Designing Mission Operations for the Gravity Recovery and Interior Laboratory Mission

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NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission, to understand the internal structure and thermal evolution of the Moon, offered unique challenges to mission operations. From launch through end of mission, the twin GRAIL orbiters had to be operated in parallel. The journey to the Moon and into the low science orbit involved numerous maneuvers, planned on tight timelines, to ultimately place the orbiters into the required formation-flying configuration necessary. The baseline GRAIL mission is short, only 9 months in duration, but progressed quickly through seven very unique mission phases. Compressed into this short mission timeline, operations activities and maneuvers for both orbiters had to be planned and coordinated carefully. To prepare for these challenges, development of the GRAIL Mission Operations System began in 2008. Based on high heritage multi-mission operations developed by NASA's Jet Propulsion Laboratory and Lockheed Martin, the GRAIL mission operations system was adapted to meet the unique challenges posed by the GRAIL mission design. This paper describes GRAIL's system engineering development process for defining GRAIL's operations scenarios and generating requirements, tracing the evolution from operations concept through final design, implementation, and validation.

I. Introduction

THE Gravity Recovery and Interior Laboratory (GRAIL) mission [1] has successfully placed two orbiters in a low altitude polar orbit around the Moon, flying in formation to study its internal structure.[2] The primary science objectives for this mission are to understand the internal structures and thermal evolution of the Moon, and extend this knowledge to other terrestrial planets within the solar system. GRAIL's science objectives are accomplished by precisely measuring the relative velocity between the two orbiters, as well as measuring of the absolute position of the orbiters about the Moon as determined from Earth via tracking by NASA's Deep Space Network (DSN). By combining this information together, the GRAIL science team determines the distribution of mass within the Moon very accurately, producing a lunar gravity field map to unprecedented accuracy.

In order to meet the science objectives of the GRAIL mission, the development of GRAIL's mission operations system began in early 2008 in parallel with the overall project development. Although MOS development began in parallel, with management and key systems engineers in place, the bulk of the MOS development workforce ramped more slowly than rest of the project. MOS preliminary design review (PDR) trailed the project PDR by 11 months, and the MOS critical design review (CDR) occurred 6 months after the project CDR in the original schedule. This strategy was used to limit costs, taking advantage of high ground system heritage, and adapting existing designs from previous missions. MOS development began with mission scenario definition to define detailed operations requirements and formulate a complete operations concept for the MOS PDR, with the detailed design finalized for MOS CDR. Now caught up with the rest of the project, MOS system-level verification and validation in Phase D occurred in parallel with the Flight System. This paper details the MOS development for the GRAIL mission operations, including the key lessons learned regarding how well the development process performed.

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II. Mission Overview

The GRAIL mission is divided into seven mission phases as illustrated in Fig. 1.[3] The primary mission was designed to avoid the lunar eclipses occurring on December 10, 2011 and June 4, 2012. Survival of a lunar eclipse was not a spacecraft design requirement.

The twin orbiters, referred to as GRAIL-A and GRAIL-B herein, were later named "Ebb" and "Flow" by students from Emily Dickinson Elementary School in Bozeman, Montana after a NASA sponsored contest. They were launched side-by-side on a Delta II 7920H launch vehicle from the Cape Canaveral Air Force Station on September 10, 2011. Delayed due to weather, the launch occurred two days into the defined launch period, spanning 42-days from September 8 through October 19, 2011. Regardless of when GRAIL might have launched within that period, the arrival at the Moon would always have occurred on fixed dates for each orbiter due to the design of the trans-lunar cruise trajectory. After launch, the orbiters followed a low energy trajectory heading towards the Sun near the interior Sun–Earth Lagrange Point (EL1). The low-energy transfer to the Moon reduced the LOI delta-V requirements, and permitted the use of an extended launch period (versus a direct Apollo-like trajectory).

The Trans-Lunar Cruise (TLC) phase timeline (Fig. 2) [4] allowed for spacecraft and payload calibrations, and included five Trajectory Correction Maneuvers (TCMs) for each orbiter. Only the second and third TCMs were deterministic to separate the GRAIL-A and GRAIL-B arrival times at the Moon by 25 hours. The remaining maneuvers were statistical in nature to remove trajectory errors. During operations, calibrations and maneuvers are commanded via absolute-timed mini-sequences that act as an overlay to the normal background sequences always active onboard each orbiter. Background sequences manage DSN contacts as well as other housekeeping functions throughout the mission.

During Lunar Orbit Insertion (LOI) phase, each orbiter conducted an approximately 39 minute burn to place it into an elliptical orbit around the Moon with a period of approximately 11.5 hours. GRAIL-A Lunar Orbit Insertion (LOI) occurred successfully on December 31, 2011, with GRAIL-B arriving one day later on January 1, 2012.

Once in lunar orbit, the mission entered the Orbit Period Reduction (OPR) phase, shown in Fig. 3, where a series of seven maneuvers were performed.[5] These maneuvers (three maneuvers in the first cluster, four maneuvers in the second cluster) were referred to as Period Reduction Maneuvers (PRMs), where each of the maneuvers within a cluster was performed in the same inertial direction and with the same delta-V. This strategy increases mission robustness to a missed maneuver, simplifies operations by minimizing the number of separate maneuver designs,

