**Gravity Recovery and Interior Laboratory (GRAIL): Mapping the Lunar Interior from Crust to Core**

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**Abstract.** The Gravity Recovery and Interior Laboratory (GRAIL) is a spacecraft-to-spacecraft tracking mission that was developed to map the structure of the lunar interior by producing a detailed map of the gravity field. The resulting model of the interior will be used to address outstanding questions regarding the Moon's thermal evolution, and will be applicable more generally to the evolution of all terrestrial planets. Each GRAIL orbiter contains a Lunar Gravity Ranging System instrument that conducts dual-one-way ranging measurements to measure precisely the relative motion between them, which in turn are used to develop the lunar gravity field map. Each orbiter also carries an Education/Public Outreach payload, Moon Knowledge Acquired by Middle-School Students (MoonKAM), in which middle school students target images of the Moon for subsequent classroom analysis. Subsequent to a successful launch on September 10, 2011, the twin GRAIL orbiters embarked on independent trajectories on a 3.5-month-long cruise to the Moon via the EL-1 Lagrange point. The spacecraft were inserted into polar orbits on December 31, 2011 and January 1, 2012. After a succession of 19 maneuvers the two orbiters settled into precision formation to begin science operations in March 1, 2012 with an average altitude of 55 km. The Primary Mission, which consisted of three 27.3-day mapping cycles, was successfully completed in June 2012. The extended mission will permit a second three-month mapping phase at an average altitude of 23 km. This paper provides an overview of the mission: science objectives and measurements, spacecraft and instruments, mission development and design, and data flow and data products.

**Keywords.** Gravity - Moon - Lunar - Remote sensing - Spacecraft

## 1 Introduction

In December 2007, NASA competitively selected the Gravity Recovery and Interior Laboratory (GRAIL) mission under the Solar System Exploration Division Discovery Program. GRAIL was developed to map the structure of the lunar interior from crust to core. This objective will be accomplished by producing detailed maps of the lunar gravity field at unprecedented resolution. These gravity maps will be interpreted in the context of other observations of the Moon's interior and surface obtained by orbital remote sensing and surface samples, as well as experimental measurements of planetary materials. The resulting improved knowledge of the interior will be used to understand the Moon's thermal evolution, and by comparative planetological analysis, the evolution of other terrestrial planets. GRAIL is unique in that it provides a focused measurement to address broad scientific objectives.

The GRAIL mission is led by the Massachusetts Institute of Technology. The project is managed by the Jet Propulsion Laboratory (JPL), with Lockheed-Martin Space Systems Corporation (LMSSC) contracted to provide the spacecraft. GRAIL's science instrument was developed by JPL. Education and Outreach is implemented by Sally Ride Science. The Science Team contains representation from 15 academic institutions and NASA Centers.

After a successful launch on September 10, 2011 and a 3.5-month-long trans-lunar cruise, the twin GRAIL orbiters, named Ebb and Flow, were placed into a polar orbit on December 31, 2011 and January 1, 2012. After a succession of 19 maneuvers the two orbiters settled into a precision formation to begin science operations a week earlier than planned, on March 1, 2012, at an average altitude of 55 km. The Primary Mission (PM) was completed on May 29, 2012. On the basis of a competitive proposal evaluation, NASA decided to extend the GRAIL mission until December 2012.

Each GRAIL orbiter contains a Lunar Gravity Ranging System (LGRS) (Klipstein *et al.*, 2012) instrument that conducts dual-one-way ranging to precisely measure the relative motion between the two spacecraft. These distance changes are used to develop the lunar gravity field map (Thomas, 1999). The LGRS is a modified version of an instrument used on the Gravity Recovery and Climate Experiment (GRACE) (Tapley *et al.*, 2004) mission which is currently gravity mapping the Earth. GRAIL's twin spacecraft have heritage derived from an experimental U.S. Air Force satellite (XSS-11) and the Mars Reconnaissance Orbiter (MRO) mission (Johnson *et al.*, 2005), both developed by LMSSC. Each orbiter carries an Education/Public Outreach (E/PO) payload called GRAIL MoonKAM (or Moon Knowledge Acquired by Middle-School Students) in which middle school students target images of the Moon.

In this paper, Section 2 motivates study of the Moon's interior and describes previous attempts to measure the gravity field; Section 3 summarizes the GRAIL science objectives in the context of outstanding questions in lunar science; Section 4 summarizes the spacecraft and instruments; Section 5 covers the Mission Development and Design; Section 6 describes GRAIL's extended mission; Section 7 describes data flow; and Section 8 describes GRAIL's data products. All acronyms are defined in the Appendix.

## 2 The lunar interior and the measurement of planetary gravity

The Moon is the most accessible and best studied of the rocky (a.k.a. "terrestrial") bodies beyond Earth. Unlike Earth, the Moon's surface geology preserves the record of nearly the entirety of 4.5 billion years of solar system history. Orbital observations combined with samples of surface rocks returned to Earth from known locations make the Moon unique in providing a detailed, global record of the geological history of a terrestrial planetary body, particularly the early history subsequent to accretion.

The structure and composition of the lunar interior (and by inference the nature and timing of compositional differentiation and of internal dynamics) hold the key to reconstructing this history. For example, longstanding questions such as the origin of the maria, the reason for the nearside-farside asymmetry in crustal thickness, the role of mantle dynamics in lunar thermal evolution, and the explanation for the puzzling magnetization of crustal rocks, all require a greatly improved understanding of the Moon's interior.

Moreover, deciphering the structure of the interior will bring understanding of the evolution of not only the Moon itself, but also of the other terrestrial planets (Paulikas *et al.*, 2007). For example, while the Moon was once thought to be unique in developing a "magma ocean" shortly after accretion (Wood *et al.*, 1970), such a phenomenon has now been credibly proposed for Mars as well (Elkins-Tanton, 2008). Insight into fundamental processes such as the role of impacts in perturbing internal thermal state and in the re-distribution of crust are relevant to all solid planetary bodies.

Gravity is the primary means of mapping the mass distribution of the interior, but the Moon presents a special challenge in sampling the global field. A spacecraft in orbit is perturbed by the distribution of mass at the surface and within a planetary body, particularly that beneath the spacecraft as it orbits overhead. The measurement of planetary gravity has most commonly been achieved by monitoring the frequency shift of a spacecraft's radio system measured in the line of sight between the spacecraft, while in orbit about a planetary body, and a tracking station on Earth (Phillips *et al.*, 1978). The Doppler shift of the radio frequency provides a measure of spacecraft velocity, which when differenced provides accelerations. Correcting for accelerations due to spacecraft thrusting and maneuvering as well as other non-gravitational forces (Asmar *et al.*, 2012) yields the gravitational field of the planet. For this approach to work, all parts of the planetary surface must be visible in the line-of-sight of the ground station as the planet rotates beneath the spacecraft. However, because the Moon is in synchronous rotation about Earth the farside is never directly visible; thus gravity on the nearside is sensed much more accurately than on the farside.

The Moon was the first planetary body beyond Earth for which gravity field information was obtained with a spacecraft, beginning with the Russian Luna 10 (Akim, 1966). Subsequent U.S. efforts included Lunar Orbiters 1-5, the Deep Space Program Science Experiment (DSPSE; Clementine) (Zuber *et al.*, 1994; Lemoine *et al.*, 1997) and Lunar Prospector (Konopliv *et al.*, 1998; Konopliv *et al.*, 2001).

The geometrical shortcoming associated with lack of visibility from Earth of a spacecraft over the farside motivated the use of sub-satellites in the recent Kaguya mission (Namiki *et al.*, 2009). A sub-satellite can be tracked by the orbiter on the farside to measure gravitational perturbations when not in the line of sight from Earth.

The line-of-sight method produced reasonable measurement of gravity of the Moon's nearside that most famously led to the early identification of "mascons" (Muller and Sjogren, 1968; Phillips *et al.*, 1972), lunar mass concentrations spatially associated with the Moon's mare basins. Other analyses developed local gravity representations using surface mass models (Wong *et al.*, 1971; Ananda, 1977). The most natural representation of the gravity field is a spherical harmonic expansion, since spherical harmonics are the solution to Laplace's equation, $\nabla^2 U = 0$, which describes the gravitational potential $U$, on a sphere. The spherical harmonic solution for the gravitational potential with normalized coefficients ($\bar{C}_{nm}$, $\bar{S}_{nm}$) can be expressed (Kaula, 1966; Heiskanen and Moritz, 1967)

$$U = \frac{GM}{r} + \frac{GM}{r}\sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R_e}{r}\right)^n \bar{P}_{nm}(\sin\phi_{lat})\left[\bar{C}_{nm}\cos(m\lambda) + \bar{S}_{nm}\sin(m\lambda)\right] , \tag{1}$$

where $GM$ is the gravitational constant times the mass of the Moon, $n$ is the degree, $m$ is the order, $\bar{P}_{nm}$ are the fully normalized associated Legendre polynomials, $R_e$ is the reference radius of the Moon, $\phi_{lat}$ is the latitude, and λ is the longitude (east positive). The gravity coefficients are normalized and are related to the unnormalized coefficients according to (Kaula, 1966)

$$\begin{pmatrix} C_{nm} \\ S_{nm} \end{pmatrix} = \left[\frac{(n-m)!(2n+1)(2-\delta_{0m})}{(n+m)!}\right]^{1/2} \begin{pmatrix} \bar{C}_{nm} \\ \bar{S}_{nm} \end{pmatrix} = f_{nm} \begin{pmatrix} \bar{C}_{nm} \\ \bar{S}_{nm} \end{pmatrix}. \tag{2}$$

The coefficients contain the information about the variation of gravity, and $n$ and $m$ describe the resolution of the field, which in practice is dictated by coverage and spacecraft altitude. A comparison of recent spherical harmonic solutions for the lunar gravitational field to that expected from GRAIL is given in Table 1. A companion paper (Asmar *et al.*, 2012) discusses extensive simulations that assessed the expected quality of the GRAIL field on the basis of quantitative assessment of various deterministic and stochastic errors on the measurements and on the recovery of the gravitational field.

