orbit Determination Schedule of Tasks for the SCI-XM Phase.

The maneuver support cycle was performed again on Tuesday for the GRAIL-A OTM along with routine support for GRAIL-B. These solutions were then used to design the following week’s ECMs, with Navigation internal approval of the maneuver design on Tuesday afternoon and project concurrence on Wednesday morning. Planning for the next week’s orbit determination activities also occurred on Wednesday. These tasks included developing a staffing plan and scheduling tracking data cut-offs and orbit determination solution deliveries consistent with the maneuver support schedule. On Thursday, the Orbit Determination team delivered the ECM burn and no-burn trajectory predictions to the DSN for the generation and validation of the Monday tracking products. Friday's activity included pre-configuring the real-time tracking data monitoring system for the Monday ECM supports. Figure 5 shows the weekly orbit determination schedule of tasks during the SCI-XM phase.

BASELINE FILTER SETUP, DATA AND OPERATIONAL ISSUES

A relatively simple baseline orbit determination filter was employed throughout the low altitude lunar operations phases. Estimated parameters included the spacecraft state, a solar radiation pressure scale factor, finite burns for OCM, ECM, OTM, and BTD maneuvers and impulsive burns for momentum wheel desaturations.

The main challenge for the orbit determination filter strategy was to be robust in the presence of large, expected gravity mismodeling, while still achieving trajectory predictions consistent with mission requirements. Pre-launch analysis and testing demonstrated conclusively that estimating local gravity fields were impractical due to throughput and file size issues, as well as yielding poor and inconsistent trajectory predictions. The technique that worked best under simulated conditions was to simply ignore the gravity error and de-weight the Doppler data and accept a relatively poor fit (i.e., large data residuals). This resulted in a reasonable average estimate of the orbit, especially the period, and yielded the best trajectory prediction compared to a number of techniques investigated.

In-flight experience in the two months of orbital operation prior to the start of the SCI phase showed that the above conclusion was only partially correct. The large residuals were indicative of large state errors, especially at the end of the data arc. This resulted in a state error at the start of the trajectory runout and yielded a poor trajectory prediction.

To correct this deficiency, impulsive burns were estimated at each periapsis within the data arc to account for some of the mismodeling in the gravity field. The impulsive burns reduced the state error in each orbit, while placing a heavily constrained *a priori* covariance on the maneuvers maintained some of the orbit period information. GRAIL used this technique with great success prior to the start of the SCI phase.

The tracking data available dictated the data arc employed each day. But many factors related to tracking data were known to have a significant effect on orbit determination accuracy and trajectory prediction. General guidelines relating to these factors existed and we attempted to adhere to them whenever possible. These included placing the beginning of the trajectory integration and the end of the data arc as close to apoapsis as possible. A data arc length between 16 and 24 hours was used when the orbit plane was in an edge-on or skewed geometry with respect to the Earth. A data arc length of 30 to 36 hours was used for face-on geometries, in an attempt to include more along-track information content in the tracking data. Occasionally, fits as long as 48 hours were used when there were significant gaps in the tracking data. Each day the integration epoch was advanced about 24 hours, resulting in several orbits of common data between successive solutions. Maneuvers and momentum wheel desaturations were kept near the middle of the data arc when possible. Ideally, the final orbit of the fit should have data distributed evenly around the entire orbit to avoid biasing the trajectory runout. This goal was rarely achievable due to occultation and unfavorable allocation of the tracking resources.