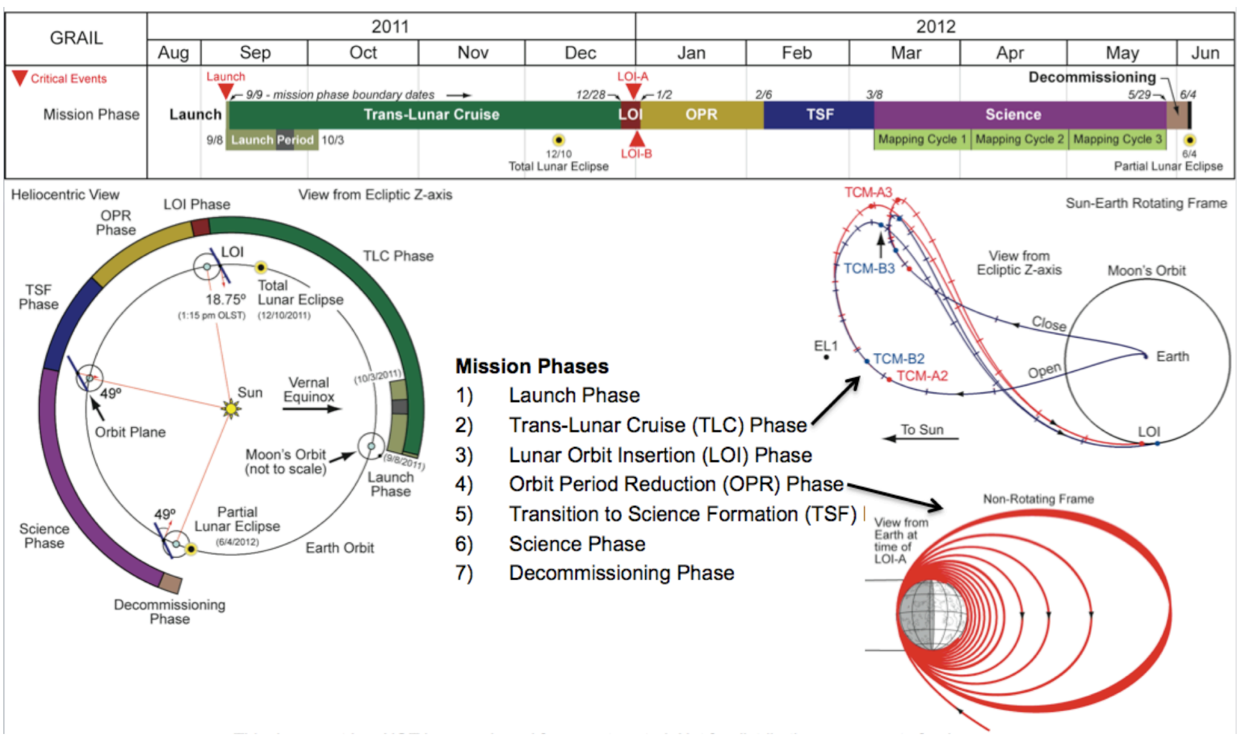

Figure 1. GRAIL primary mission timeline, extending over nine months with seven distinct mission phases.

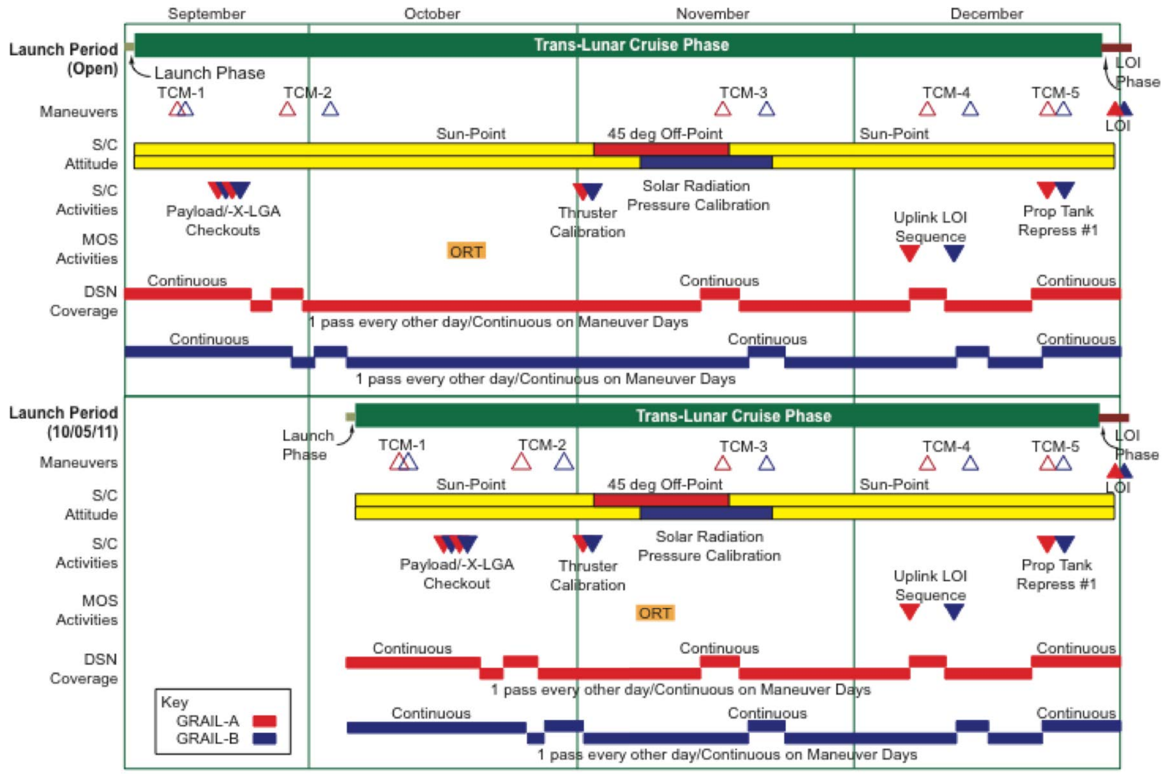

Figure 2. Launch and TLC phase operations, showing TCMs and calibration timelines for the open and close of the launch period. Final LOI maneuver planning and validation is completed such that commands are uplinked 2-3 weeks in advance of this critical event.

and reduces gravity losses. At the end of OPR phase the orbit period on each orbiter had been reduced to slightly less than two hours.

The end of OPR phase marked a change in operations strategy: since launch, the two orbiters had essentially been operated independently. Activities on GRAIL-A and GRAIL-B were separated in time to reduce operations conflicts and competition for ground resources, but the two orbiters were not operated in a coordinated manner. From the next mission phase through the end of the prime mission, operations for both orbiters had to be more coordinated. For navigation in particular it became important to know the position of each orbiter with respect to the other.

During the Transition to Science Formation (TSF) phase, shown in Fig. 4, a series of five maneuvers established the final orbits and proper orbiter-to-orbiter formation necessary for the collection of gravity science data. These maneuvers set the desired initial separation distance and ensured that GRAIL-B was ahead of GRAIL-A in the formation. Since the configuration of the two GRAIL orbiters is slightly different, the order in which they orbit the Moon is important. Once these maneuvers achieved the desired orbital conditions, and the orbiters transitioned into their orbiter-point configuration, a set of calibrations was preformed to verify that the Ka-band science payloads on each orbiter now operated as a single instrument to measure gravity. The science phase officially began on March 8th.

