The Gravity Recovery and Interior Laboratory Mission

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Abstract—**The Gravity Recovery and Interior Laboratory (GRAIL) mission, launched in September 2011, successfully completed its Primary Science Mission in June 2012 and is currently in Extended Mission operations. Competitively selected under a NASA Announcement of Opportunity in December 2007, GRAIL is a Discovery Program mission subject to a mandatory project cost cap. The purpose of the mission is to precisely map the gravitational field of the Moon to reveal its internal structure from crust to core, determine its thermal evolution, and extend this knowledge to other planets. The mission uses twin spacecraft flying in tandem to provide the gravity map. The GRAIL Flight System, consisting of the spacecraft and payload, was developed based on significant heritage from previous missions such an experimental U.S. Air Force satellite, the Mars Reconnaissance Orbiter (MRO) mission, and the Gravity Recovery and Climate Experiment (GRACE) mission. The Mission Operations System (MOS) was based on high-heritage multimission operations developed by NASA's Jet Propulsion Laboratory and Lockheed Martin. Both the Flight System and MOS were adapted to meet the unique challenges posed by the GRAIL mission design.**

This paper summarizes the implementation challenges and accomplishments of getting GRAIL ready for launch. It also discusses the in-flight challenges and experiences of operating two spacecraft, and mission results.

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1. INTRODUCTION

In December 2007, NASA competitively selected the Gravity Recovery and Interior Laboratory (GRAIL) mission under the Discovery Program for solar system exploration. GRAIL was developed to map the structure of the lunar interior from crust to core. This is accomplished by producing a detailed map of the lunar gravity field that will enable scientists to explore a planetary interior at unprecedented resolution.

The GRAIL Principal Investigator is Dr. Maria T. Zuber from the Massachusetts Institute of Technology (MIT). The GRAIL project is managed by the Jet Propulsion Laboratory (JPL) with Lockheed Martin Space Systems Company (LM) contracted to provide the spacecraft and operations team. The science instrument was developed by JPL. After successful launch on September 10, 2011 (see Figure 1), twin GRAIL orbiters were placed into lunar 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 on March 1, 2012, with an average altitude of 55 km. The Primary Mission was successfully completed in May 2012. In March 2012, NASA decided on the basis of a competitive review to extend the mission operations until December 2012.

Each GRAIL orbiter contains a Lunar Gravity Ranging System (LGRS) instrument that conducts dual one-way ranging measurements to measure precisely the relative motion between them. This measurement, in turn, is used to develop the lunar gravity field map. The instrument is a modified version of a similar instrument used on the Gravity Recovery and Climate Experiment (GRACE), which is currently gravity-mapping the Earth [1]. The twin spacecraft have heritage derived from an experimental U.S. Air Force satellite and the Mars Reconnaissance Orbiter (MRO) mission [2], both developed by LM. Combining the high heritage of these successful missions allowed the GRAIL mission to provide high-value science at a reasonable cost and risk.

Each orbiter carries an education and public outreach (E/PO) payload called MoonKAM (for Moon Knowledge Acquired by Middle-School Students), which is used to provide lunar images for middle school students.

2. SCIENCE OBJECTIVES

The Moon is the most accessible and best studied of the rocky (a.k.a. "terrestrial") planetary 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 make the Moon unique in providing a detailed, global record of the geological history of a terrestrial planetary body.

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Figure 1. GRAIL Launch, September 10, 2011

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, long-standing questions such as the origin of the maria, the reason for the nearside-farside asymmetry in crustal thickness, 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 not only of the Moon itself, but also of other planets in the solar system [3]. For example, while the Moon was once thought to be unique in developing a "magma ocean" shortly after accretion [4], such a phenomenon has now been credibly proposed for Mars as well [5].

This need to understand the 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 to further the understanding of the thermal evolution of the Moon. The GRAIL mission accomplishes these goals by performing 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 using a Ka-band ranging instrument.

GRAIL's primary mission consists of 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 deep interior structure from tides

(6) Place limits on the size of the possible inner core

Table 1 shows the science objectives, science investigations, and requirements for GRAIL's Primary Mission. The table also includes a listing of the full science requirements, the minimum science requirements stipulated by NASA, and the status of achieving these requirements to date.

Table 1. Primary Mission Science Objectives

Science Objectives	Science Investigations	Area (10^6 km^2)	Resolu-tion (km)	Requirement (30-km block)	Full Science Requirements	Minimum Science Requirements
Determine the structure of the lunar interior	1. Crust & Lithosphere	~10	30	± 10 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	2. Thermal Evolution	~4	30	± 2 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	3. Impact Basins	~1	30	± 1 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
	4. Magmatism	~0.1	30	± 0.1 mGal	Completed 5/2012 (due 6/2013)	Completed 5/2012 (due 6/2013)
Advance understanding of the thermal evolution of the Moon	5. Deep Interior	N/A	N/A	k_2 $\pm 6\times10^{-4}$ (3%)	Work in Process (due 6/2013)	N/A
	6. Inner Core Detection	N/A	N/A	k_2 $\pm 2.2\times10^{-4}$ (3%) $c_{21}\pm1\times10^{-10}$	Work in Process (due 6/2013)	N/A

3. Mission Overview

Following launch, the orbiters began a 9-month Primary Mission, summarized in Figure 2 [6]. The GRAIL mission began with the Trans-Lunar Cruise (TLC) Phase, which used an approximately 4-month-long low-energy trajectory via the Sun-Earth Lagrange point (EL-1) to get to the Moon. This unique mission design provides several key features important to the GRAIL mission. First, the low-energy trajectory allowed for an extended launch period of 42 days versus the typical 3–6 days for a direct trajectory. Second, this trajectory allowed for a smaller required delta-V for Lunar Orbit Insertion (LOI), which in turn allowed for a smaller propulsion system. Third, this mission design allowed for a fixed LOI for any date within the 42-day launch period. Finally, the TLC Phase allowed time to perform spacecraft and payload checkout, time for the Ultrastable Oscillator (USO) in the LGRS to stabilize, and time for spacecraft outgassing.