Table 6. Baseline Filter Configuration Excluding Maneuvers

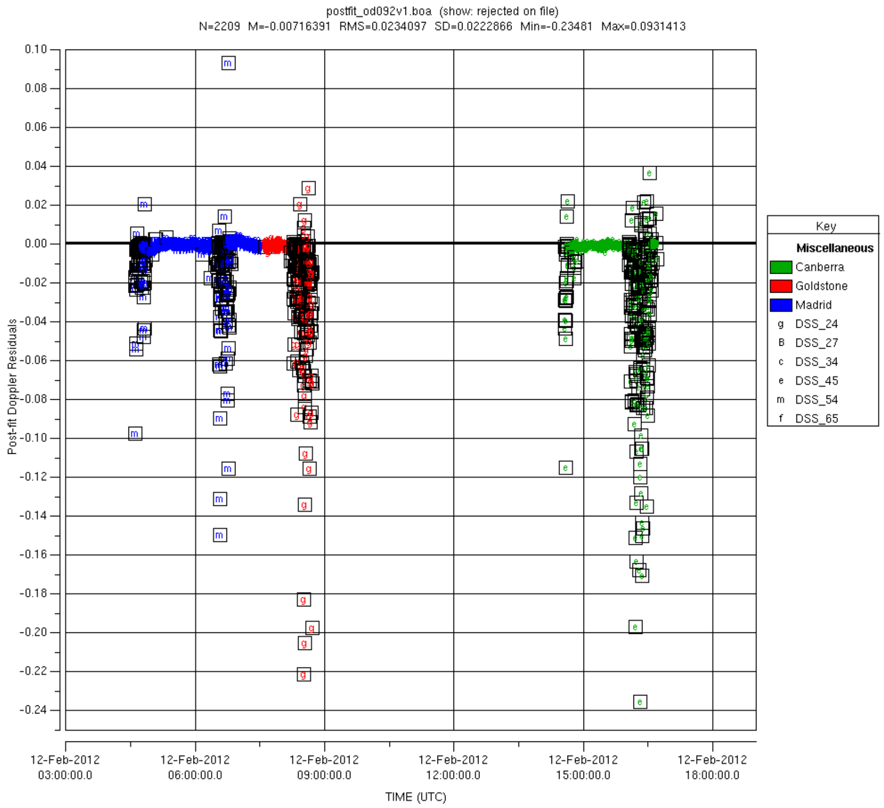
Error Source	Estimate Type	A Priori Uncertainty (1σ)	Comments
S-Band 2-way Doppler (hz)	-	Per Pass	0.0015 Hz Floor
State Position (km) State Velocity (km/s)	Estimate	1000 1	Moon Centered Cartesian
Solar Radiation Pressure Scale Factor (% of total)	Estimate	5	
AMD Event Δv (mm/sec)	Estimate	Various	Per Axis, Per Event
Periapsis Event Δv (mm/sec)	Estimate	Various	2-5 mm/sec Per Event
Future Acceleration (km/sec^2)	Stochastic	Various (Periodic)	Account for gravity errors
Ionosphere – day/night (cm) Troposphere – wet/dry (cm)	Stochastic	20 2	White Noise, Per Pass White Noise, Per Pass
Earth-Moon Ephemeris Earth GM (km^2/sec^2) Moon GM (km^2/sec^2)	Consider Consider Consider	DE421 Covariance 1.40 E-3 1.00 E-4	4 m lunar postion error
Station Locations (km,deg,km)	Consider	Covariance	
Pole X,Y (cm) UT1 (cm)	Consider Consider	10.0,10.0 10.0	1.5 E-8 radians 0.3 E-3 sec

Table 7. Additional Filter Parameters for Maneuver Support

Maneuver Errors (3σ)	Estimate Type	Model	ΔV Magnitude		Pointing		Comments
			Fixed	Propor-tional	Fixed	Propor-tional	
OCMs	Estimate	Main Engine	7.0 mm/sec	0.25 %	1.0 mm/sec	0.00436 radians	Force and Pointing
ECMs, BTDs	Estimate	Main Engine	9.0 mm/sec	0.045 %	0.0 mm/sec	0.0075 radians	Force and Pointing
OTMs	Estimate	ACS Thrusters	0.03 mm/sec	6.0 %	0.3 mm/sec	0.1050 radians	Force and Pointing

A key data feature was the use of an automatic process to perform data editing and weighting. The auto-editor detected and removed blunder points based on preset criteria and its auto-weight function computed and assigned per-pass data weights. An additional de-weighting scale factor of ~3.4 was applied to the computed per-pass noise to account for interplanetary solar plasma effects. The auto-weighting also had a floor value of 0.0015 Hz for S-band Doppler data. This was equivalent to setting a minimum threshold to protect against the possibility of over-weighting unusual passes.