The initial conditions of the GRAIL orbiters (near-polar, near-circular orbit with a mean altitude of 55 km.) were designed to use the natural perturbations of the lunar gravity field to allow the orbit to evolve, minimizing the need for orbit maintenance maneuvers. During the 82-day science phase, the Moon rotates three times underneath the GRAIL orbit, resulting in three mapping cycles of 27.3 days. From the start of Mapping Cycle 1 and into Mapping Cycle 2, the mean separation distance was designed to drift from approximately 100 km to 225 km. A small Orbit Trim Maneuver (OTM) executed at the end of Mapping Cycle 1 was designed to change the separation drift rate to bring the orbiters closer together again, targeting 65 km at the end of Mapping Cycle 3 (end of the science phase). Data collected at the shorter separation distances help to determine the local gravity field, while the data collected at longer separation distances provides a greater sensitivity to large-scale features on the Moon. Figure 5 shows a summary week-in-the-life timeline for science operations.

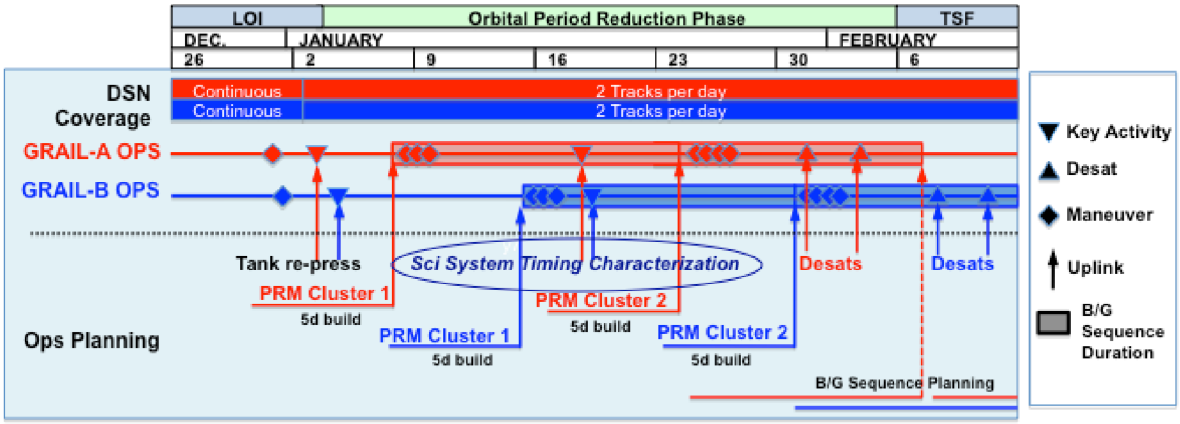

Figure 3. Orbital Period Reduction phase operations began with propulsion system repressurization after the long LOI burn. PRM cluster planning and execution occurred on alternating weeks. Maneuver planning was conducted on a 5-day timeline; maneuvers within each cluster executed one day apart. Background sequences were merged with maneuver sequences to manage dynamic sequence timing.

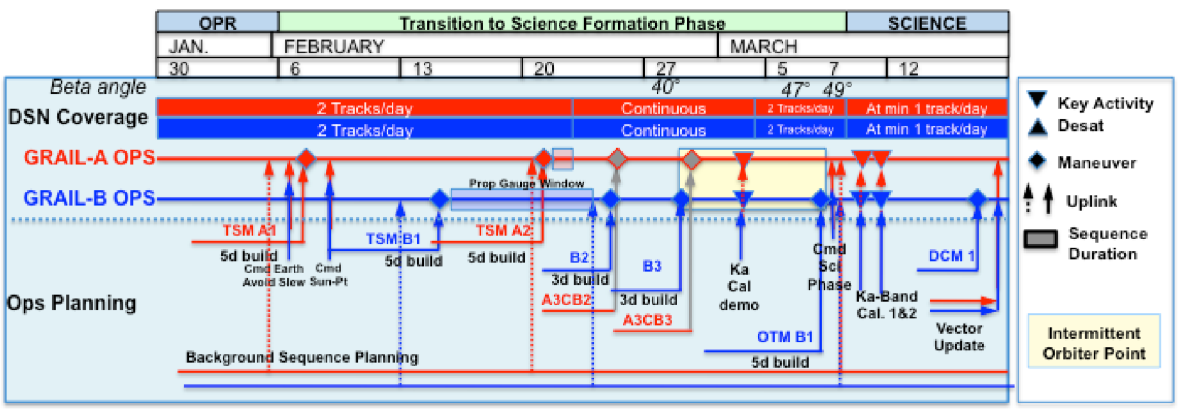

Figure 4. Transition to Science Formation operations contained five TSMs (A1, B1, A2, B2, and B3) to place the two orbiters into science formation with GRAIL-B leading GRAIL-A. GRAIL-A contingency maneuvers were prepared as backups for the final two TSMs. Once achieved, orbiters transitioned to orbiter pointing, power and thermal margins permitting. Timeline included a daily intermittent orbiter point period to allow payload checkout while confirming power and thermal constraints. Ka-band boresight calibrations were conducted to determine optimum pointing for orbiter-to-orbiter link.

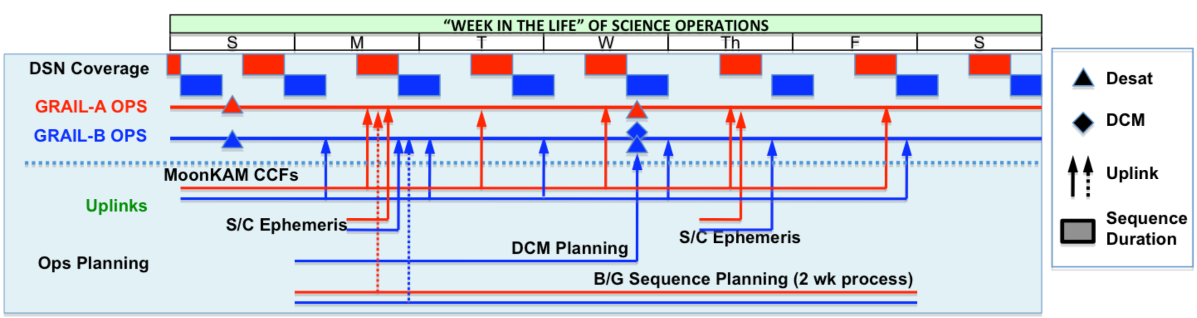

Figure 5. Science operations feature daily DSN tracking of RSB X-band data, and downlink science and E/PO data. MoonKAM image and downlink requests are uplinked each weekday. Twice weekly ephemeris updates maintain precise orbiter pointing. Background sequences are prepared on two-week cycles and include momentum wheel desaturations ("desats") near the lunar poles. Delta-V correction maneuvers (DCMs) are planned as needed to correct pointing.