## 3 Primary Mission Science Objectives

The necessity to understand the Moon's internal structure in order to reconstruct planetary evolution motivates the GRAIL primary science objectives, which are to:

- Determine the structure of the lunar interior from crust to core, and
- Advance understanding of the thermal evolution of the Moon.

In addition GRAIL has one secondary objective:

- Extend knowledge gained on the internal structure and thermal evolution of the Moon to other terrestrial planets.

The primary objectives are closely related; interior structure along with surface geology and chemistry are required to reconstruct thermal evolution. Of these, it is knowledge of the internal structure that is currently most lacking (Hood and Zuber, 2000). The secondary objective adds a comparative planetological focus to the mission and affords the opportunity to engage a broader cross section of the scientific community with expertise in terrestrial planet evolution.

GRAIL's Primary Mission includes six lunar science investigations, to:

1. Map the structure of the crust and lithosphere.
2. Understand the Moon's asymmetric thermal evolution.
3. Determine the subsurface structure of impact basins and the origin of mascons.
4. Ascertain the temporal evolution of crustal brecciation and magmatism.
5. Constrain the deep interior structure from tides.
6. Place limits on the size of the possible inner core.

Measurement requirements for GRAIL's science investigations are given in Table 2 and Figure 1. The GRAIL Science Team, listed in Table 3, carries out the science investigations.

The mission accomplishes its broad lunar science objectives via a focused, extremely precise measurement: the distance change between two spacecraft. Specifically, GRAIL obtains global, regional and local high-resolution (30×30-km), high-accuracy (<10-mGal) gravity field measurements with twin, low-altitude (55 km) polar-orbiting spacecraft.

## 4 Spacecraft and Instruments

The GRAIL orbiters (Hoffman, 2009) are nearly identical spacecraft with heritage to past spacecraft and spacecraft subsystems built at LMSSC. The main structure and propulsion system are based on the design used on the U.S. Air Force Experimental Satellite System 11 (XSS-11), built under contract by LMSSC, that was designed to demonstrate autonomous rendezvous and proximity maneuvers. Some components of the GRAIL spacecraft, most notably the flight computer, traced heritage to the Mars Reconnaissance Orbiter (MRO), built by LMSSC under contract to the Jet Propulsion Laboratory. While MRO was a larger spacecraft with numerous instruments and complex targeting requirements, the basic processing functions from MRO were transferrable to GRAIL. Functionally, the GRAIL flight computer is a simplification of that on MRO, inspiring the moniker "MRO-Lite". Both XSS-11 and MRO were successful projects and collectively formed a sound basis for the design heritage of the GRAIL mission. The two orbiters were designed to be as identical as possible to reduce cost, eliminate configuration complexities and streamline integration and test flows. Small differences in design were necessitated by geometrical constraints associated with satellite-to-satellite ranging. Two views of the spacecraft are shown in Figures 2a and 2b.

A key attribute of the orbiters is that they are single string for almost every component. A single-string mission allows for a much more simplified system in terms of design, and integration, test and operations, but it entails increased risk. The approach was made to fit with the GRAIL mission's guiding principle of "low risk implementation" due to the relatively short primary mission life (9 months) coupled with the adoption of a robust reliability program (Taylor *et al.*, 2012). The single string approach also reduced the overall development cost of the mission, and in addition minimized mass, allowing both spacecraft to be launched on a Delta-II Heavy with considerable mass margin. The only exceptions to the single-string philosophy were areas where redundancy either came at no cost or where the absence of redundancy would pose a risk to the project (Hoffman, 2009).

There are two payloads on each GRAIL orbiter. The science instrument is the Lunar Gravity Ranging System (LGRS) (Klipstein *et al.*, 2012) and the Education/Public Outreach (E/PO) payload is Moon Knowledge Acquired by Middle-School Students (MoonKAM). GRAIL is unique in that the science for the mission is achieved with a single instrument. Each of the payloads is briefly described herein, and detailed discussion of the LGRS is given by (Klipstein *et al.*, 2012).

The LGRS instrument utilizes a dual-one-way ranging (DOWR) measurement to precisely measure the relative motion between the two orbiters. The fundamental method used for the ranging measurement has a long history of use over dozens of missions as a primary navigation tool. This method was extended on the GRACE mission (Dunn *et al.*, 2002), which has been successfully mapping the Earth's gravity field since launch in March, 2002 (Tapley *et al.*, 2004).

As shown in the block diagram in Figure 3, the instrument consists of a Ka-band antenna for transmitting and receiving inter-satellite signals; a microwave assembly (MWA) for generating Ka-band signals for transmission and mixing down the inter-satellite signals; a Gravity Recovery Processor Assembly (GPA) for processing both the Ka-band signals and those from the S-band Time Transfer System (TTS), the latter of which is used to correlate inter-satellite ranges; an Ultra-Stable Oscillator (USO) that provides timing for both the Ka-band and S-band systems; and a Radio Science Beacon (RSB) that provides an X-band Doppler carrier to support daily calibration of the USO frequency by the DSN. The elements of the instrument work together to achieve micron-level precision relative range differences.

Overall science implementation is achieved through the LGRS instrument measuring the change in range between the two orbiters. The gravity field of the Moon influences the motion of the center-of-mass (CM) of each spacecraft, which essentially acts like a proof mass in orbit about the Moon. Surface features such as craters, mass concentrations (mascons), and deep interior structure and dynamics perturb the spacecraft orbits and introduce variations in the relative motion between the spacecraft (Thomas, 1999).

The fundamental measurement is the Line of Sight (LOS) range rate, which was designed to achieve an accuracy of 4.5 $\mu$m $s^{-1}$ over a 5-second sample interval. These data are collected along with DSN tracking data over a period of 27.3 days, providing global coverage of the Moon, six times over. The entire set of mapping cycle data is then processed to recover the global gravity map.

The MoonKAM payload is a set of cameras, designed and built by Ecliptic Enterprises Corporation, that image the lunar surface. The MoonKAM investigation was led by America's first woman in space, Dr. Sally K. Ride, and since her untimely passing in July 2012 continues to be implemented by Sally Ride Science (SRS). MoonKAM is the first planetary imaging experiment dedicated entirely to education and outreach. GRAIL's MoonKAMs consist of electronics and four camera heads per spacecraft to allow imaging at a variety of directions and resolutions.

The MoonKAM investigation is targeted at the middle school level but accepts participation from all supervised student groups and clubs. At the end of the PM the program had enlisted over 2800 participating classrooms and/or student organizations and over 100,000 individual participants. Students use trajectory software based on JPL's "Eyes on the Solar System" (http://solarsystem.nasa.gov/eyes/) to target images of the lunar surface. The cameras are operated by undergraduates at the University of California, San Diego, who are supervised by personnel at SRS. All acquired images are posted to a public website  and classroom activities developed by staff at Sally Ride Science are available for subsequent scientific analysis of the lunar surface. The MoonKAM investigation is intended to motivate interest in science, technology and mathematics by providing meaningful, early exposure to the challenges and processes used in spacecraft operations, and genuine participation in exploration and scientific analysis.

## 5 Mission Development and Design

A summary of key dates in the development of the GRAIL mission is given in Table 4. GRAIL's development initiated subsequent to competitive selection as NASA's 11th Discovery mission in December 2007. During its development phase, GRAIL met all milestones on time, including reviews, and the delivery of gate products and the delivery of NASA life- cycle prescribed documentation and development products, and hardware. The LGRS instrument was delivered for integration to LMSSC 2 weeks early. In addition, the Project team compressed the Assembly and Test schedule to deliver both spacecraft to the launch facility a week early (Taylor *et al.*, 2012). This early delivery was in support of a risk reduction request from the launch vehicle team at NASA Kennedy Space Center to allow additional processing time due GRAIL's status as the last east coast Delta launch.  GRAIL's development concluded with a successful launch, on schedule and under budget (GAO, 2012), of the twin spacecraft on a single Delta-II 7920H rocket from the Cape Canaveral Air Force Station (CCAFS) in Florida on September 10, 2011.

The GRAIL orbiters must fly in precise formation to map the Moon while at the same time pointing their body-fixed solar panels toward the sun. Because of the importance of the sun's direction, a parameter of particular relevance in the GRAIL mission design is the solar beta angle ($\beta$), defined as the angle between the orbital plane and a line drawn from the Sun to the Moon. Over the course of a year, the position of the sun with respect to the orbit plane dictates the times and duration of periods when the solar panels receive enough sunlight to power the spacecraft and perform science operations. The GRAIL orbiters, which carried small onboard batteries (Hoffman, 2009), were designed to map at solar beta angles $\beta > 49^o$ but in practice nominal operations were possible for $\beta > 40^o$, which enabled science mapping to initiate a week early in the PM. It is convenient and informative to graphically depict GRAIL's mission phases from a heliocentric perspective, presented in Figure 4 (Roncoli and Fujii, 2010).

Following launch, the Delta upper stage that contained both spacecraft entered a parking orbit and then injected into the trans-lunar trajectory, initiating the Trans-Lunar Cruise (TLC) phase of the mission (Chung *et al.*, 2010). Subsequent to injection toward the Moon, the two spacecraft were deployed from the launch vehicle and traveled to the Moon upon similar but separate trajectories. As shown schematically in Figure 5, the TLC phase (Chung *et al.*, 2010) utilized a 3.5-month, low-energy trajectory via the Sun-Earth Lagrange point (EL-1) to transit to the Moon. This unique mission design (Roncoli and Fujii, 2010) provides several key features important to the GRAIL mission. First, the low energy trajectory allowed for an extended launch window, providing a 42-day window versus a 3-6-day window for a direct trajectory. Second, the low-energy trajectory allowed for a smaller required delta-V for lunar orbit insertion that in turn allowed for smaller propulsion system on the spacecraft; this prevented a large-scale redesign of the heritage spacecraft. Third, this particular mission design allowed for a fixed

Lunar Orbit Insertion phase for any date within the 42-day launch window, which allowed planning for cruise operations to be decoupled from orbital operations; an additional benefit is that the orbit insertions were able to be separated by 25 hours to avoid the execution of two critical events in a single day. Finally, the TLC period allowed time to perform spacecraft and payload checkout, allowed time for the Ultra-Stable Oscillator (USO) to stabilize, and allowed the spacecraft to outgas. Outgassing is a non-conservative force that could influence gravity measurements if not done prior to gravity mapping.