Signatures were present in the Doppler tracking data residuals, particularly at low altitude when the spacecraft was near periapsis. Consequently, 20-40 minutes of data, centered around periapsis, was sometimes be removed from the tracking data to improve the overall fit. This technique was also frequently employed as an alternate data editing strategy to help verify that the estimated trajectory was not being corrupted by gravity modeling errors.



Figures 6. Doppler Tracking Data Corrupted by Multi-Path Noise.

Corrupted tracking signals were often found in the two-way Doppler data. A combination of low altitude, spacecraft orientation and orbit geometry caused a portion of the direct-to-Earth signal to follow a multi-path route, due to reflection off the lunar surface, before reaching the ground receiver. These corrupted data, most pronounced when the spacecraft was over the lunar poles, were not usable for orbit determination and imposed a challenge to separate from other dynamic mismodeling signatures, such as gravity. Analyst would often pre-process this data by fitting short segments of data or by adding artificial propulsive events, to reduce the magnitude of the dynamic signatures to more easily identify the multi-path data through pass-through techniques. The corrupted data would then be eliminated from the normal orbit determination process. An example of post-fit Doppler tracking residuals with the deleted multi-path data marked in boxes is shown in Figure 6.

Another important factor was the disciplined attempt to keep the two orbit determination teams synchronized. This included frequent communications and periodic reviews to verify that both teams employed the same models. Solutions, data arcs and arc length and delivery times were matched as much as possible.

Several operational considerations were implemented based on lessons learned from pre-launch testing. It was found to be impractical to include variational partials in the converged solution trajectory runout. This process was too slow and resource intensive and would have precluded meeting the tight time deadlines associated with the SCI-XM phase. Finally, a number of important software safety features were implemented to validate program inputs and usage. This included software "traps" to prevent use of one spacecraft's inputs in the other spacecraft's operational environment, a mass checker which would alert the user if the modeled spacecraft mass was inconsistent with the mission plan mass, the echoing of momentum wheel desaturations specifications in an easily readable format, and the setting of color coded computers prompts, consistent with the GRAIL project color conventions (red for GRAIL-A and blue for GRAIL-B). Table 6 and 7 show the baseline in-orbit configuration.

ORBIT DETERMINATION RESULTS

General Orbit Determination Results

The GRAIL Orbit Determination Team generated solutions approximately six days per week during low altitude lunar orbit. One measure of the consistency of orbit determination process was to track the trajectory differences for periods of data common to adjacent daily solutions. Generally the largest positional difference was on the order of 50 meters in the down-track direction.