LOI maneuvers for the two spacecraft were separated by one day, with the first occurring December 31, 2011. These maneuvers involved a 39-minute continuous main engine propulsive burn of ~190 m/s to slow the spacecraft sufficiently to enter lunar capture orbit. The LOI burn was conducted to allow for continuous command and telemetry coverage from the NASA Deep Space Network (DSN).

After LOI, the two spacecraft began an approximately two-month-long period in which they underwent orbit circularization and were positioned into formation to prepare for science operations. The first part of this period lasted approximately one month and was called the Orbit Period Reduction (OPR) Phase. The main activity during this phase was to perform a series of Period Reduction Maneuvers (PRMs), designed to place the spacecraft into a 55-km altitude circular orbit with the approximate desired separation (60 to 225 km) and formation required for science. After OPR, the 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.

During the 89-day Science Phase, the GRAIL spacecraft completed three 27.3-day mapping cycles (lunar sidereal period) of the Moon and returned 637 Mbytes of science volume or >99.99% of possible data. This phase ended May 29, 2012. The GRAIL operations team and orbiters performed flawlessly a total of 28 maneuvers during the Primary Mission to reach and maintain the science orbits. In performing the Science Phase, GRAIL provided the first robotic demonstration of precision formation flying around a planetary body other than Earth [7].