The first Lunar Orbit Insertion (LOI) maneuver (Hatch *et al.*, 2010) occurred on December 31, 2011. And the second occurred on January 1, 2012. These maneuvers involved 39-minute-long continuous main engine propulsive burns of ~190 m/s to slow the spacecraft sufficiently to enter lunar capture orbits. The LOI burns were conducted so as to allow for continuous command and telemetry coverage from the NASA Deep Space Network (DSN).

After LOI, the two spacecraft underwent orbit circularization and were positioned into formation to prepare for science operation. Orbit circularization took approximately one month during the mission's Orbit Period Reduction (OPR) phase, which is shown schematically in Figure 6. The main activity during this phase was to perform Period Reduction Maneuvers (PRMs) (Hatch *et al.*, 2010), that were designed to place each spacecraft into a 55-km altitude circular orbit with the approximate desired separation and formation required for science. After OPR, the dual spacecraft went through a month-long Transition to Science Formation (TSF) phase during which a series of maneuvers established the proper formation and separation between the two spacecraft prior to the start of science collection. A total of 19 maneuvers following LOI were required in a two-month period prior to the start of science collection. However, during PM science mapping only one burn was executed, to adjust the drift rate between the two spacecraft. Figure 7 shows the actual variation of periapsis and apoapsis during the PM and Figure 8 shows the corresponding evolution of distance and drift rate between the spacecraft.

During the 89-day Science phase, the GRAIL spacecraft completed over three 27.3-day mapping cycles (lunar sidereal periods) of the Moon and returned 637 Mbytes of science volume or >99.99% of possible data. In performing its science mission, GRAIL achieved the first robotic demonstration of precision formation flying around another planetary body besides Earth (Roncoli and Fujii, 2010). The PM ended with maneuvers to raise the spacecraft orbits on May 29, 2012. From launch through the PM, a total of 28 spacecraft maneuvers were performed, all flawlessly, by the GRAIL operations team.

## 6 Extended Mission

On the basis of competitive review, NASA has approved an Extended Mission (XM) for GRAIL, through December 2012, or approximately three months of data acquisition, that will enable collection of higher-resolution gravity data by flying the dual spacecraft in formation at an even lower altitude. The XM dramatically expands the scope of GRAIL's gravity science investigation beyond what was possible during the PM. By operating the dual spacecraft in the lowest orbit the flight team can safely support, it increases the resolution of the gravity field measurement by over a factor of two, sufficient to distinguish gravitational features down to a fraction of the crustal thickness. We defined "safely support" to mean that a missed or off-nominal maneuver could be recovered from in less than a week. Thus, GRAIL's XM enters a new realm of lunar science: crustal geophysics at the spatial scale of regional geology. It provides a singular opportunity to globally map the detailed structure of a planetary crust.

A heliocentric view of the GRAIL XM is shown in Figure 9 (Sweetser *et al.*, 2012). In late May 2012, when the PM was completed, periapsis raise maneuvers circularized the spacecraft orbits at an altitude of ~84 km for the low-activity Low Beta Angle phase. For ten weeks subsequent to the lunar eclipse passage on June 4, the orientation of the orbit plane relative to the Sun did not allow for operation of the LGRS payloads while in orbiter-point configuration due to the Sun-Moon-Earth geometry. A second three-month science phase initiated successfully on August 30 when the solar beta angle reached $40^{o}$, at which time the solar panels were oriented in a manner that allows them to adequately charge the spacecraft while in ranging configuration.

GRAIL's XM average altitude is 23-km, less than half the average altitude of the PM. Because of the low orbital altitude, operations in the Extended Mission are far more complex than in the PM (Wallace *et al.*, 2012). Unlike the PM, which featured only one thrust maneuver to change the drift rate of the spacecraft over three months of mapping, the XM requires three maneuvers a week to maintain the mapping altitude (Sweetser *et al.*, 2012). During extended science mapping, weekly eccentricity correction maneuvers (ECMs) on both orbiters maintain the orbits. There will also be a weekly Orbit Trim Maneuver (OTM) on one orbiter, a day after the ECMs, to control the orbiter separation distance. The XM contains 46 baseline maneuvers. The altitude variation about the mean will be constrained to ±12 km. Figure 10 shows the variation in altitudes of the spacecraft during the XM. The XM mapping orbit is deemed by analysis (Wallace *et al.*, 2012) to be the lowest orbit the flight team can safely support; the resulting resolution of the gravity field measurements will correspond to spatial blocksizes from ~30 km to <10 km. In addition, the accuracy will be improved by over an order of magnitude at 30-km block size resolution, permitting GRAIL to map structure globally within the upper crust.

The orbiters will experience a penumbral lunar eclipse on November 28. Subsequent to this event the altitude of the orbiters will again be decreased, to an average altitude of 11 km, for additional mapping in the mission's "limbo phase". High-resolution of the Orientale Basin, the youngest large impact basin on the Moon, is planned for this period. Science mapping will end on December 14, after which a series of engineering experiments is planned prior to deorbit on December 17, 2012. The mission end game includes a burn to depletion maneuver for each spacecraft.

The GRAIL XM has one overarching science objective:

- Determine the structure of lunar highland crust and maria, addressing impact, magmatic, tectonic and volatile processes that have shaped the near surface.

To address this objective the GRAIL extended mission undertakes 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.

The science objective and six investigations are new to the GRAIL mission. The XM objectives and measurement requirements are shown in Table 5 and Figure 11. These investigations do not cover the full scope of research that will be enabled by the GRAIL XM, but they are indicative of the kinds of analyses that will be possible by gravitational mapping of the Moon's upper crust with unprecedented resolution and accuracy.

## 7 Data Flow and Processing

The GRAIL Science Data System (SDS) is the infrastructure at JPL for the collection of all science and ancillary data relevant to the GRAIL mission. The SDS includes hardware, software tools, procedures and trained personnel. The SDS receives data from three sources, collectively called Level 0 data, as described below, and carries out calibration, editing, and processing to produce Level-1A and -1B GRAIL science data. The SDS distributes Level-0, -1A, and -1B data to the Science Team and submits the same products for archiving at the NASA Planetary Data System (PDS) Geosciences Node. Higher-level data products including the gravitational field harmonic coefficients, are archived with the PDS by the Principal Investigator at MIT.

Figure 12 shows the downlinked data flow. The Mission Operation System (MOS) receives packets from the DSN and places them on the Telemetry Delivery System (TDS). The science data and engineering data packets are then transferred from the multimission TDS to the GRAIL science server. Timed scripts push the packets to the SDS computers on a regular basis. The SDS also receives Level-1A Doppler (tracking) data from the DSN. Finally, the SDS receives high-rate telemetry data from the Multimission Distributed Object Manager (MMDOM), placed there by the Lockheed Martin Mission Operations Center (MOC). Data are transferred to secure servers at MIT and the Goddard Space Flight Center for access and use by the GRAIL Science Team.

## 8 Data Accessibility

The GRAIL mission will archive all acquired science data at all levels along with ancillary data and relevant information and documentation to NASA’s Planetary Data System (PDS) in order for the science community at large to benefit from the knowledge gained by the mission.

The archival will be complete and timely per NASA's guidelines and will allow future users to choose to either interpret available higher products or re-derive results from available lower data products. Additional documentation or software may also be provided at the discretion of the GRAIL Science Team.

The process of data accessibility in captured Table 6, which lists the archival data sets, and Table 7, which lists the data product identification for PDS labels, data levels, and expected volumes. Figure 12 shows the flow of data from the flight system to the ground system and ultimate users.

Images from the MoonKAM investigation are not required for the fulfillment of any GRAIL science objective and therefore are neither calibrated nor archived in the PDS. However, the images are posted as soon as possible after acquisition to a public website: http://images.moonkam.ucsd.edu/main.php, where they can be freely accessed by students and the public. Over 101,000 student images were acquired in the PM.

## 9 Summary

GRAIL successfully completed its Primary Mission on schedule and under budget. The mission achieved NASA's baseline mission success criteria (Investigation 1–4) for the PM in May 2012, one year ahead of schedule. GRAIL was successful in collecting its required data with a total science data volume at the end of the PM of 637 Mbytes or >99.99% of possible data. Following the PM, the two GRAIL spacecraft successfully transited the partial lunar eclipse of June 4, 2012 and initiated Extended Mission data gathering at very low mean altitude (23 km). Finally, GRAIL is on track to provide a comprehensive data set that will guide future scientific discoveries and future exploration of the Moon (Zuber *et al.*, 2012).