The payload[6] on each orbiter consist of the Lunar Gravity Ranging System (LGRS) for science, and a MoonKAM camera system for Education and Public Outreach (E/PO). The LGRS, based on the Earth-orbiting GRACE mission's instrument, automatically generates, transmits, and receives both Ka-band and S-band signals. These signals, forming a link between the orbiters, precisely measure the range rate of change over time between the two orbiters. The MoonKAM consists of a single digital video recording unit with four camera heads to capture images and video of the lunar surface. Supervised students at the University of California at San Diego operate these cameras.

At the conclusion of the science phase, the final phase of the primary mission had been designated as Decommissioning phase, where a final Ka-band boresight calibration would be conducted prior to disposal on the lunar surface after passing through the partial lunar eclipse on June 4, 2012. In March 2012, however, NASA approved GRAIL's extended mission proposal to continue operations through December 2012. More details on the GRAIL prime mission operations and a preview of the extended mission can be found in reference 1.

III. MOS Architecture Description

A. Project and Mission System Overview

The GRAIL project consists of the components depicted in Fig. 6: the Flight System (FS), the Ground System, which includes the Mission System and Science Data System (SDS), and the Launch System (LS). The Flight System is composed of the two GRAIL orbiters and their Launch Vehicle Adapter Assembly. Each orbiter consists of the Spacecraft hardware and software, as well as the Payload hardware and software. The Mission System is composed of Mission Design and Navigation (MDN), and the Mission Operations System (MOS), which includes the Deep Space Network (DSN) and Ground Data System (GDS). The SDS is responsible for the processing, distribution, and archival of GRAIL science data products. The Launch System provides the Launch Vehicle and associated facilities and services.

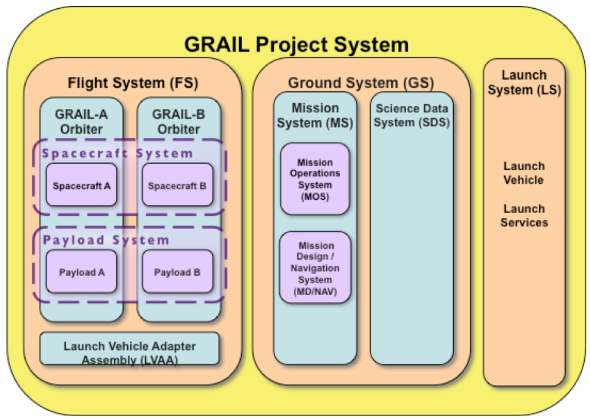

Figure 6. GRAIL project architecture.

Within the Mission System, the MDN is responsible for the formulation of the interplanetary trajectory and orbital design during the development phases of the mission. The MOS is composed of the people, processes and procedures, ground hardware and software, and facilities required to operate the GRAIL FS. The MOS provides support for FS testing during the Assembly, Test and Launch Operations (ATLO).

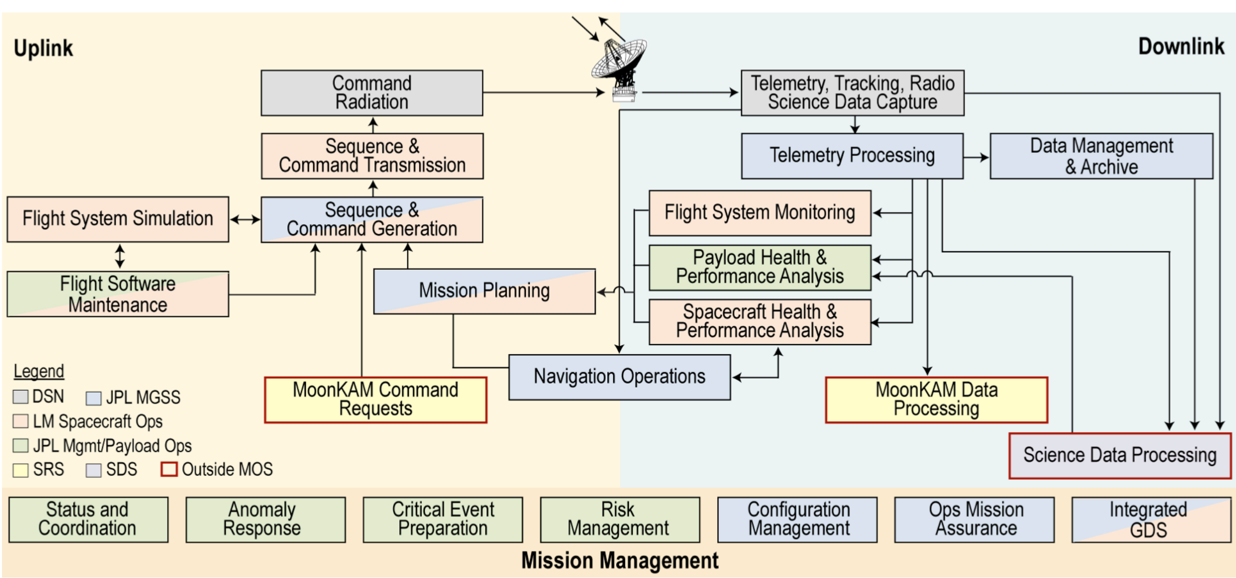

Figure 7. Operational view of MOS, showing key relationships and responsible organizations.

B. MOS Operational View

The MOS is distributed between JPL and Lockheed Martin (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 the Level-0 and Level-1 data archiving in the Planetary Data System (PDS), in cooperation with the GRAIL Science Team led by the GRAIL Principal Investigator (PI) at the Massachusetts Institute of Technology (MIT). MoonKAM Operations, led by Sally Ride Science (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 Fig. 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.

C. MOS Functional Elements

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 Fig. 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. Each operations team includes the people, processes, and procedures to perform specific operational functions. Most of the operations teams for GRAIL are located at JPL, with many of the functions (shown in blue) provided by JPL's Multimission Ground Systems and Services (MGSS). LM provides the GRAIL Spacecraft Team.