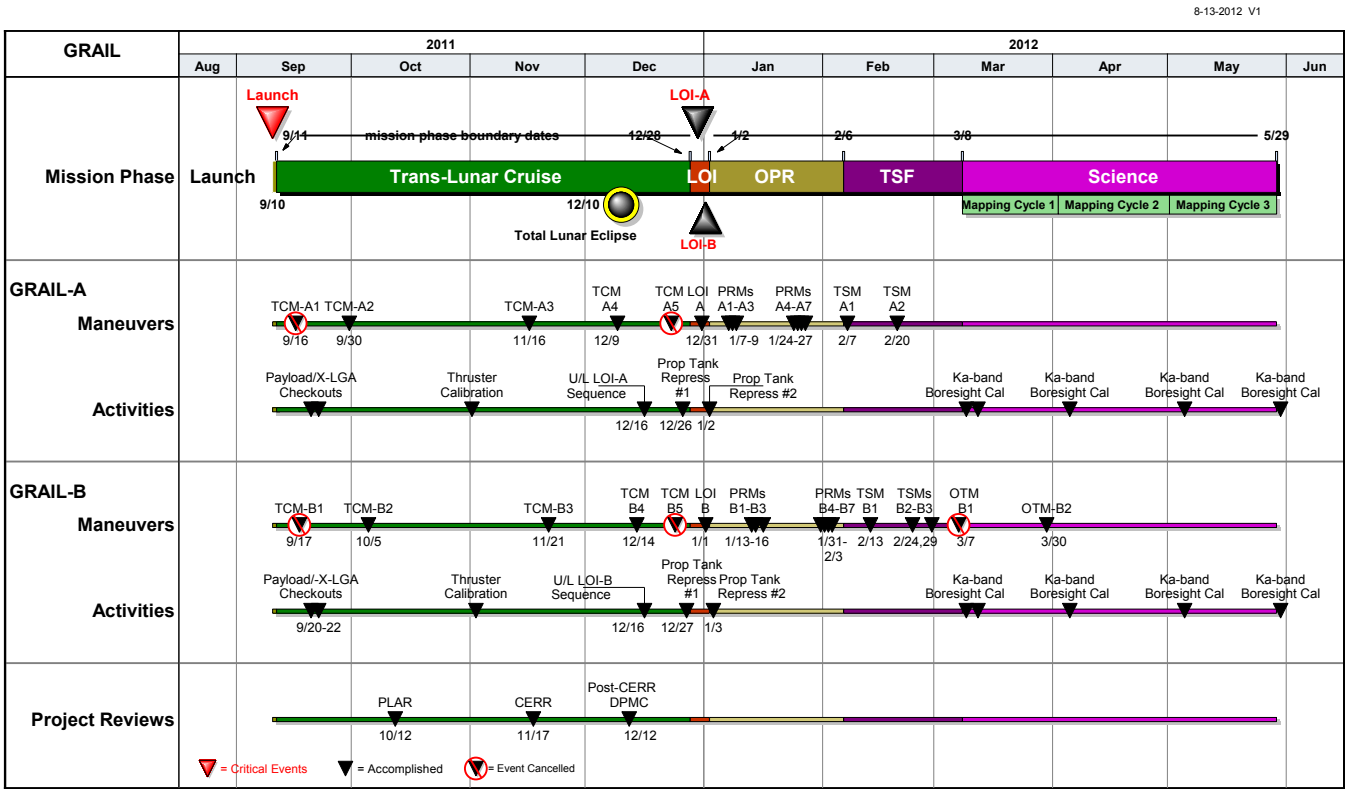

Figure 2. GRAIL's Primary Mission Timeline

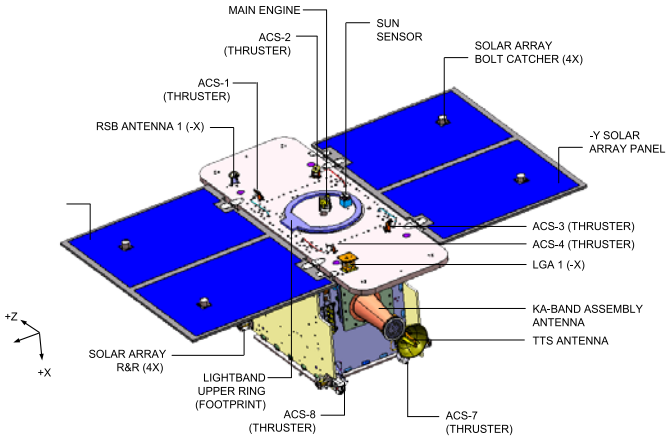

Figure 3. GRAIL Orbiter View 1

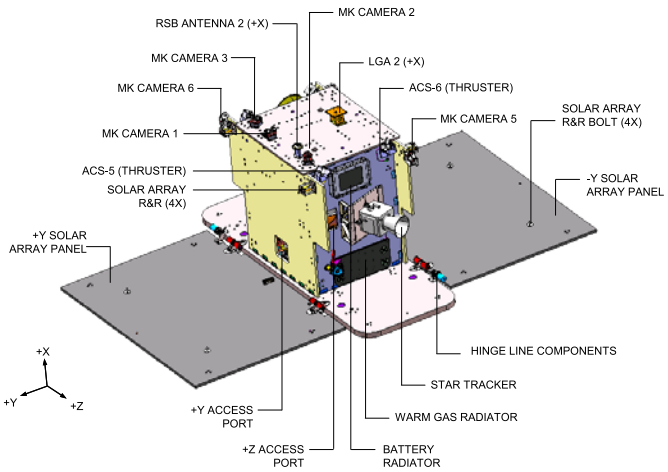

Figure 4. GRAIL Orbiter View 2

4. FLIGHT SYSTEM

The GRAIL project consists of the Flight System [8] (which consists of the twin orbiters), the Launch System, and the Mission Operations System (MOS). Figures 3 and 4 show two views of the orbiters, and Figure 5 shows the Flight System installed in the launch vehicle (LV) payload fairing. GRAIL's Launch System was a Delta II Heavy rocket, provided by United Launch Alliance (ULA) under contract with NASA's Kennedy Space Center (KSC).

The twin orbiters, or spacecraft, are derivatives of the Experimental Small Spacecraft-11 (XSS-11) and MRO designs. (GRAIL implemented a simplification of the MRO flight avionics, "MRO-lite.") The GRAIL spacecraft are twins, but not identical twins; a small number of hardware components are mirror images because they need to point at each other across space. The spacecraft are approximately the size of an apartment-sized washer-dryer set. Each has an avionics module and a propulsion module in addition to deployable solar panels. With very limited exceptions, the spacecraft are single-string (i.e., with no redundancy). Each has preloaded flight software, with capability to receive uploads during flight operations. The structure, propulsion, avionics, and software were built in-house by LM; hardware for remaining subsystems was provided by subcontractors.

The launch mass of each orbiter was 306 kg, including 108 kg of fuel. The orbiters are 3-axis stabilized with reaction wheels and hydrazine 1-N warm-gas thrusters for attitude control, and a star-tracker and an inertial reference unit for attitude determination. A 22-N hydrazine main engine operating in blow-down mode provides thrust for all maneuvers, except for small Orbit Trim Maneuvers that are performed with the attitude-control thrusters.

There are two payloads on each of the GRAIL orbiters, the LGRS science instrument and the E/PO MoonKAM. GRAIL is somewhat unusual in that the science for the mission is achieved with a single instrument. Each of these two payloads is briefly described in the following paragraphs.

The LGRS instrument utilizes a dual-one-way ranging measurement to measure precisely the relative motion between the two orbiters. The fundamental method used for the ranging measurement has a long history of use over

Figure 5. Flight System in LV Payload Fairing

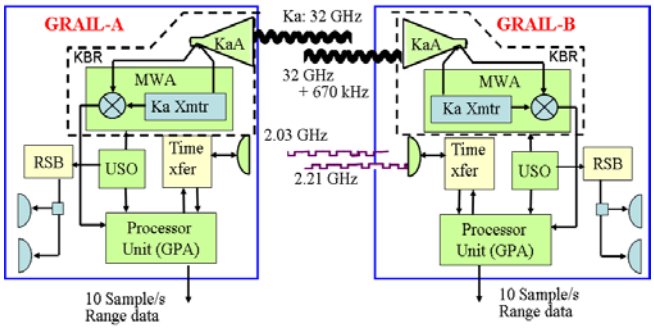

Figure 6. LGRS Block Diagram

dozens of missions as a primary navigation tool. This method was further successfully extended on the GRACE mission [9], which has been successfully mapping the Earth's gravity field since launch in March 2002.

The LGRS consists of a Ka-band antenna for transmitting and receiving intersatellite signals; a microwave assembly (MWA) for generating Ka-band signals for transmission and mixing down the intersatellite signals; a Gravity Recovery Processor Assembly (GPA) for processing both the Ka-band signals and those from the S-band Time Transfer System (TTS) that is used to correlate intersatellite ranges; a USO, which provides timing for both the Ka-band and S-band systems; and a Radio Science Beacon (RSB), which provides an X-band Doppler carrier derived from the USO 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 between the two orbiters. The LGRS block diagram and interactions are shown in Figure 6.

The overall science implementation is achieved through the LGRS instrument measuring the range between the two orbiters. The gravity field of the Moon influences the motion of the center of mass (CM) of each spacecraft, which responds like a proof mass in orbit about the Moon. Surface features, such as craters, internal mass concentrations (mascons), or deep interior structure or convective motions perturb the spacecraft orbits and introduce variations in the relative motion between the spacecraft.

The key measurement is the line-of-sight (LOS) range rate, made with an accuracy of 4.5 micron/s over a 5-s sample interval. These data were collected during the primary mission along with DSN tracking data, providing global coverage of the Moon. The entire set of mapping cycle data is then processed to recover the global gravity map.