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## Appendix

### Acronyms and Abbreviations

| | |
|---|---|
| **CBE** | Current Best Estimate |
| **CCAFS** | Cape Canaveral Air Force Station |
| **C&DH** | Command & Data Handling |
| **CM** | Center of Mass |
| **DSN** | Deep Space Network |
| **ECM** | Eccentricity Correction Maneuver |
| **E/PO** | Education and Public Outreach |
| **GB** | Gigabytes |
| **GDS** | Ground Data System |
| **GPA** | Gravity Processing Assembly |
| **GR-A** | GRAIL-A Spacecraft (Ebb) |
| **GR-B** | GRAIL-B Spacecraft (Flow) |
| **GRACE** | Gravity Recovery and Climate Experiment |
| **GRAIL** | Gravity Recovery and Interior Laboratory |
| **GSFC** | Goddard Space Flight Center |
| **ITAR** | International Traffic in Arms Regulations |
| **JPL** | Jet Propulsion Laboratory |
| **KBR** | Ka-Band Ranging |
| **LGRS** | Lunar Gravity Ranging System |
| **LMSSC** | Lockheed Martin Space Systems Company (Denver) |
| **LOI** | Lunar Orbit Insertion |
| **LOLA** | Lunar Orbiter Laser Altimeter |
| **LOS** | Line of Sight |
| **LRO** | Lunar Reconnaissance Orbiter |
| **mascon** | Mass Concentration |
| **mGal** | milliGal (where 1 Gal = 0.01 m $s^{-2}$) |
| **MIT** | Massachusetts Institute of Technology |
| **MoonKAM** | Moon Knowledge Acquired by Middle school students |
| **MOC** | Mission Operations Center |
| **MOS** | Mission Operations System |
| **MGSS** | Multi-mission Ground System Services |
| **MMDOM** | Multimission Distributed Object Manager |
| **MPST** | Mission Planning and Sequence Team |
| **MWA** | Microwave Assembly |
| **NAIF** | Navigation and Ancillary Information Facility |
| **NASA** | National Aeronautics and Space Administration |
| **OPR** | Orbital Period Reduction |
| **OTM** | Orbit Trim Maneuver |
| **PDS** | Planetary Data System |
| **PM** | Primary Mission |

| | |
|---|---|
| **RSB** | Radio Science Beacon |
| **SCT** | Spacecraft Team |
| **SDS** | Science Data System |
| **SIS** | Software Interface Specification |
| **SRS** | Sally Ride Science |
| **TCM** | Trajectory Correction Maneuver |
| **TDS** | Telemetry Delivery System |
| **TLC** | Trans-Lunar Cruise |
| **TSF** | Transition to Science Formation |
| **TSM** | Transition to Science Maneuver |
| **TTS** | Time Transfer System |
| **USO** | Ultra-stable Oscillator |
| **XM** | Extended Mission |
| **XSS-11** | Experimental Satellite System 11 |

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**Figure Captions**

**Fig. 1** Primary Mission science measurement performance and requirements. CBE refers to the "current best estimate" of GRAIL Prime Mission performance prior to launch

**Fig. 2** GRAIL *(a)* –X spacecraft view; *(b)* +X spacecraft view.

**Fig. 3** Lunar Gravity Ranging System block diagram.

**Fig. 4** Heliocentric view of the GRAIL Primary Mission timeline, extending over nine months with seven distinct mission phases.

**Fig. 5** Trans-lunar cruise trajectories in sun-fixed coordinate system, viewed normal to the ecliptic plane. EL1 is the Sun-Earth Lagrange point.

**Fig. 6** Schematic of Orbit Period Reduction phase as viewed from the Moon's north pole (top) and from Earth (bottom). Also shown at bottom in gold is the LOI burn arc for GRAIL-A (Ebb).

**Fig. 7** Periapsis and apoapsis altitudes in the Primary Mission.

**Fig. 8** Spacecraft *(top)* separation distance and *(bottom)* drift rate during the Primary Mission.

**Fig. 9** Heliocentric view of the GRAIL's Extended Mission timeline, extending over seven months with five distinct mission phases.

**Fig. 10** Maximum (red) and minimum (blue) altitudes of GRAIL in the Extended Mission. Thick lines are altitudes with respect to a sphere of radius 1737.4 km and thin lines are with respect to LRO/LOLA topography. For comparison, light green lines show the periapsis altitudes in the Primary Mission.

**Fig. 11** Extended Mission science measurement performance and requirements. The current best estimate (CBE) has significant margin over the requirements. The demonstrated instrument performance during test in cruise was 0.001 mGal at 1 Hz.

**Fig. 12** GRAIL Science downlink data flow diagram.

# Tables

**Table 1** Summary of recent lunar gravity models

| Reference | Field | Data Used | Spherical Harmonic Degree and Order |
|---|---|---|---|
| Lemoine *et al.* (1997) | GLGM-1 | Lunar Orbiter 1-5, Apollo subsatellites, Clementine | 70x70 (78-km blocksize) |
| Konopliv *et al.* (2001) | LP100, LP150 | Lunar Orbiter 1-5, Apollo sub-satellites, Clementine, Lunar Prospector | 100x100 (54-km blocksize) later updated to 150x150 (36-km blocksize) ; Useful for geophysical modeling to 110,110 (blocksize = 50 km) |
| Matsumoto *et al.* (2010) | SGM100h | Kaguya S-band and X-band; Orbiter, Relay subsatellite, VLBI subsatellite | 100x100 (54-km blocksize) ; Useful for global geophysics to 7 0x70 (78-km blocksize) |
| Mazarico *et al.* (2010) | GLGM-3 | Lunar Orbiter 1-5, Apollo sub-satellites, Clementine, Lunar Prospector | 150x150 (36-km blocksize) |
| GRAIL | | Satellite-to-satellite tracking (Ka-band); | At least 180x180 (30-km blocksize) expected |

**Table 2** Primary Mission science investigations.

| Science Objective | Science Investigation | Area ($10^6$ km$^2$) | Reso-lution (km) | Requirements (30-km block) |
|---|---|---|---|---|
| Determine the structure of the lunar interior. | 1. Crust & Lithosphere | ~10 | 30 | ±10 mGal |
| | 2. Thermal Evolution | ~4 | 30 | ±2 mGal |
| | 3. Impact Basins | ~1 | 30 | ±0.5 mGal |
| | 4. Magmatism | ~0.1 | 30 | ±0.1 mGal |
| Advance understanding of the thermal evolution of the Moon. | 5. Deep Interior | N/A | N/A | $k_2 \pm 6 \times 10^{-4}$ (3%) |
| | 6. Inner Core Detection | N/A | N/A | $k_2 \pm 2.2 \times 10^{-4}$ (1%) $C_{2,1} \pm 1 \times 10^{-10}$ |

**Table 3** GRAIL science team

| Team Member | Role | Institution |
|---|---|---|
| Maria T. Zuber | Principal Investigator | Massachusetts Institute of Technology |
| David E. Smith | Deputy Principal Investigator | Massachusetts Institute of Technology |
| Michael M. Watkins | Co-Investigator/ Project Scientist | Jet Propulsion Laboratory |
| Sami W. Asmar | Co-Investigator/ Project Scientist | Jet Propulsion Laboratory |
| Alexander S. Konopliv | Co-Investigator | Jet Propulsion Laboratory |
| Frank G. Lemoine | Co-Investigator | NASA/Goddard Space Flight Center |
| H. Jay Melosh | Co-Investigator | Purdue University |
| Gregory A. Neumann | Co-Investigator | NASA/Goddard Space Flight Center |
| Roger J. Phillips | Co-Investigator | Southwest Research Institute |
| Sean C. Solomon | Co-Investigator | Lamont-Doherty Earth Observatory of Columbia University |
| Mark A. Wieczorek | Co-Investigator | Institute de Physique du Globe de Paris |
| James G. Williams | Co-Investigator | Jet Propulsion Laboratory |
| Jeffrey Andrews-Hanna | Guest Scientist | Colorado School of Mines |
| James Head | Guest Scientist | Brown University |
| Walter Kiefer | Guest Scientist | Lunar and Planetary Institute |
| Isamu Matsuyama | Guest Scientist | University of Arizona |
| Patrick McGovern | Guest Scientist | Lunar and Planetary Institute |
| Francis Nimmo | Guest Scientist | University of California, Santa Cruz |
| Christopher Stubbs | Guest Scientist | Harvard University |
| G. Jeffrey Taylor | Guest Scientist | University of Hawaii, Honolulu |
| Renee Weber | Guest Scientist | NASA/Marshall Space Flight Center |

**Table 4** Summary of key GRAIL events.

| Event | Date |
|---|---|
| GRAIL Selection as a Discovery Mission | Dec. 2007 |
| Preliminary Design Review | Nov. 2008 |
| Confirmation Review | Jan. 2009 |
| Critical Design Review | Nov. 2009 |
| Systems Integration Review | June 2010 |
| Pre-Ship Review | May 2011 |
| Orbiters delivered to launch site | May 2011 |
| Launch | Sept. 10, 2011 |
| Lunar Orbit Insertion | Dec. 31, 2011 (GR-A)/Jan. 1, 2012 (GR-B) |
| Primary Science Phase Begins | March 2012 |
| Primary Science Phase Ends | June 2012 |
| Extended Science Phase Ends | December 2012 |
| Archive of Prime Mission Levels 0 and 1 data | December 2012 |
| Archive of Prime Mission Levels 2 and 3 data | September 2013 |
| Archive of Extended Mission Levels 0 and 1 data | June 2013 |
| Archive of Extended Mission Levels 2 and 3 data | June 2014 |

**Table 5** Extended Mission science investigations.

| Investigation | Spatial Scale & Accuracy Reqt |
|---|---|
| Structure of impact craters | 12 km, 0.02 mGal |
| Near-surface magmatism | 30 km, 0.01 mGal |
| Mechanisms and timing of deformation | 12 km, 0.005 mGal |
| Cause(s) of crustal magnetization | 12 km. 0.002 mGal |
| Estimation of upper crustal density | 12 km, 0.005 mGal |
| Mass bounds on polar volatiles* | 30 km, 0.002 mGal |

*Assumes a 10-m-thick layer composed of 5% $H_2O$ ice, 95% regolith.*

**Table 6** GRAIL archive summary

| Archive Component | Data Sets |
|---|---|
| LGRS (levels 0, 1A, & 1B) | Raw Ka-band phase, Time Transfer System (TTS) range data, and payload housekeeping information |
| DSN Tracking Data | DSN Doppler data at S-band<br>DSN tracking data message files at X-band<br>DSN Doppler data at X-band (optional) |
| Ancillary | High-rate engineering data<br>Engineering data<br>Spacecraft properties<br>Spacecraft and planetary ephemeris<br>DSN media calibration and Earth orientation parameters files<br>Mission history log files<br>Uplink products<br>Data quality report files (levels 1A & 1B) |
| Software | None needed (files in ASCII format) |
| Documentation | GRAIL Gravity Theoretical Description and Data Processing Handbook, Software Interface Specifications (SIS), and calibration reports |