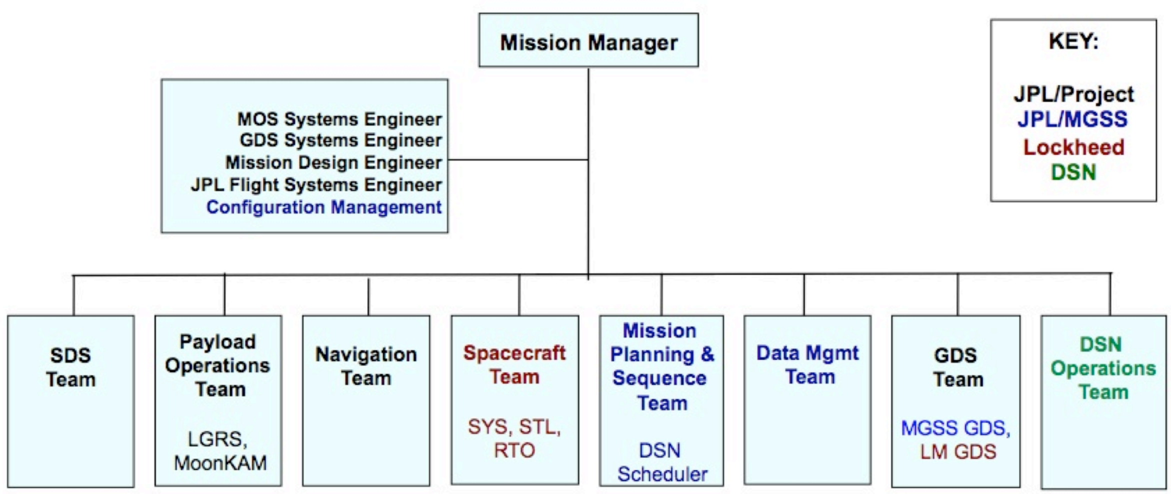

Figure 8. The eight MOS functional elements are the basis of the flight team organization.

IV. MOS Development Process

MOS development for GRAIL occurred nominally over the project lifecycle from system concept, system design, and finally system implementation. An overview of this process is shown in Fig. 9, which illustrates the progression of the MOS development.

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. These operations scenarios can be considered preliminary operations processes, taking advantage of heritage from previous JPL/LM missions. The collection of these scenarios and their detailed descriptions (including GDS design and interfaces) formed the basis for GRAIL's Mission Operations Concept Document, which constantly evolved leading up to the MOS PDR.

During system design (Phase C), each of the operations scenarios, or processes, 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. Each OIA defined the following: types information by the interface, Software Interface Specifications (SIS) when applicable, identification of the teams delivering and receiving the products, how often, and by what method of delivery. This detailed design, building on the operations concept, was documented in the MOS FDD (Functional Design Document).

With the design baselined, final system implementation could begin. As with many missions, system implementation actually began in parallel with the final design process. GRAIL's GDS was developed via phased software releases, where early releases included accepted heritage capabilities, as well as the preliminary adaptations required for flight system testing. The MOS FDD led to the detailed Flight Operations Plan (FOP), a collection of distinct documents and databases that together specify how mission operations are conducted. The FOP includes team operations procedures, OIAs, SISs, flight rules, flight system telemetry and command databases and dictionaries, and operations contingency plans. The elements of the FOP are considered living documents and must be maintained throughout the life of the mission. MOS Verification and Validation (MOS V&V) and MOS team training are key efforts during the implementation phase, to demonstrate that the MOS processes with ground software perform as designed to meet mission objectives, and that the operations team is ready to operate the GRAIL orbiters and meet all mission timelines.

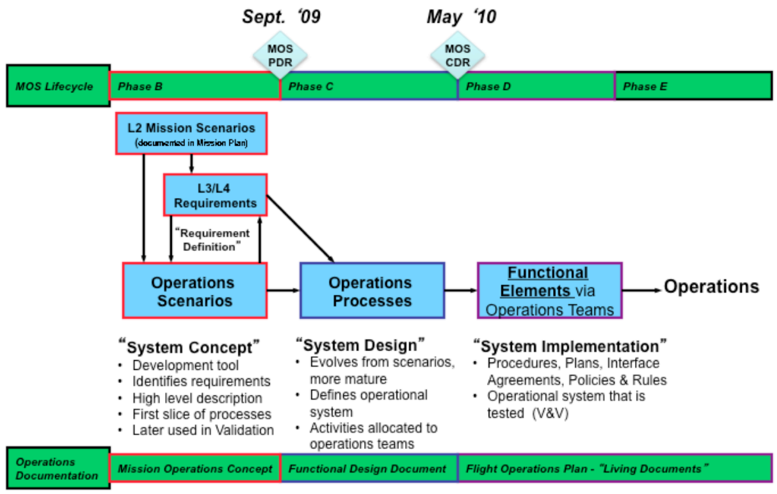

Figure 9. GRAIL Mission Operations System development process.

A. Relationship of Mission Scenarios to Operations Scenarios

Scenario development on GRAIL occurred at both the project level (L2) and the system level (L3). These scenarios, that described how the GRAIL mission would ultimately be flown, were described in three key documents, shown in Fig. 10: the Mission Plan, the Baseline Reference Mission (BRM) and Operations Concept.

Figure 10. GRAIL Scenario Documentation.

The Mission Plan was delivered by the MDN and defined the top level timelines and activities conducted in each phase of the mission. The BRM described the FS implementation per mission phase, such as system and subsystem configurations and key command sequences to conduct mission activities.

The Operation Concept, which evolved into the MOS FDD, defined how operations are conducted on the ground. Mission phase scenarios defined high-level operations strategies and timelines for each operations scenario to implement the mission activities defined in the Mission Plan. Many operations scenarios applied only to specific mission phases, while others were implemented throughout the mission. The Operations Concept contained a complete mapping of how operations scenarios were utilized. Table 1 provides a listing to the 33 operational scenarios that were developed for GRAIL.

In defining operational scenarios, GRAIL took advantage of web-based scenario and OIA tools provided by MGSS.[7] The scenario tool allowed for linking between other scenarios, applicable OIAs, and MOS requirements contained in a DOORS (Dynamic Object-Oriented Requirements System) database.[8] The OIA tool provided a standard form for defining each interface, with online approval capability for configuration management.

Table 1. Listing of Operations scenarios developed to conduct GRAIL mission.