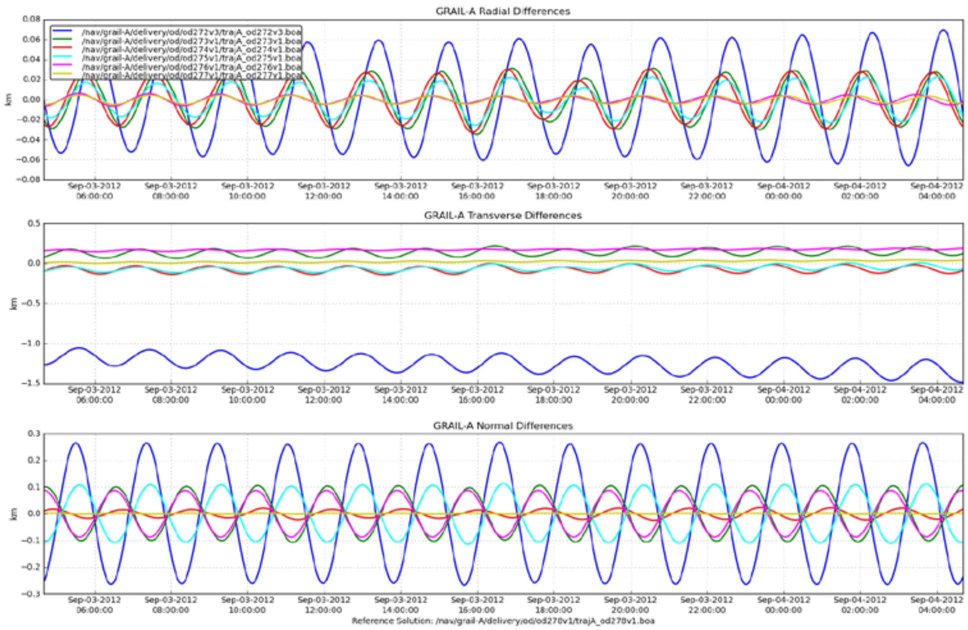


Figure 7 – One Week Trajectory Prediction Differences

The primary deliverable of the GRAIL Orbit Determination Team was a predicted trajectory to be used by various groups within the project for planning and execution of the mission. Down-track errors in the predicted trajectory corresponded directly to timing error in the spacecraft background sequence. A timing error on the order of 10 seconds relative to the on-board one-week sequence would trigger a sequence patch. A direct measure of this error was evaluated by comparing relative trajectory differences between daily solutions over a one-week period. An example of the one-week trajectory differences is shown in Figure 7. This indicates a short-term down-track error on the order of 10 meters, corresponding to a timing offset of just 0.005 seconds, well under the threshold for triggering a sequence update.

Another measure of trajectory prediction of consequence to the timing of on-board sequence events, was the difference between the current and predicted time of occultation entry and exit as viewed from the Earth. This had important implications for spacecraft and DSN operations.

A different type of requirement, related to maintenance of the science acquisition formation, was the spacecraft-to-spacecraft pointing. The Navigation component of the total pointing error was ±0.073 degrees. Errors in cross-track trajectory difference had the largest impact on meeting this requirement. Tracking the time history of this angle gave an indication of orbit errors, as shown in Figure 8.