**Table 7** GRAIL PDS data sets

| Data Set (Volume ID)<br>PDS-Assigned Data Set ID | Description | Data Volume (GB) | NASA Processing Level |
|---|---|---|---|
| **LGRS EDR (GRAIL_0001)**<br>GRAIL-L-LGRS-2-EDR-V1.0 | Raw science data in time order with duplicates and transmission errors removed | 0.13 | 0 |
| **LGRS CDR (GRAIL_0101)**<br>GRAIL-L-LGRS-3-CDR-V1.0 | Calibrated & resampled data | 20 | 1A & 1B |
| **RSS EDR (GRAIL_0201)**<br>GRAIL-L-RSS-2-EDR-V1.0 | Raw Radio Science data (includes DSN Doppler tracking data, troposphere and ionosphere media calibrations) | 137 | 0 |
| **LGRS SPICE (GRAIL_0301)**<br>GRAIL-L-SPICE-6-ADR-V1.0 | SPICE geometry and navigation kernels (to be defined with help from NAIF) | 6.7 | N/A |
| **LGRS RDR (GRAIL_1001)**<br>GRAIL-L-LGRS-5-RDR-GRAVITY-V1.0 | Lunar gravitational field (includes gravity coefficient and covariance matrices, free-air gravity map, geoid and uncertainty maps, and Bouguer gravity map) | 45 | 2 |

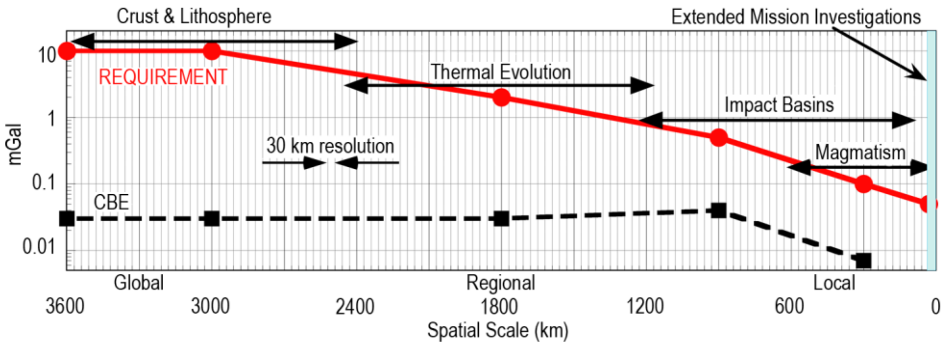
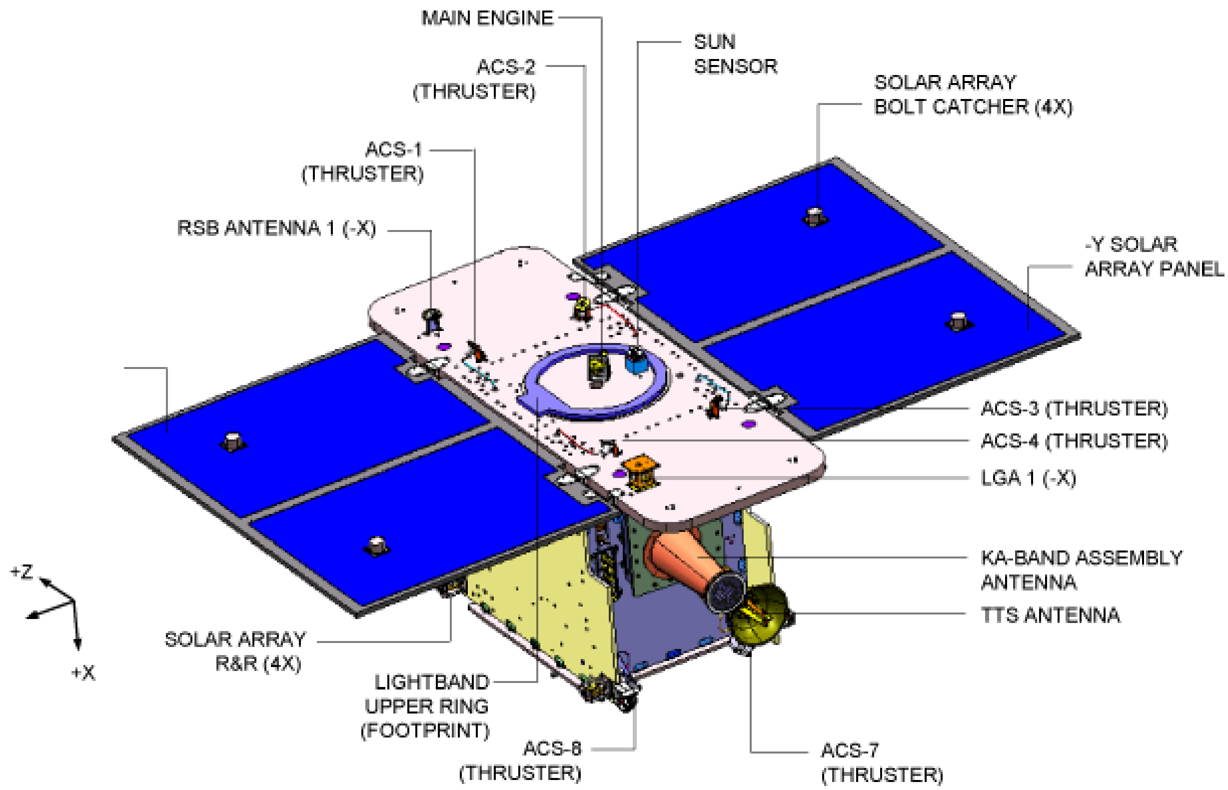

Crust & Lithosphere
Extended Mission Investigations
REQUIREMENT
Thermal Evolution
Impact Basins
30 km resolution
Magmatism
CBE
mGal
10
1
0.1
0.01
Global
Regional
Local
3600
3000
2400
1800
1200
600
0
Spatial Scale (km)

Fig. 1


MAIN ENGINE
SUN SENSOR
ACS-2 (THRUSTER)
SOLAR ARRAY BOLT CATCHER (4X)
ACS-1 (THRUSTER)
RSB ANTENNA 1 (-X)
-Y SOLAR ARRAY PANEL
ACS-3 (THRUSTER)
ACS-4 (THRUSTER)
LGA 1 (-X)
KA-BAND ASSEMBLY ANTENNA
TTS ANTENNA
+Z
+X
SOLAR ARRAY R&R (4X)
LIGHTBAND UPPER RING (FOOTPRINT)
ACS-8 (THRUSTER)
ACS-7 (THRUSTER)

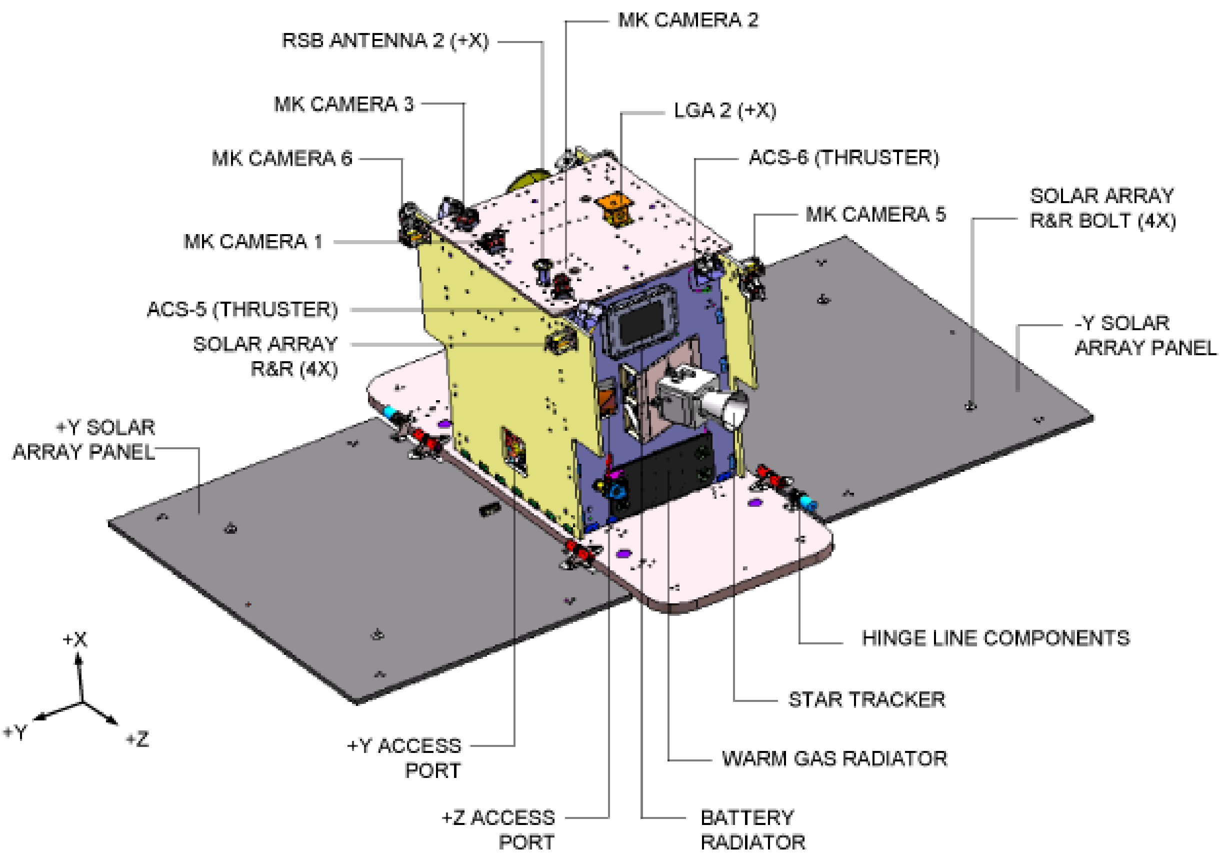

RSB ANTENNA 2 (+X)
MK CAMERA 2
MK CAMERA 3
LGA 2 (+X)
MK CAMERA 6
ACS-6 (THRUSTER)
MK CAMERA 5
SOLAR ARRAY
R&R BOLT (4X)
MK CAMERA 1
ACS-5 (THRUSTER)
SOLAR ARRAY
R&R (4X)
-Y SOLAR
ARRAY PANEL
+Y SOLAR
ARRAY PANEL
+X
+Y
+Z
HINGE LINE COMPONENTS
STAR TRACKER
+Y ACCESS
PORT
WARM GAS RADIATOR
+Z ACCESS
PORT
BATTERY
RADIATOR