The MoonKAM payload is a set of cameras that image the lunar surface. Images are targeted by middle school students, and the cameras are operated by trained and supervised undergraduates. The MoonKAM investigation, conceived by the late Dr. Sally K. Ride, is intended to provide students with an early exposure to the challenges and processes used in spacecraft operations and the thrill of scientific discovery. During the Primary and Extended Mission over 119,000 lunar surface images were acquired, and over 100,000 students in nearly 2000 classrooms participated in the program [10].

The main technical challenge for the orbiter design was to minimize any error sources that can contribute to the overall error in the range measurement between the two orbiters. Some of the key contributors to ranging error are thermal effects of the lunar environment, instrument measurement errors, spacecraft CM movement, and effects of nongravitational forces such as solar pressure and lunar albedo. Fortunately, the GRACE project provided valuable lessons learned for the engineers in the design of the GRAIL subsystems [8] and these lessons learned were a significant contributor to the success of the project.

Getting GRAIL ready for launch was a challenge, but the team worked extremely hard preparing all elements and overcoming implementation challenges. The key challenges faced by the GRAIL team during development and the methods to overcome these challenges are shown in Table 2. Because of this hard work and dedication of the team to the GRAIL mission, the payload was delivered 3 weeks ahead of schedule for integration with the spacecraft in September 2010, and the orbiters were shipped to the launch site 1 week ahead of the original plan in May 2011. The development ended with a successful launch on schedule and under budget [11,12].

Table 2. GRAIL Development Challenges

#	Key Development Challenges	GRAIL Method to Overcome Challenges
1	Late identification and ordering of long-lead payload parts	Established a parts acquisition tiger team consisting of engineers, parts specialist and procurement personnel; the end result was that the parts were delivered when needed and the payload was delivered 3-weeks early.
2	Difficulty in transitioning an advanced research development into flight avionics	This was the #1 issue of the project and the flight avionics was delivered approximately 6 months late and required a major team effort to overcome numerous manufacturing issues. Despite the long delay, it did not result in delaying the launch of GRAIL.
3	Incorrect launch loads uncovered after Project CDR	This required the addition of a load attenuation ride system requiring the expense of ~$1M, but it did not impact schedule margin.
4	Reaction wheel development issues related to a loss of pre-load during qual testing	A tiger team was put in place to update the design and to develop an adequate test program. Despite the delay in delivering the reaction wheels, it had no impact on the overall project schedule.

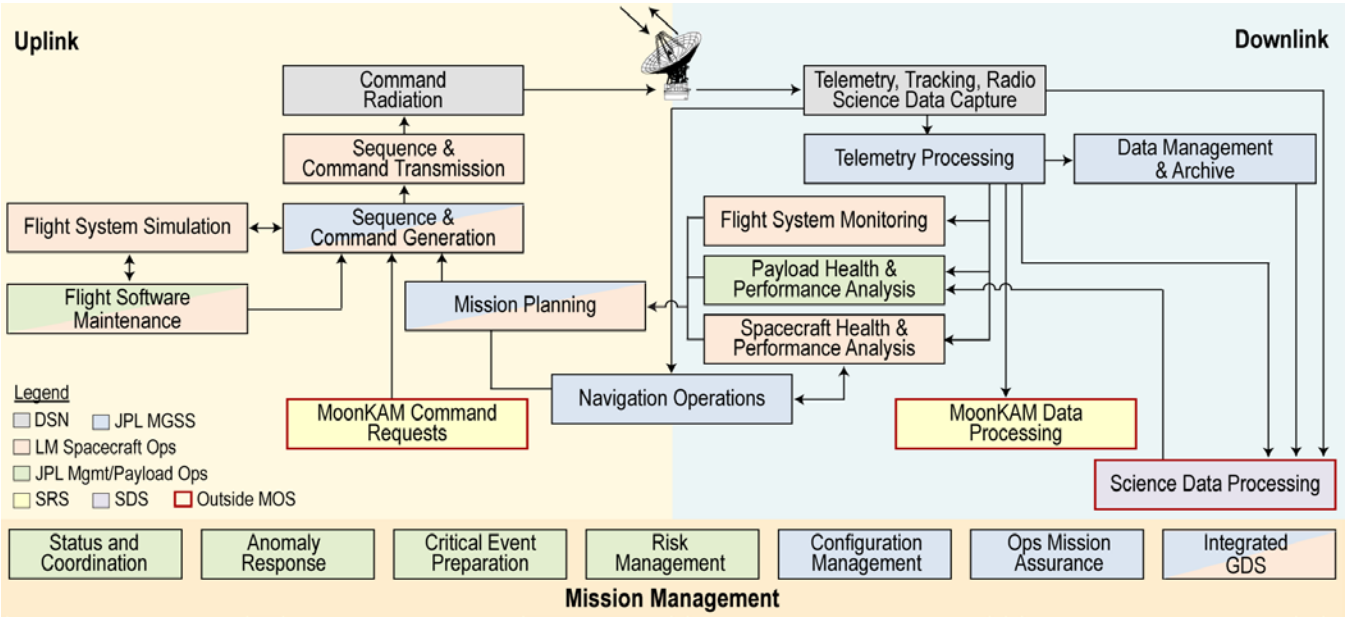

Figure 7. Operational View of the MOS, Showing Key Relationships and Responsible Organizations

5. Mission Operations System

The GRAIL MOS [13] is distributed, and its foundation is the multimission capabilities at JPL and LM, including NASA's DSN. It is supplemented by a Science Data System (SDS), with MIT and JPL elements, and science data is currently being prepared for submission to NASA's Planetary Data System (PDS) for archiving. Sally Ride Science (SRS) uses the MoonKAM operations center at UC San Diego, with trained undergraduate students performing the actual operations under experienced supervision.