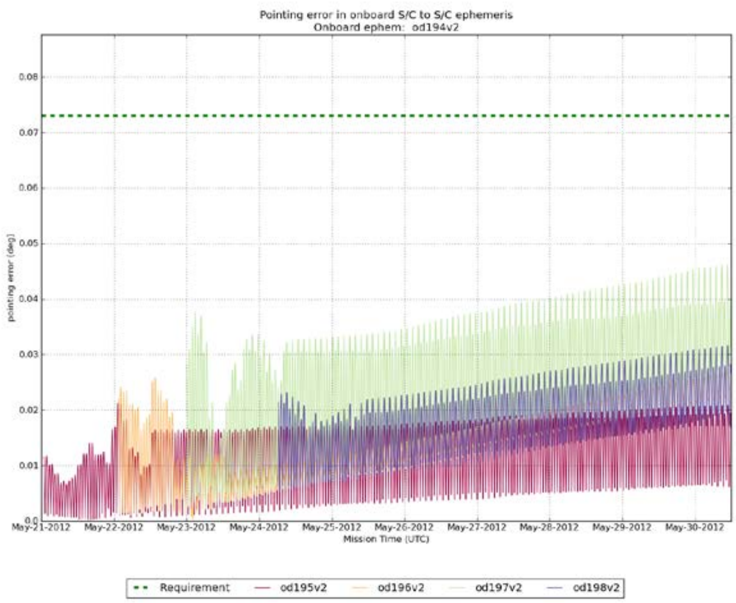


Figure 8 – Spacecraft-to-Spacecraft Pointing

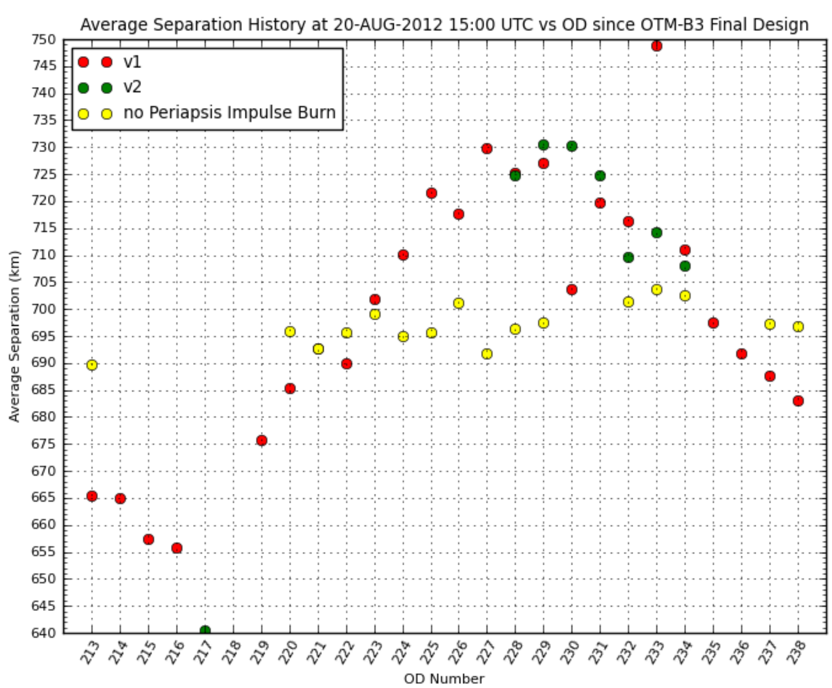


Figure 9 – Spacecraft-to-Spacecraft Relative Range during the LBA Phase

Low Beta Angle Phase Results

Long-term consistency of trajectory prediction had important implications for mission planning and operations. Drift in the spacecraft relative orbits over time could move the trajectories away from target orbits, forcing the use of contingency trajectory correction maneuver slots and wasting propellant. This type of error was evaluated by trending relative orbital elements over long time periods, and observing the long-term evolution of the spacecraft-to-spacecraft relative range.

This type of analysis lead to the discovery of a long term orbit drift during the LBA phase of the mission. The relative range was observed to change by an alarming 5 km per day. This raised concerns that a trajectory correction maneuver would need to be performed in early August 2012. Further analysis by the spacecraft and navigation teams found no evidence of any physical cause for the drift, primarily because the two spacecraft were experiencing nearly identical accelerations due to their proximity to one another. This indicated that the observed drift was not real and likely due to a likely filter modeling error. The error was eventually traced to biasing caused by the per-periapsis impulsive burns. This was an unexpected result because the technique had been used successfully during the SCI and no drift in spacecraft-to-spacecraft range had been observed at that time. Figure 9 plots the consistency of spacecraft-to-spacecraft range for solutions performed during the LEC and early LBA phases. In this example, the spacecraft-to-spacecraft range, mapped to August 20, 2012, is plotted as a function of orbit determination solution number (corresponding to near daily solutions from June 11, 2012 through July 18 2012). The “v1” solutions, shown as red points, used the baseline filter and editing strategy, which at that time included the per-periapsis impulsive burns. The “v2” solutions, shown as green points, employed the alternate data editing strategy of deleting data around periapsis. A third series of ”v3” solutions were also performed using the baseline data editing strategy but without the per-periapsis impulsive burns, shown as yellow points. As can be seen, the solutions using the “v3” modeling showed a relatively consistent spacecraft-to-spacecraft range. Consequently, the use of per-periapsis burns was eliminated from the baseline orbit determination filter setup for the remainder of the mission and no trajectory correction maneuver was performed.