Fig. 2ab

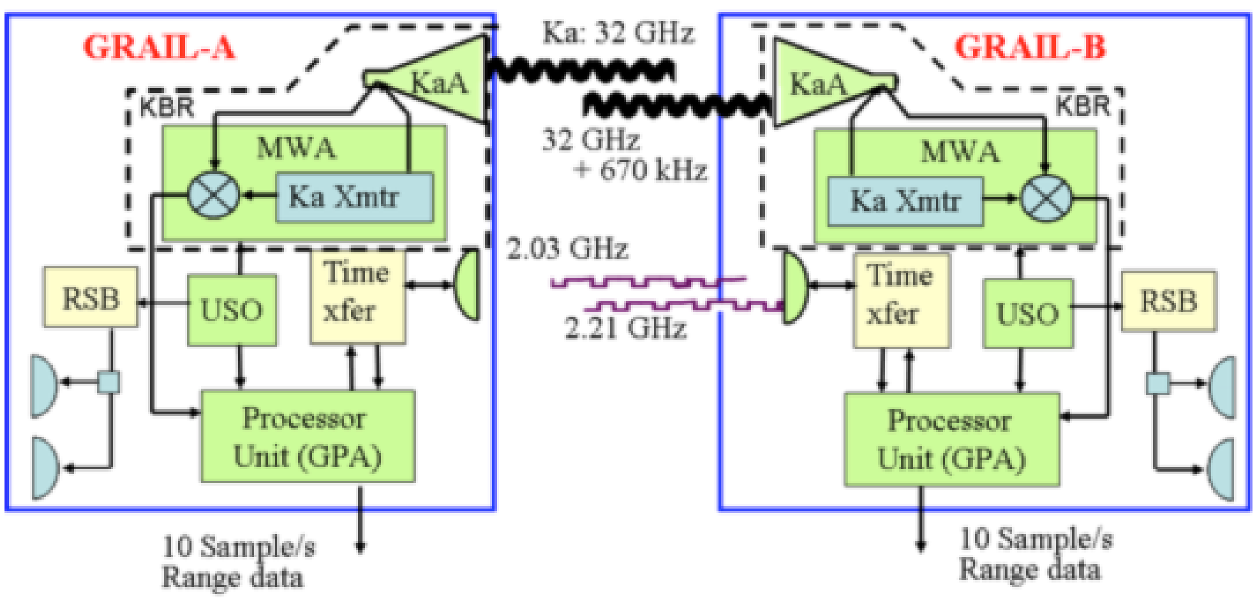
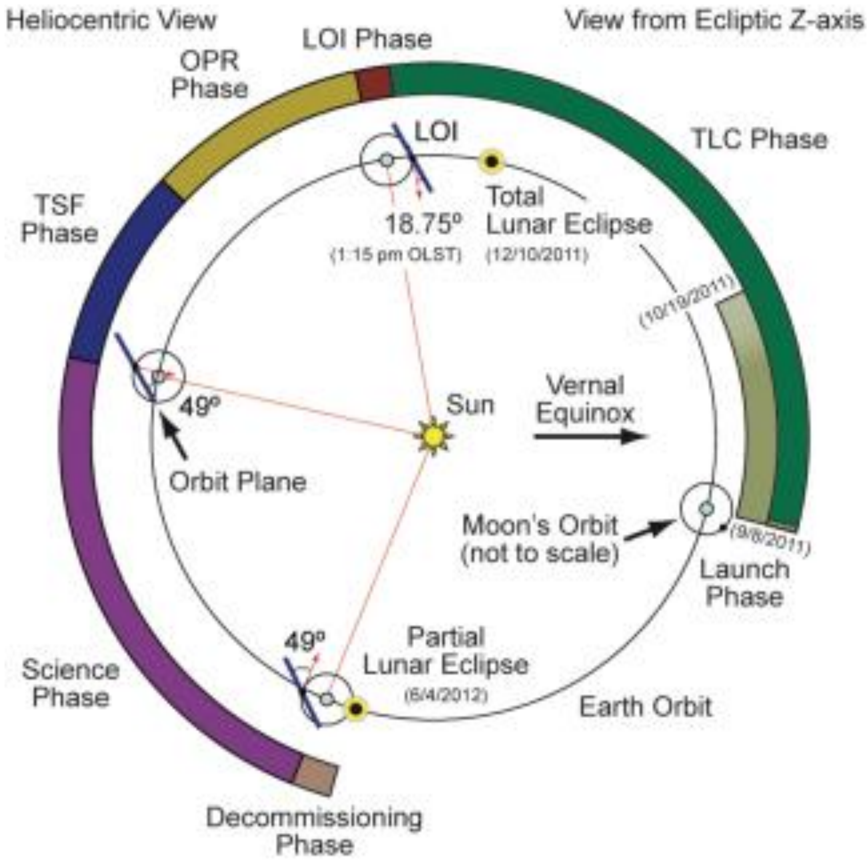
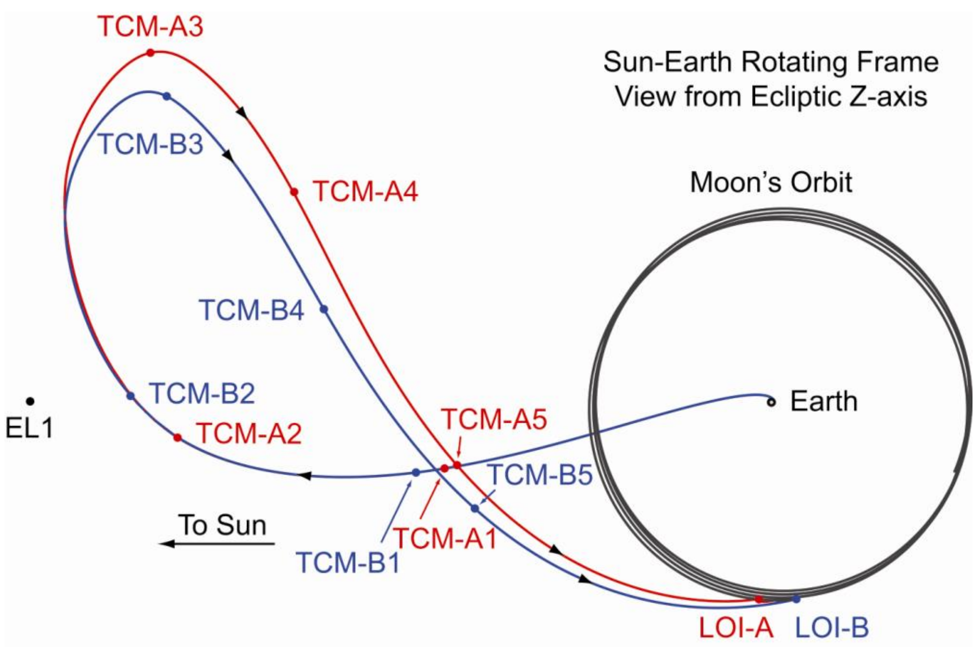

GRAIL-A
Ka: 32 GHz
GRAIL-B
KaA
KaA
KBR
KBR
MWA
MWA
32 GHz
+ 670 kHz
Ka Xmtr
Ka Xmtr
2.03 GHz
Time
xfer
Time
xfer
RSB
USO
USO
RSB
2.21 GHz
Processor
Unit (GPA)
Processor
Unit (GPA)
10 Sample/s
Range data
10 Sample/s
Range data

Fig. 3



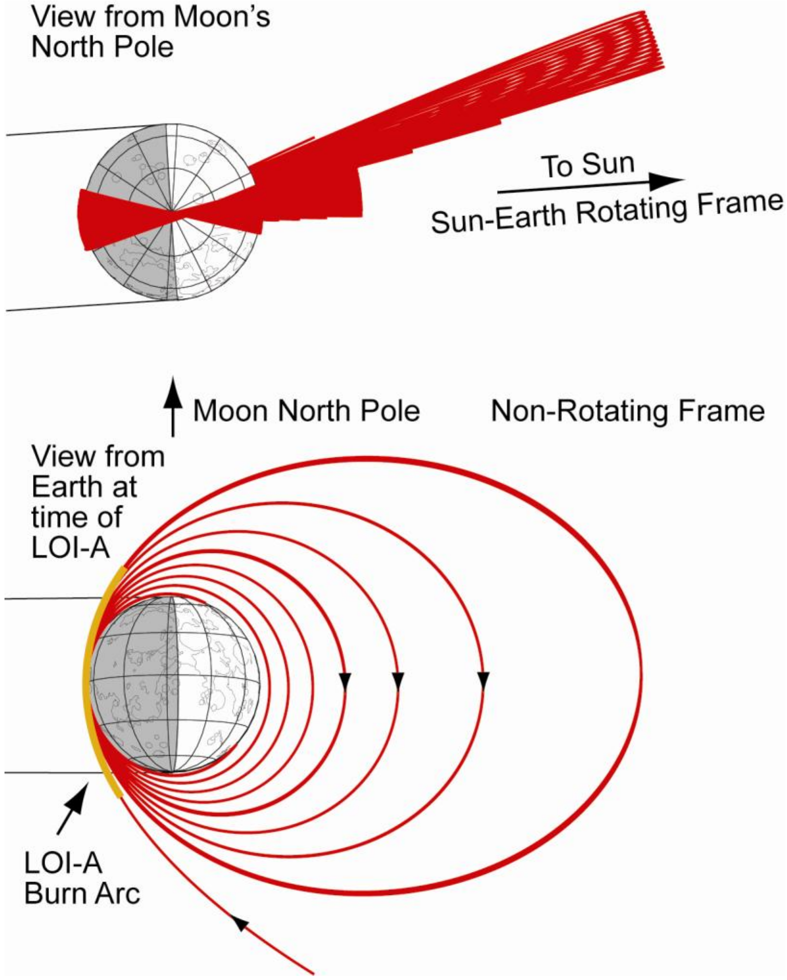
Heliocentric View
View from Ecliptic Z-axis
LOI Phase
OPR Phase
TLC Phase
LOI
TSF Phase
Total Lunar Eclipse
(12/10/2011)
18.75º
(1:15 pm OLST)
(10/19/2011)
49º
Sun
Vernal Equinox
Orbit Plane
Moon's Orbit (not to scale)
(9/8/2011)
Launch Phase
49º
Partial Lunar Eclipse
(6/4/2012)
Science Phase
Earth Orbit
Decommissioning Phase