The MOS is composed of the people, processes and procedures, ground hardware and software, and facilities required to operate the GRAIL Flight System. The MOS provided support for Flight System integration and testing during Assembly, Test and Launch Operations (ATLO).

The MOS is distributed between JPL and LM. JPL is responsible for overall mission management and provides many of the operations teams needed to conduct operations. LM provides the primary Mission Control Center, and is responsible for spacecraft and real-time operations of the two orbiters, as well as two high-fidelity flight system simulators. The SDS operates from JPL, performing Level-1 data processing and Level-0 and Level-1 data archiving in the PDS, in cooperation with the GRAIL Science Team. MoonKAM operations, led by SRS, located in San Diego, CA, is responsible for day-to-day MoonKAM E/PO operations, interfacing directly with the MOS payload operations team. The color-coding in Figure 7 indicates which operational functions each organization contributes. An operations function is defined as a group of related activities that when combined with other operations functions supports the overall accomplishment of mission operations.

GRAIL's MOS can also be broken down into eight functional elements. Each functional element is composed of the people, processes, procedures, hardware, software, and facilities required to perform specific mission operations functions. These eight functional elements, shown in Figure 8, are also the basis for the GRAIL MOS development and flight team organization. The flight team is the collection of all eight operations teams based on the functional elements. Most of the operations teams for GRAIL are located at JPL, with many of the functions provided by JPL's Multimission Ground Systems and Services (MGSS). LM provides the GRAIL Spacecraft Team.

MOS development for GRAIL occurred nominally over the project life cycle through system concept development, system design, and finally system implementation. An overview of this process is shown in Figure 9.

During system concept development (Phase B), GRAIL's Mission Operations System Design Team (MOSDT) was formed and began formulating operations scenarios to support the baseline mission design. Operations scenarios respond to driving Level-2 project requirements and become the source for deriving additional Level-3 and Level-4 MOS requirements.

During system design (Phase C), each of the operations scenarios was defined in greater detail. All activities were allocated to one of the eight operations teams, and Operations Interface Agreements (OIAs) were established to document the interfaces among the teams.

With the design baselined, final system implementation (Phase D) could begin. As with many missions, system implementation actually began in parallel with the final design process. GRAIL's Ground Data System (GDS) was developed via phased software releases, where early releases included accepted heritage capabilities, as well as

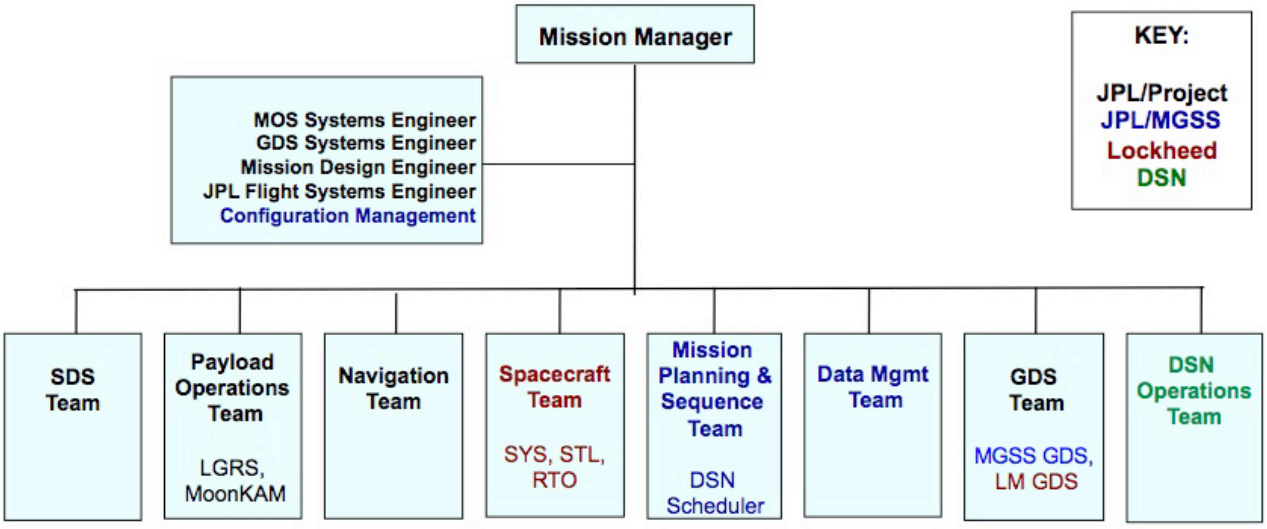

Figure 8. The eight MOS functional elements were the basis of the flight team organization.

the preliminary adaptations required for Flight System testing. MOS verification and validation (V&V) and MOS team training were key efforts during the implementation phase, to demonstrate that the MOS processes with ground software would perform as designed to meet mission objectives, and that the operations team would be ready to operate the GRAIL orbiters and meet all mission timelines.

Much of GRAIL's success following launch can be traced back to the original mission architecture, incorporating proven heritage via the LM spacecraft, the GRACE-derived payload, and multimission operations processes and ground system. Supporting a single science instrument with a straightforward data collection strategy obviated the need for complex science planning strategies and science center interfaces. The GRAIL mission did, however, have its own unique operational challenges, as discussed below.