Gravity Model Evaluation

A total of six gravity models based on GRAIL KBR data were delivered to the Orbit Determination Team for evaluation. Each new gravity model was used in parallel with the current baseline model for at least on week. An assessment was made based on improvements in the bias and standard deviation of post-fit Doppler residuals, reduction in predicted trajectory differences and pass-through Doppler residuals, and degradation in processing time. A number of truncations to the spherical harmonic expansion were also evaluated against the same criteria.

It was generally found that the larger models had smaller post-fit Doppler residual sigma’s performed better, but in many cases use of the full field or a larger sub-field offered minimal improvement in trajectory prediction at the expense of a significant increase in processing time. Each new gravity model was eventually incorporated into the Navigation process once a suitable sub-field was agreed upon. Over time, subsequently larger truncations were employed, reducing the amount of time available for analysis, but still allowing the team to meet critical project timelines.

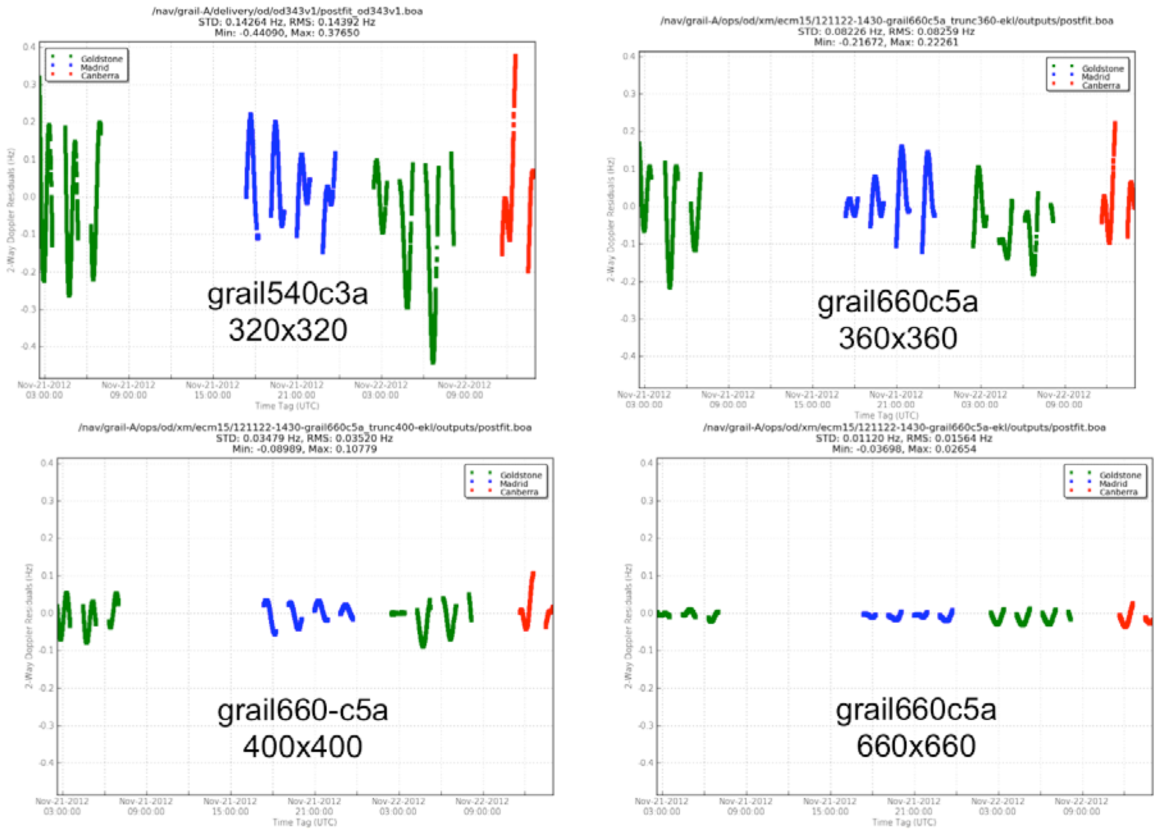


Figure 10 – Doppler Residual Comparison for Solutions Using Different Gravity Models