Mission Phase	Uplink Operations	Downlink Operations
ATLO	Mission Planning	Mission Monitoring
Launch Operations	Background Sequence Development	Spacecraft Health & Performance Monitoring
TLC Operations	Minisequence Development	Payload Health & Performance Monitoring
LOI Operations	Maneuver Planning	Navigation Trajectory & Flight Path Control
OPR Operations	Real-Time Command Generation	Navigation Trajectory Product
TSF Operations	MoonKAM Commanding	Navigation Real Time Tracking
Science Operations	Commanded Retransmission	Science Data Product Generation
	Command Processing & Radiation	MoonKAM Image Production
	Contingency Operations	**Mission Management**
	Spacecraft Flight Software Update	Anomaly Response
	LGRS Flight Software Update	Status & Coordination
	Recovery from Safing (non-science)	Critical Event Preparation
	Recovery from Safing (science)	Risk Management
		Integrated GDS
		Configuration Management
		Mission Assurance

B. MOS Verification and Validation

Verification and Validation is the culmination of the development effort, where the MOS design is literally put to the test. The MOS V&V program consisted of three key test programs: GDS Integration and Test (GDS I&T), MOS Thread Testing, and Operational Readiness Tests. Figure 11 illustrates how these three test programs (shown in red) flowed together, building on each other in conjunction with project testing, to demonstrate MOS readiness for operations. GDS I&T were conducted after each software release, with specific test cases designed to verify overall software system functionality. Once the core GDS functions were in place, MOS Thread Tests checked out each MOS operation function utilizing the responsible operations teams, identifying and implementing changes to software and processes as needed. These Thread Tests were also designed to provide MOS-built products as inputs for FS Sequence Verification Tests that were executed on the flight orbiters in ATLO. ORTs provided the final validation of the MOS, demonstrating the flight team readiness to execute all operations functions in parallel, using flight procedures and final ground software.

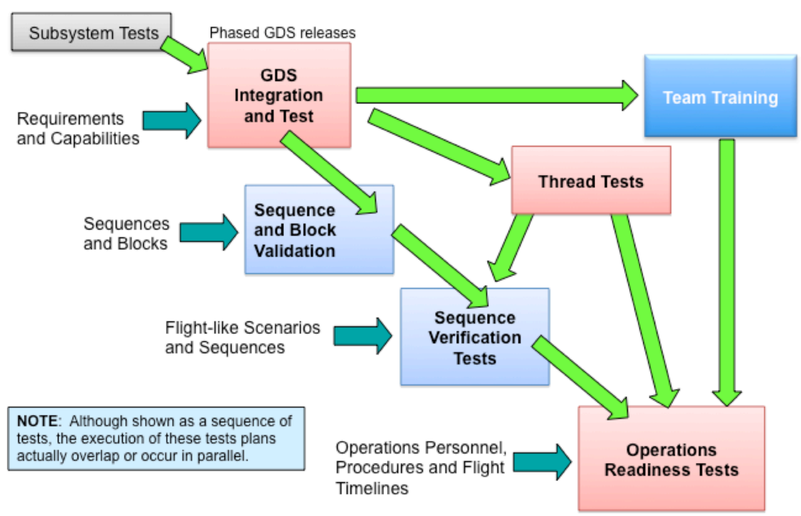

Figure 11. MOS Verification and Validation process included phase testing MOS components leading to final validation during Operational Readiness Tests.

In developing the MOS V&V test suite, the test cases were derived from the MOS scenario development effort and the detailed definitions provided in the MOS FDD. In general, Thread Test cases mapped to the various operations scenarios; ORTs demonstrated each mission phase scenario, conducting required uplink and downlink operations simultaneously. ORTs were the final demonstration of the flight team's readiness to conduct operations on nominal and anomalous mission timelines.

V. Challenges of the GRAIL Mission Operations

Much of GRAIL's success can be traced back to the original mission architecture incorporating proven heritage via the Lockheed Martin (LM) spacecraft, the GRACE-derived payload, and multi-mission operations processes and ground system. Supporting a single science instrument with a straightforward data collection strategy avoided the need for complex science planning strategies and science center interfaces. The GRAIL mission, however, offered its own unique operational challenges.

A. Dual Orbiter Operations

Throughout the mission, both orbiters must be operated in parallel. Almost all events on the mission timeline had to be executed on both orbiters. In many aspects of the design this doubled the resources required. Each orbiter 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 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 both orbiters since the status of one orbiter may impact the other.

One strategy to help manage dual orbiter operations was to de-conflict 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 focused on a single orbiter's operations, while other team members provided 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, keep orbiter command and telemetry products separate to avoid confusion by the flight team.

B. Compact Mission Timeline

The baseline prime mission for GRAIL is very short compared to most missions, only 9 months from launch to completion (prior to the extended mission addition). Once launched, however, operations progressed briskly through the next six unique mission phases representing distinct operational scenarios for the flight team. With a 42-day launch period, the flight team had to be prepared for operations beginning both at the opening and the closing of this period. Since LOI was fixed, this meant early cruise operations would have been progressively compressed for launch dates later in the period. Figure 2 shows a summary of the cruise timelines for the opening and closing of the launch period. Early operations, including 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. OPR phase included 14 maneuvers over four weeks; and TSF, the most intensive mission phase, included five maneuvers to place the orbiters into science formation and calibrate the science payload. Science phase, by design, represented the least hectic of all mission phases, where operations must be as quiescent as possible to support gravity measurements.

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 CDR, a MOS Staffing Peer Review was conducted to evaluate workforce, and consider augmentations for each operations team based on these timelines. As a result, previously proposed staffing 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.

C. Maneuver Intensive

Since each orbiter is flown separately post launch, each requires several maneuvers to establish and maintain the cruise trajectory before the critical LOI maneuver establishes the initial lunar orbit. Once in orbit, the team executed the finely choreographed sequence of PRMs to lower the orbit period, and 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, 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 prime mission.

Although the timelines for developing the different maneuver types varied, a common maneuver planning process (Fig. 12) was always employed, with standard team interfaces and validation process. Maneuver execution in lunar orbit also affected background sequence development. Background sequences were designed to accommodate nominal maneuver execution errors in scheduling DSN contacts to downlink critical engineering data. Since actual maneuver performance can vary, sequence timing included margin for DSN start and end of tracks to prevent any loss of data. Additionally, background sequence boundaries were defined strategically around each orbiter's maneuvers to limit the effects of maneuver performance on sequence timing.