Dual-Orbiter Operations: Throughout the mission, both orbiters have needed to be operated in parallel. Almost all events on the mission timeline have had to be executed on both orbiters. In many aspects of the design this has doubled the resources required. Each orbiter has required distinct ground system infrastructure to manage commanding and data return, as well as separately scheduled DSN tracking. During day-to-day operations, the flight team has had to manage the health and safety of two orbiters. It is also important to keep data from each orbiter separate to avoid any confusion in operations. But at the same time, it is equally important that the flight team is aware of status of

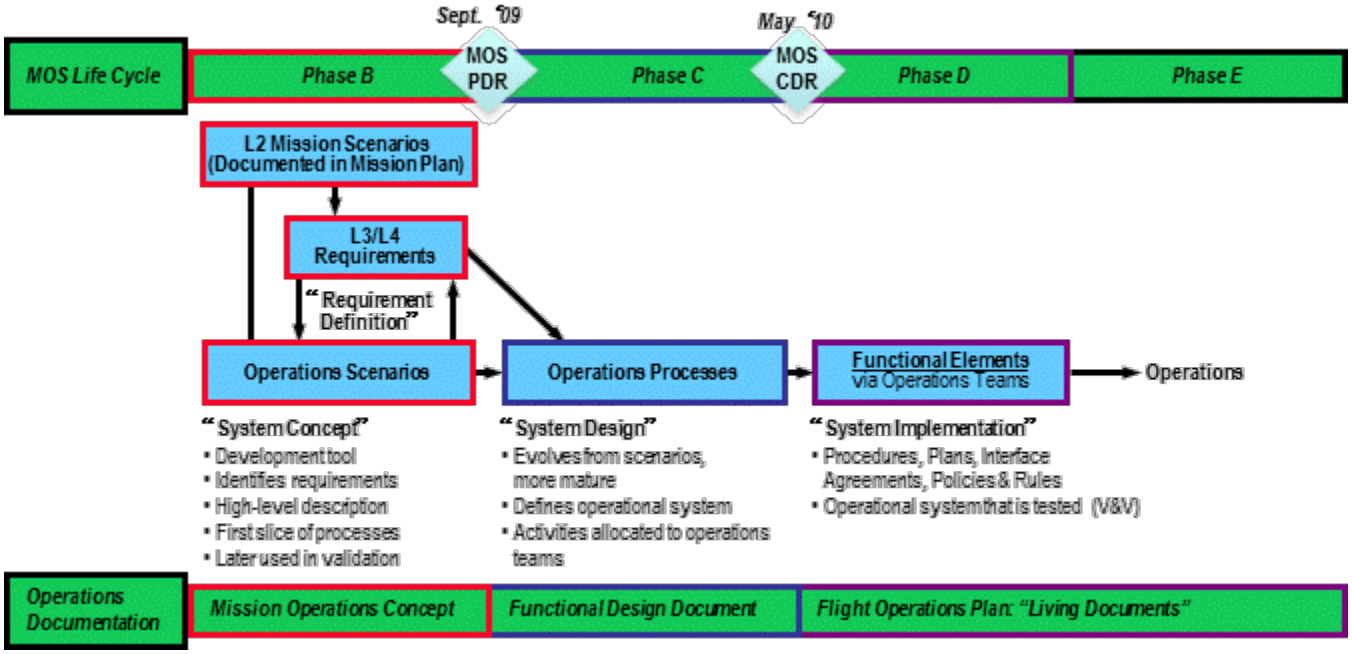

Figure 9. GRAIL MOS Development Process

both orbiters since the status of one orbiter may impact the other.

One strategy to help manage dual-orbiter operations has been to deconflict GRAIL-A and GRAIL-B mission activities in the timeline, conducting them on separate days. When establishing the staffing for the flight team, a hybrid approach was adopted where certain members of the flight team focus on a single orbiter's operations, while other team members provide crosscutting support on a daily basis to both orbiters. Twice-weekly status meetings for both orbiters are conducted jointly, so that the entire flight team is aware of the status of both orbiters. From a GDS point of view, unique spacecraft identifiers, as well as unique file-naming conventions and file repositories, kept orbiter command and telemetry products separate to avoid confusion by the flight team.

Compact Mission Timeline: The Primary Mission for GRAIL was very short compared to most missions, only 9 months from launch to completion (prior to the Extended Mission addition). After launch, operations progressed briskly through the next six unique mission phases, representing distinct operational scenarios for the flight team. The flight team had to be prepared for operations beginning both at the opening and the closing of a 42-day launch period. Since LOI was fixed, this meant early cruise operations would have been progressively compressed for launch dates later in the period. Early operations, including Trajectory Correction Maneuver-1 (TCM-1) and TCM-2 for each orbiter, were launch-relative, with the remaining maneuvers LOI-relative. Once injected into lunar orbit, the pace of operations increased further. The OPR phase included 14 maneuvers over 4 weeks; and the TSF phase, the most intensive mission phase, included five maneuvers to place the orbiters into science formation and calibrate the science payload. The Science Phase, by design, represented the least hectic of all mission phases, where operations must be as quiescent as possible to support gravity measurements.

Table 3. GRAIL Operations Challenges

#	Key Operations Challenges	GRAIL Impact and Resolution
1	Operating during high solar activity revealed vulnerability of E/PO MoonKAM	MoonKAM power supplies latched up at higher currents and had to be power cycled. In one instance, specific conditions produced a dangerous oscillation that damaged spacecraft switches when powering off the unit. As a result, MoonKAM operations were largely suspended during the extended mission.
2	Telecommunications multipath resulted as uplink and downlink signals reflect off the Moon's surface	During certain orbit geometries, multipath resulted in lost data and uplink errors. With lower altitudes, the frequency of multipath increased. The operations teams developed strategies to recover from multipath outages, including retransmission of lost data and resending failed commands.
3	Errors in orbit determination solutions were increasingly driven by the fidelity of gravitational models of the Moon during low altitude science orbit.	Use of models from previous missions resulted in higher uncertainty in orbit solutions. Utilization of GRAIL gravity models provided by the science team allowed the navigation team to continuously improve solutions as the mission progressed. High-order Primary Mission gravity models allowed the even lower-altitude Extended Mission to proceed much more smoothly as a result.