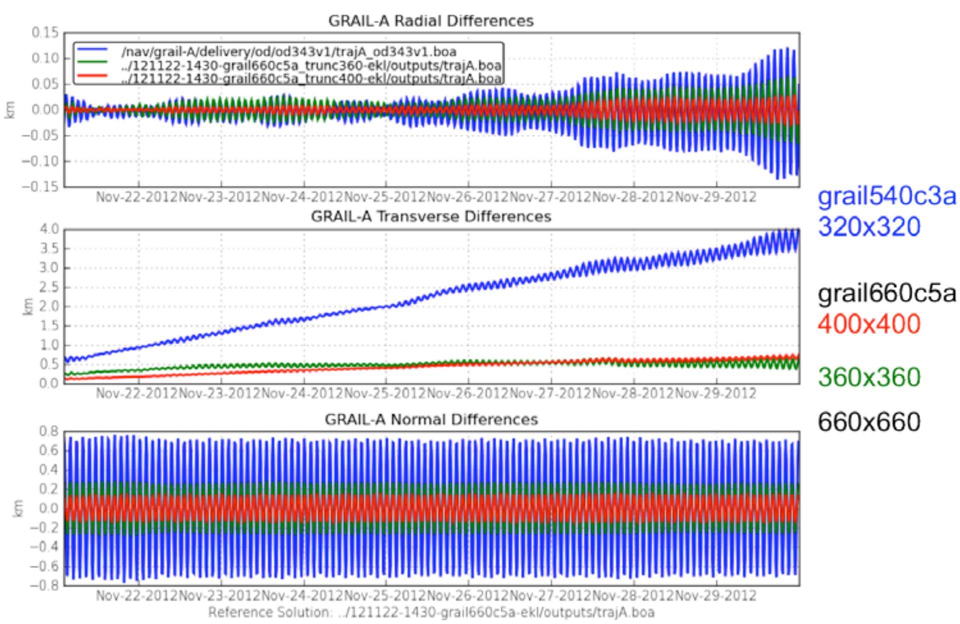


Figure 11 – Trajectory Comparison for Solutions using Different Gravity Models

Figure 10 shows the post-fit Doppler residuals for a suite of solutions using different gravity models. The upper left plot shows the post-fit Doppler residuals for an operational case. That case used the grail540c3a model with the spherical harmonic expansion truncated from 540x540 down to 320x320 to reduce processing time. The other plots show post-fit Doppler residuals from solutions performed during evaluation of the grail660c5a model, for the full 660x600 field and down to 400x400, 360x360 and 320x320 truncations. Figure 11 shows the one-week trajectory prediction difference for the same four cases, with the full grail660c5a field used as a truth model, corresponding to the zero abscissa line (horizontal axis). As can be seen, the Doppler post-fit residual mean and sigma improved as the field and sub-field size increased. A marked improvement in the trajectory prediction difference was also seen between the two gravity models, but only a small difference between the various truncations of the grail660c5a model. Consequently, grail660c5a model, truncated to a 400x400 sub-field was used during the final two weeks of mission support.

CONCLUSION

The GRAIL Orbit Determination Team overcame significant challenges posed during operations in low lunar orbit. This included implementing an operational scenario, which achieved project requirements despite the presence of significant errors in the lunar gravity model and met the tight deadlines needed for mission operations. The Orbit Determination Team delivered over 700 operational solutions and supported 52 maneuvers with a precision sufficient to carry out the mission and acquire virtually 100% of the planned science data. The mission's successful completion has lead to the development of a substantially improved gravity model for the Moon, which is the most accurate global field for any planetary body, including the Earth.

ACKNOWLEDGMENTS

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract to the National Aeronautics and Space Administration.

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