Fig. 4



TCM-A3
Sun-Earth Rotating Frame
View from Ecliptic Z-axis
TCM-B3
TCM-A4
Moon's Orbit
TCM-B4
TCM-B2
Earth
EL1
TCM-A2
TCM-A5
TCM-B5
To Sun
TCM-A1
TCM-B1
LOI-A
LOI-B


Fig. 5



View from Moon's North Pole
To Sun
Sun-Earth Rotating Frame
Moon North Pole
Non-Rotating Frame
View from Earth at time of LOI-A
LOI-A Burn Arc


Fig. 6

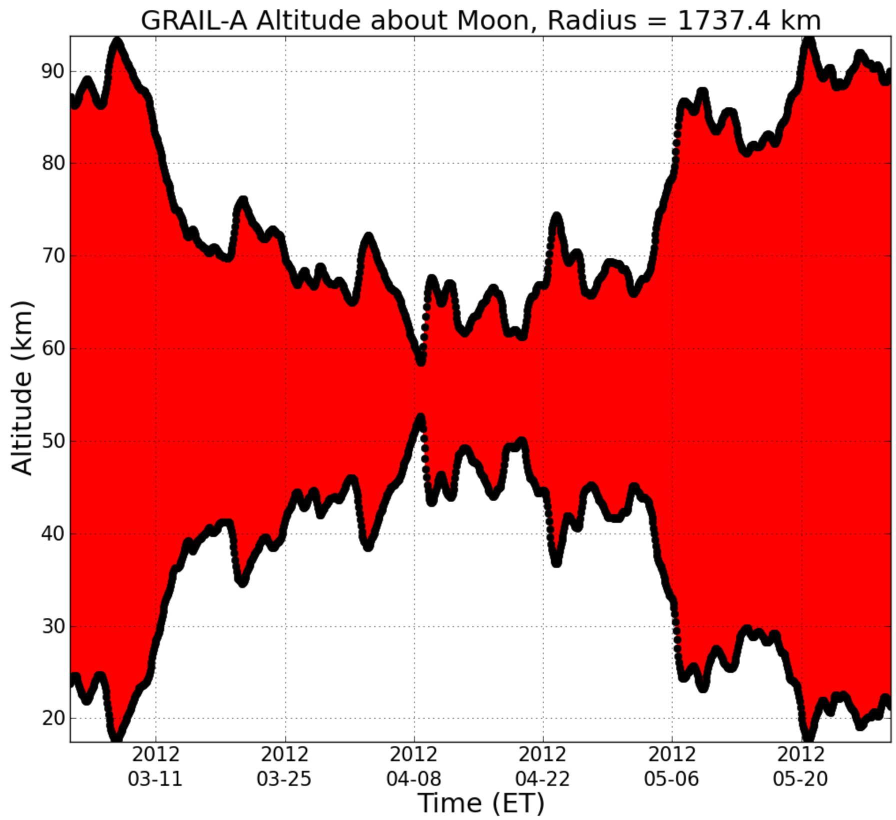

GRAIL-A Altitude about Moon, Radius = 1737.4 km
Altitude (km)
90
80
70
60
50
40
30
20
2012
03-11
2012
03-25
2012
04-08
2012
04-22
2012
05-06
2012
05-20
Time (ET)

Fig.7

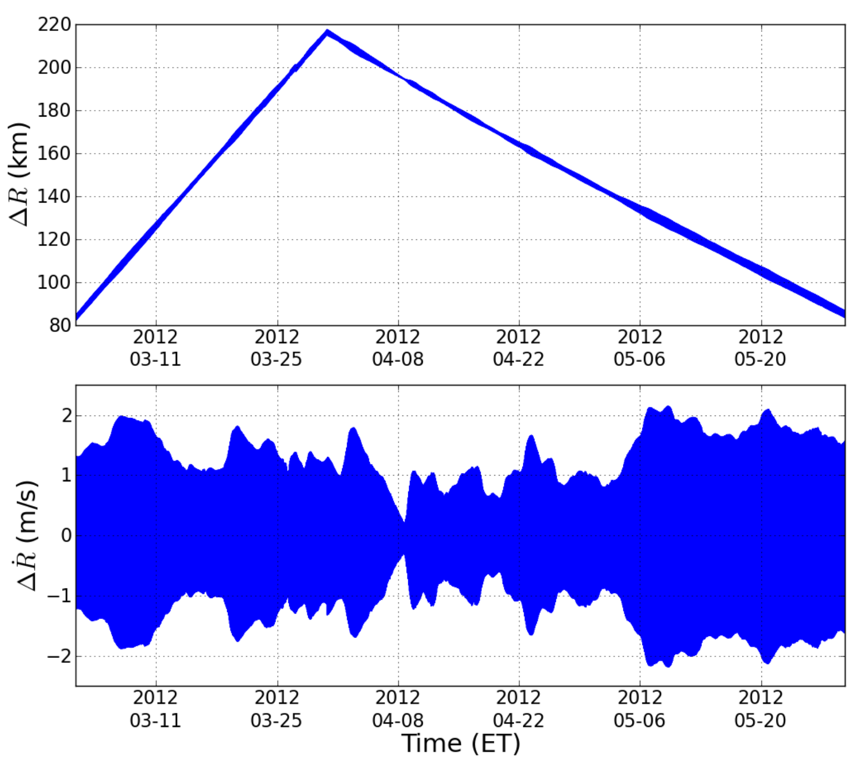
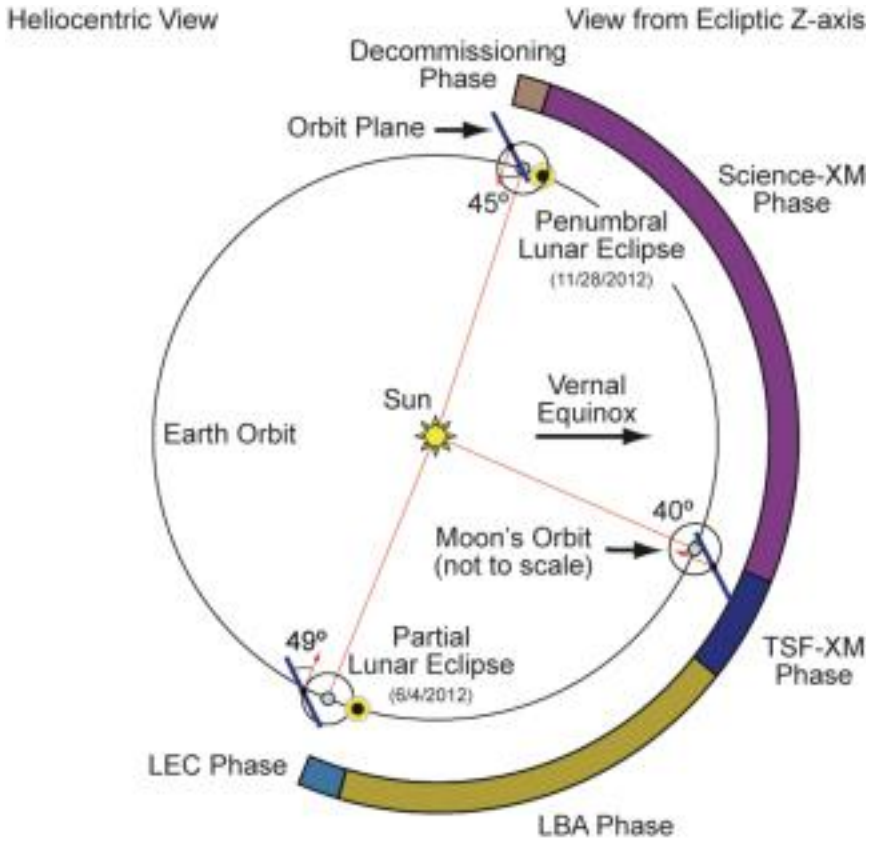
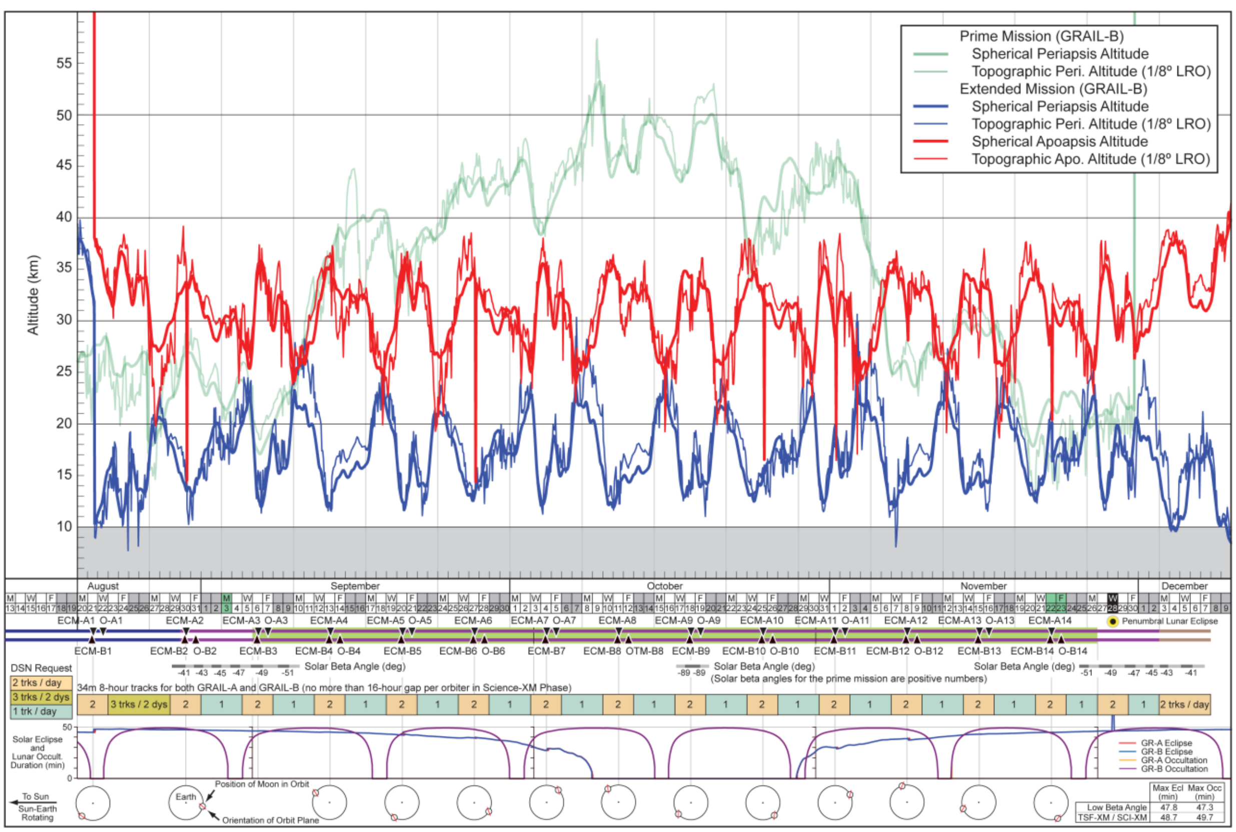