Detailed definition of operations timelines via mission-phase-scenario development was an essential step of the development process to meet this challenge. These timelines included step-by-step schedules for each uplink product required for both orbiters. Prior to the Critical Design Review (CDR), an MOS Staffing Peer Review was conducted to evaluate workforce, and to consider augmentations for each operations team based on these timelines. As a result, previously proposed liens to increase staffing were approved. Finally, rigorous V&V testing proved that the flight team could meet the operations timelines for each phase of the mission.

Maneuver-Intensive: Since each orbiter has been flown separately since deployment, each required several maneuvers to establish and maintain the cruise trajectory before the critical LOI maneuver established the initial lunar orbit. Once the spacecraft were in orbit, the team executed the finely choreographed sequence of PRMs to lower the orbit period, and Transition to Science Maneuvers (TSMs) to place the orbiters in formation for science. In all, the flight team had to be prepared to execute up to 33 maneuvers to complete the mission. Most of these maneuvers were planned over a defined 5-day timeline, but at the end of TSF phase, this tightened to 3 days. Executing these maneuvers correctly was imperative to starting science data collection on time so that three full gravity-mapping cycles could be completed during the Primary Mission.

The key operations challenges faced by the GRAIL team are shown in Table 3, along with the impact and resolution of each challenge.

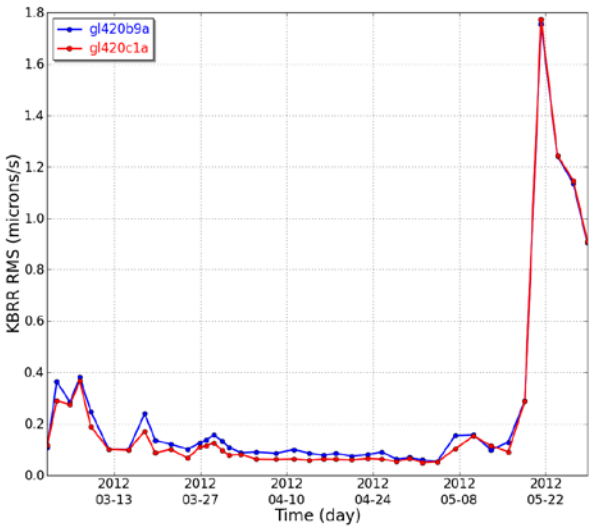

Figure 10. GRAIL KBR RMS Fits

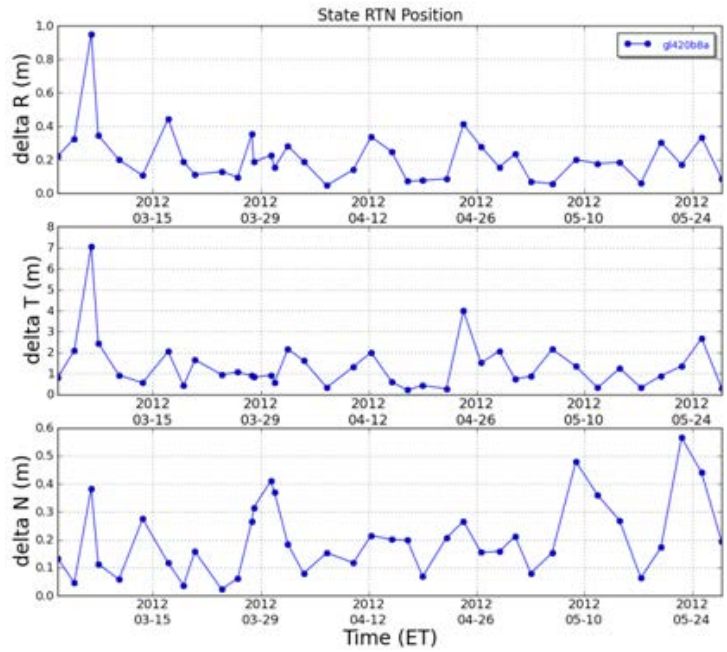

Figure 11. GRAIL Trajectory Overlap RMS

6. Mission Results

During the Primary Mission GRAIL returned high-quality satellite-to-satellite tracking data. Figure 10 shows the GRAIL Ka-band ranging (KBR) RMS fits from the mission; the data fit at the submicron/s level, much better than the requirement of 4.5 micron/s (see Section 3). Another measure of data quality is the ability to fit spacecraft orbits. Figure 11 shows the GRAIL trajectory overlap RMS, which shows fits in the radial direction at about the 40-cm level, and along-track and cross-track level at several meters. All are considerable improvements over previous missions.

The GRAIL primary mission data have been used to develop the most accurate global gravity model of the Moon to date. The current gravity field is to degree and order 420 and corresponds to ~13-km block-size surface resolution. Out of six total science requirements (see Table 1), Investigations 1 to 4 have been satisfied (i.e., high-resolution lunar gravity map). The science team is currently working on Investigations 5 and 6, i.e., deep interior (lunar tides) and detection of the inner core. These investigations are scheduled to be completed by June 2013.

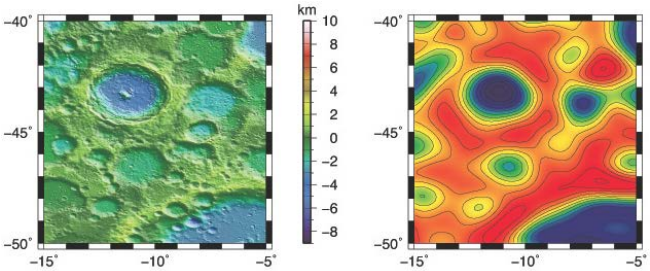

Figure 12. Tycho is shown in LOLA topography (left) and GRAIL gravity (right).