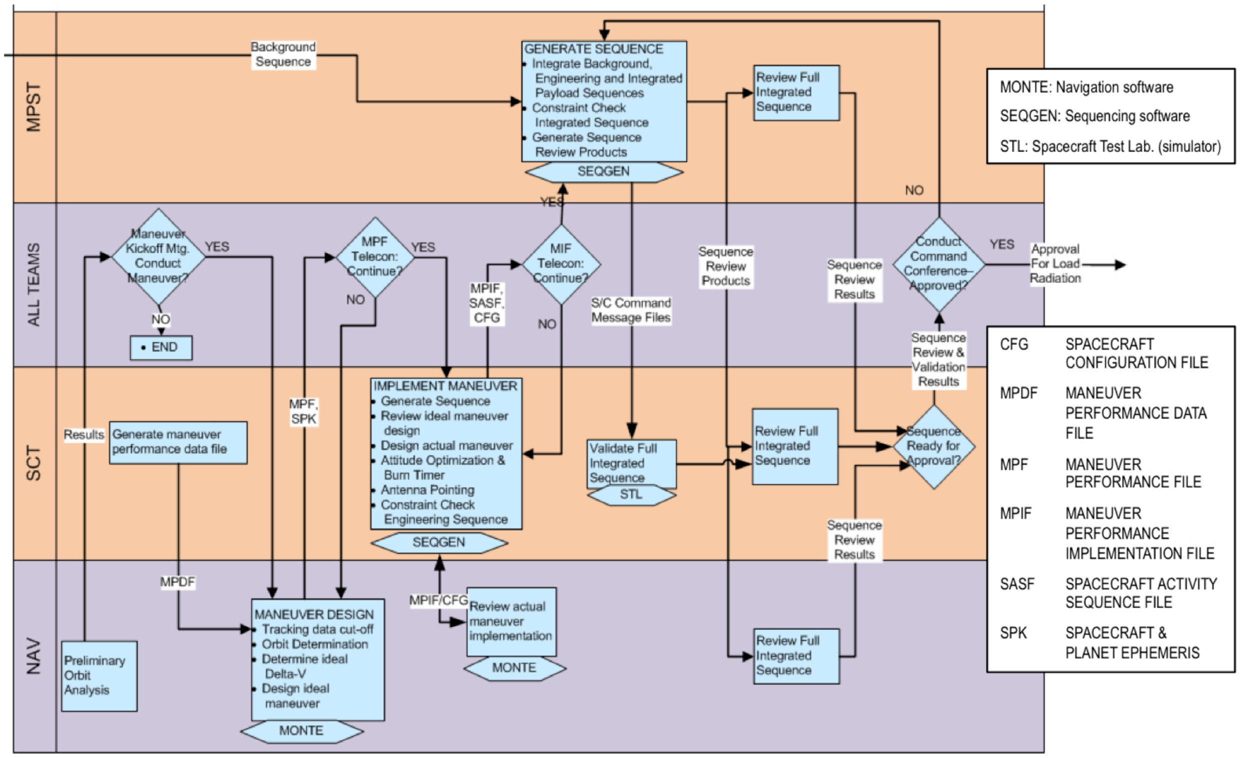

Figure 12. GRAIL maneuver planning process executes nominally over five work shifts. Typically this is implemented over five workdays. During TSF a 3-day timeline was achieved via multiple shifts per day.

D. Detailed Contingency Planning Required

In the event of anomalies, the flight team has to be cognizant of potential impacts to the other orbiter, which may be vulnerable to same anomaly. When recovering from an anomaly, fixes are typically applied to both orbiters. Once the orbiters have been recovered, contingency plans must then recover the overall mission timeline. Missed maneuvers on one orbiter may change planned maneuvers on the other orbiter. With a short 3-month science period, it is essential to balance anomaly investigation and recovery timeline with the overall impact to the science investigation.

Once in lunar orbit, missed maneuvers may disrupt the navigation plan for achieving the science orbit and can potentially delay the start of science. Because of GRAIL's time constrained science period, it is more critical than for most projects to return to the baseline mission plan as quickly as possible in order to preserve the science collection period. The GRAIL project developed a detailed set of contingency timelines, called the "Contingency Playbook" to detail maneuver strategies to recover from missed maneuvers. This was a significant effort for the MDN, requiring the development of automated tools to run over 450 cases for various missed maneuver scenarios. For the final GRAIL-B maneuvers late in TSF phase, a missed maneuver could result in GRAIL-A passing GRAIL-B as the lead orbiter. For this reason, contingency maneuvers for GRAIL-A were prepared in advance to prevent a more lengthy and complicated recovery. Contingency planning was also challenging from a sequencing point of view. Whenever maneuver timing changed, orbital timing changed as well for planned DSN contacts defined in onboard sequences. Contingency plans had to include ground time to re-plan upcoming sequenced activities, including replacing active sequences onboard.

VI. MOS Design Tenets

During GRAIL's early development phases, the following design tenets were imbedded in the project architecture and MOS operations concept in order to meet the MOS challenges.

A. Maximize use of Multi-mission Capabilities

GRAIL leverages proven multi-mission operations elements developed by JPL's Multimission Ground Systems and Services (MGSS) that provides the Advanced Multi-Mission Operations System (AMMOS), NASA's Deep Space Network (DSN), and LM's Spacecraft Team. The partnership of these multi-mission elements had been previously demonstrated on numerous missions, including Mars Global Surveyor, Mars Odyssey, GENESIS, STARDUST, the Spitzer Space Telescope, Mars Reconnaissance Orbiter, and the Phoenix lander. Additionally, GRAIL's science payload and science data system operations benefitted from GRACE mission heritage. Maximizing the use of these existing MOS elements, and minimizing the use of new elements, lowered cost and risk.

B. Consistent Organization between Development and Operations

GRAIL's Mission System development organization was based on the key functional elements used to eventually operate the mission in flight. With the short mission duration, and dense timeline of activities it was important to transition the experienced development team into flight operations. The MOS functional element organization (Fig. 8) translated directly into the operational teams needed to build the flight team, maintaining experience across the project lifecycle.

C. Keep Operations Consistent between Orbiters

Another strategy to minimize cost and risk was to maintain identical operation processes and configuration between the two orbiters. Telemetry and command dictionaries were maintained identically, as well as the onboard command block dictionaries. Change requests, with very few exceptions, were applied to both orbiters. The project documented design differences and idiosyncrasies between the orbiters. Common operations processes applied to both orbiters in order to keep operations straightforward. In developing operations products, such as flight sequences, a single operations engineer would lead development for both GRAIL-A and GRAIL-B products to ensure consistency.

D. Common Maneuver Process & Interfaces throughout Mission

GRAIL's 33 planned maneuvers (originally 44 at time of PDR!) consisted of 10 Trajectory Correction Maneuvers (TCM), 2 for Lunar Orbit (LOI), 14 Period Reduction Maneuvers (PRMs), 5 Transition to Science Maneuvers (TSMs), and 2 Orbital Trim Maneuvers (OTMs). Each maneuver type had unique design objectives, such as targeted orbital parameters, as well as unique planning timeline constraints. In order to maintain straightforward operations, a common maneuver planning process with defined interfaces between teams was employed.