$\Delta R$ (km)
220
200
180
160
140
120
100
80
$\Delta \dot{R}$ (m/s)
2
1
0
−1
−2
2012
03-11
2012
03-25
2012
04-08
2012
04-22
2012
05-06
2012
05-20
Time (ET)

Fig. 8



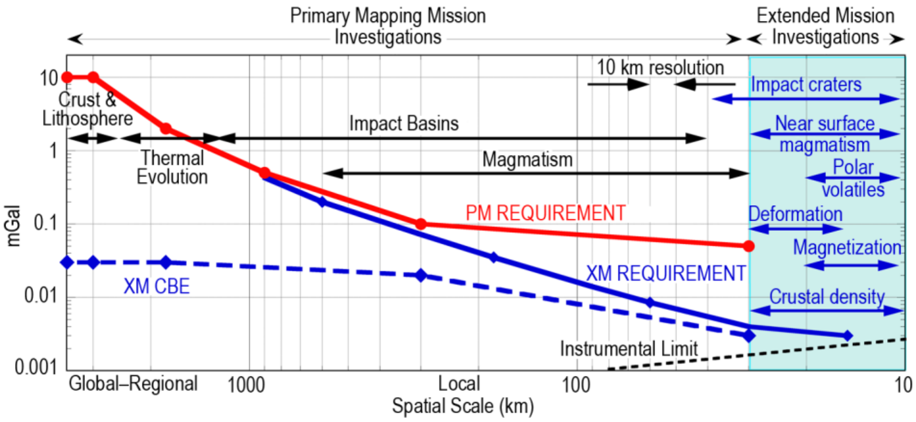
Heliocentric View
View from Ecliptic Z-axis
Decommissioning Phase
Orbit Plane
Science-XM Phase
45º
Penumbral Lunar Eclipse
(11/28/2012)
Sun
Vernal Equinox
Earth Orbit
40º
Moon's Orbit (not to scale)
49º
Partial Lunar Eclipse
(6/4/2012)
TSF-XM Phase
LEC Phase
LBA Phase


Fig. 9



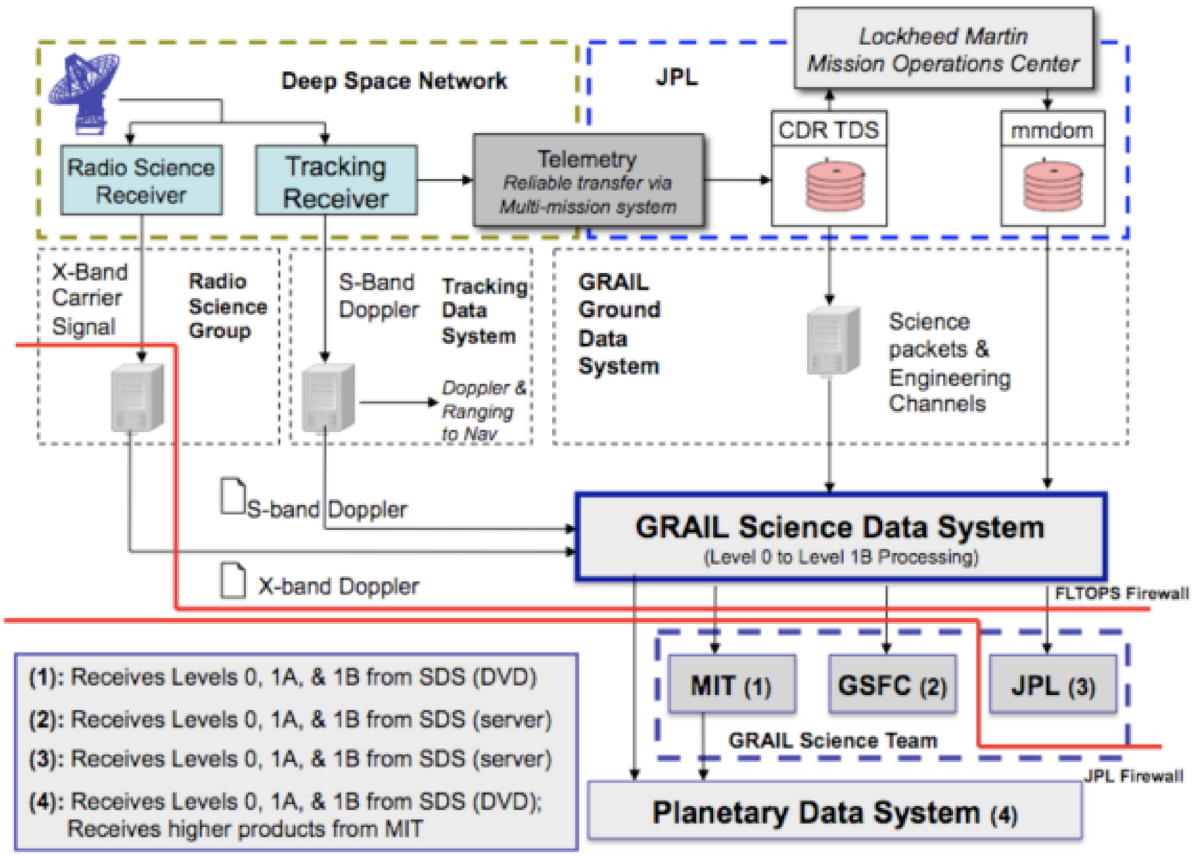
Prime Mission (GRAIL-B)
Spherical Periapsis Altitude
Topographic Peri. Altitude (1/8º LRO)
Extended Mission (GRAIL-B)
Spherical Periapsis Altitude
Topographic Peri. Altitude (1/8º LRO)
Spherical Apoapsis Altitude
Topographic Apo. Altitude (1/8º LRO)
Altitude (km)
August
September
October
November
December
DSN Request
34m 8-hour tracks for both GRAIL-A and GRAIL-B (no more than 16-hour gap per orbiter in Science-XM Phase)
Solar Beta Angle (deg)
Solar Eclipse and Lunar Occult. Duration (min)
Penumbral Lunar Eclipse


Fig. 10



Primary Mapping Mission Investigations
Extended Mission Investigations
10 km resolution
Impact craters
Near surface magmatism
Polar volatiles
Deformation
Magnetization
Crustal density
Crust & Lithosphere
Thermal Evolution
Impact Basins
Magmatism
PM REQUIREMENT
XM REQUIREMENT
XM CBE
Instrumental Limit
mGal
10
1
0.1
0.01
0.001
Global–Regional
1000
Local
100
10
Spatial Scale (km)


Fig. 11



Deep Space Network
JPL
Lockheed Martin Mission Operations Center
CDR TDS
mmdom
Radio Science Receiver
Tracking Receiver
Telemetry
Reliable transfer via Multi-mission system
X-Band Carrier Signal
Radio Science Group
S-Band Doppler
Tracking Data System
Doppler & Ranging to Nav
GRAIL Ground Data System
Science packets & Engineering Channels
S-band Doppler
X-band Doppler
GRAIL Science Data System
(Level 0 to Level 1B Processing)
FLTOPS Firewall
MIT (1)
GSFC (2)
JPL (3)
GRAIL Science Team
JPL Firewall
Planetary Data System (4)
(1): Receives Levels 0, 1A, & 1B from SDS (DVD)
(2): Receives Levels 0, 1A, & 1B from SDS (server)
(3): Receives Levels 0, 1A, & 1B from SDS (server)
(4): Receives Levels 0, 1A, & 1B from SDS (DVD); Receives higher products from MIT


Fig. 12