GRAIL is revealing gravity details that correlate with the lunar topography obtained from measurements by the Lunar Orbiter Laser Altimeter (LOLA) on the Lunar Reconnaissance Orbiter (LRO) mission. Figure 12 compares the LOLA topography with GRAIL gravity data in the region of Tycho, a prominent 86-km-diameter complex crater on the Moon's nearside. Tycho is in the upper left of each figure. In the gravity map, reds correspond to mass excesses and blues to mass deficits. GRAIL resolves not only the Tycho structure but also nearby simple craters.

7. Extended Mission

On the basis of competitive review, NASA approved a 6-month extended mission for GRAIL that ends in December 2012. This extended mission will enable collection of higher-resolution gravity data by flying at an even lower altitude [6]. The timeline for the Extended Mission is shown in Figure 13. GRAIL's Extended Mission will deliver geophysics at the scale of surface geology by flying in formation at an average altitude of 23 km over the surface of the Moon. The objective of the Extended Mission is to determine the structure of lunar highland crust and maria, addressing impact, magmatic, tectonic, and volatile processes that have shaped the near surface. A summary of GRAIL's Extended Mission science investigations and measurement requirements is given in Table 4.

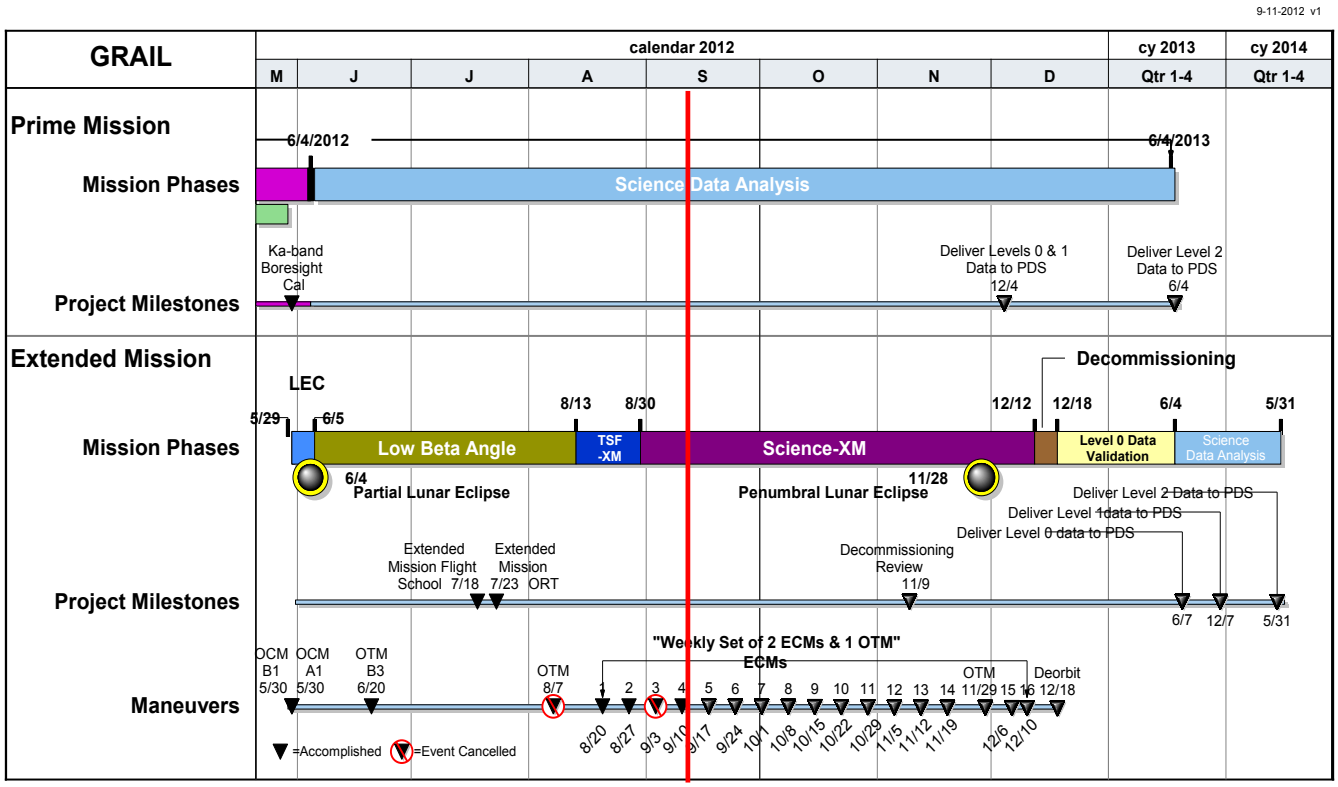

Figure 13. GRAIL's Extended Mission Timeline

Table 4. Extended Mission Science Objectives

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
Elimination of upper crustal density	12 km, 0.005 mGal
Mass bounds on polar volatiles (assumes a 10-m-thick layer composed of 5% H_2O ice, 95% regolith)	30 km, 0.002 mGal

8. Summary

GRAIL successfully completed its Primary Mission on schedule and under budget. The mission achieved NASA's minimum mission success criteria for the primary mission in May 2012, one year ahead of schedule (Investigations 1–4). GRAIL was successful in collecting its required data with a total science data volume at the end of Primary Mission of 637 Mbytes or >99.99% of possible data. Following the Primary Mission, the two GRAIL spacecraft successfully transited the partial lunar eclipse of June 4, 2012, and the mission team is currently in the Extended Mission Science Phase, operating at very low altitude (23 km).

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DEDICATION AND ACKNOWLEDGMENT

This paper is dedicated to the memory of the late Dr. Sally K. Ride. She devoted her post-NASA career to encouraging middle school students, especially girls, to pursue classes and careers in science, technology, engineering and mathematics. GRAIL's MoonKAM program was conceived by Sally and implemented by SRS.

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