E. Automated Science and E/PO operations

Once GRAIL entered Science phase, it was imperative to maintain quiescent operations, to limit any perturbations to the science data. Limiting complexity of operations was important to minimizing the risk of anomalies, such as safe mode, which would interrupt science data collection. GRAIL's science operations are inherently simple. Once the LGRS payloads are turned on, with the orbiters in the science formation, there are no interactions required nominally in order to collect science data. On the other hand, for E/PO operations with MoonKAM, routine and frequent commanding is required to capture images and downlink them. Due to the off-the-shelf nature of the camera system selected, E/PO operations are inherently more complex than science. While E/PO operations are important to the project, science operations are the clear priority, and E/PO operations must be non-interactive with science operations. In the operations design, this was accomplished by automating MoonKAM commanding and data distribution interfaces with SRS, so that the flight team could remain focused on overall mission operations and avoid distraction from science operations. This was accomplished via the development of two GRAIL-unique ground software components: MoonKommand which allowed SRS, based remotely in San Diego, to non-interactively send MoonKAM commands to the orbiters; and MoonKIDS which automatically delivers JPL and LM generated planning files and acquired image data to SRS servers.

F. MOS Readiness for Full Mission at Launch

Many missions feature quiet cruise periods where operations development can continue for later mission phases. For GRAIL's fast-paced mission, the MOS determined early on that operations were too busy to accommodate any deferred development work after launch. To that end, the MOS development team adopted the objective to complete all development work for all prime mission phases prior to launch. The team was successful in that endeavor, including the completion of all team procedures and GDS releases. One exception was the scheduling of inflight refresher training during TLC in preparation for the upcoming LOI, OPR, and TSF mission phases.

VII. Lesson's Learned

By and large GRAIL's MOS development process went very smoothly, avoiding any significant requirement changes or re-designs along the way. From a mission operations perspective, the key lessons learned from GRAIL's development are listed below, defining what worked well, along with what could have been improved.

1) **Use of heritage multi-mission systems provided significant benefit to operations.** Extensive use of existing MGSS, DSN, and LM multi-mission operations designs and organizations allowed GRAIL to have a stable and mature system, providing a strong foundation for the GRAIL MOS design. GRAIL mission operations requirements matched existing multi-mission capabilities very well. For early development this allowed the MOS development team to fully staffed later than the rest of project, reducing development costs. Use of an MGSS provided Mission Support Area (MSA) for GRAIL also reduced project development scope.
2) **MOS delayed development reduced cost, but increased stress in Phase D.** GRAIL MOS design reviews were scheduled 6-9 months after corresponding project design reviews. The schedule was generally successful and resulted in reduced operations development costs, however, it lead to persistent concerns among review board members that the MOS was behind schedule. In the case of the Navigation and Mission Planning and Sequence teams, it caused additional stress, including overtime hours, to meet the reviews schedule in Phase D, in parallel with product deliveries and ORT participation.
3) **Early Mission Design for maneuver turnaround underestimated project/review board risk tolerance.** Original mission design included two maneuvers per day during the second PRM cluster in OPR, and two day turn-around for planning maneuvers in late TSF. Although within the capabilities of the flight team, the perceived risk was too high for project review boards. Later in the development process, as orbiter propellant margins increased, these timelines were relaxed. During OPR the second maneuver per day was eliminated during the second PRM cluster; during TSF the minimum turn-around for maneuver planning was expanded to three days.
4) **Automation of E/PO MoonKAM operations increased development effort, but paid off during flight.** Interfaces for MoonKAM were not a good fit for existing multi-mission capabilities. The project required these operations to be non-interactive, but the existing camera controller required extensive commanding via ASCII file loads. GDS engineers invested significant effort to automate this interface to reduce operational effort for JPL and LM teams. Command checking was added to insure MoonKAM operations could not interfere with science operations. E/PO MoonKAM operations actually required more development effort than science operations for the MOS team. Additional resources were required as the MoonKAM ground software development effort progressed.
5) **GDS Inheritance review in phase B was extremely helpful to understanding GDS development scope and effort.** This review allowed fresh eyes to review scope and resources for the GDS development baselined in the Phase A proposal, prior to competitive selection. This review identified areas where plans required adjustment, such as MoonKAM ground software interfaces, which were under-estimated.
6) **MOS Staffing Peer Review was successful in ensuring the right MOS workforce.** The staffing levels required for MOS development, testing, and operations had been underestimated. GRAIL's mission timeline, operating two orbiters with numerous maneuvers was operationally intensive. Flight team preparations for operations required more significant V&V activities, such as longer ORTs. As part of the review, operations team leads presented baseline-staffing levels and proposed adjustments.

VIII. Conclusion

GRAIL mission operations have proceeded smoothly, with only minor anomalies, and the project is well on its way to meeting all prime mission objectives. A methodic pre-launch development effort, leveraging use of existing multi-mission operations heritage helped minimize cost and risk. Rigorous operational testing prepared the mission operations system and its team for the challenges of the GRAIL mission.

Appendix A
Acronym List

AMMOS	Advanced Multi-Mission Operations System
ASCII	American Standard Code for Information Interchange
ATLO	Assembly Test and Launch Operations
CCF	Camera Control File
CDR	Critical Design Review
DCM	Delta-V Correction Maneuver
Desat	Momentum wheel desaturation
DSN	Deep Space Network
E/PO	Education and Public Outreach
FOP	Flight Operations Plan
FS	Flight System
GDS	Ground Data System
GDS I&T	GDS Integration and Test
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
JPL	Jet Propulsion Laboratory
LGA	Low Gain Antenna
LGRS	Lunar Gravity Ranging System
LM	Lockheed Martin
LOI	Lunar Orbit Insertion
MDN	Mission Design and Navigation
MGSS	Multimission Ground Systems and Services
MoonKAM	Moon Knowledge Acquired by Middle School Students
MOS	Mission Operations System
MOS FDD	MOS Functional Design Document
MOS V&V	MOS Verification and Validation
MSA	Mission Support Area
OIA	Operational Interface Agreement
OPR	Orbital Period Reduction
ORT	Operational Readiness Test
PDR	Preliminary Design Review
PDS	Planetary Data System
PI	Principal Investigator
PRM	Period Reduction Maneuver
RSB	Radio Science Beacon
RTO	Real-Time Operations
SDS	Science Data System
SIS	Software Interface Agreement
SRS	Sally Ride Science
STL	Spacecraft Test Lab
TCM	Trajectory Correction Maneuver
TLC	Trans-Lunar Cruise
TSF	Transition to Science Formation
TSM	Transition to Science Maneuver

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