Managing GRAIL: Getting to Launch on Cost, on Schedule, and on Spec

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Abstract—The Gravity Recovery And Interior Laboratory (GRAIL) mission launched September 2011. GRAIL is a Discovery Program mission with a project cost cap. Led by Principal Investigator (PI) Dr. Maria T. Zuber of MIT and managed by NASA's Jet Propulsion Laboratory, GRAIL will 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. Dr. Sally Ride leads education and public outreach.

This paper summarizes development challenges and accomplishments. Critical success factors are discussed, including key personnel, technical margins, and schedule/cost management practices.[1]

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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. As discussed in Section 4, GRAIL is a Principal Investigator (PI)-led mission. As stated in the selected proposal, "GRAIL will 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" [1]. GRAIL will provide a higher-spatial-resolution global gravity field of the Moon than exists for the Earth.

GRAIL will place twin spacecraft in a low-altitude, near-circular polar orbit around the Moon. The mission is "the first robotic demonstration of precision formation flying around another planetary body" [2]. GRAIL will perform high-resolution range-rate measurements between the orbiters using a Ka-band payload. The spacecraft range-rate data (changes in separation distance between the orbiters), time-correlated by NASA's Deep Space Network, provides a direct measure of lunar gravity [3]. GRAIL will conduct science operations for approximately 82 days, constituting three mapping cycles. There are six science investigations associated with the Science Phase, as discussed in section 2.

NASA successfully launched GRAIL on September 10, 2011. "The mission… launched on spec, on time and under budget…" [4]. The spacecraft are scheduled to enter lunar orbit on December 31, 2011 and January 1, 2012, to begin science data-taking in March 2012, and to complete the prime mission in June 2012.

2. PROJECT CONCEPT AND SCIENCE

GRAIL benefitted significantly from technological, operational, and scientific advances demonstrated by the Gravity Recovery and Climate Experiment (GRACE), launched in 2002 and now in an extended mission. GRACE is measuring Earth's gravity field, calculating the separation distance between two spacecraft using GPS to correlate spacecraft timing and a microwave ranging system to measure spacecraft distance changes indicative of the distribution of mass in the Earth's interior. GRACE, led by Principal Investigator Dr. Byron Tapley of the University of Texas, is a joint program of NASA and the German Aerospace Center (DLR) [5].

For the Discovery announcement of opportunity competition, Dr. Zuber and JPL conceived a "GRACE at the Moon" mission. On the basis of a competitive process of evaluation, the team selected Lockheed Martin (LM) to build the spacecraft, an American launch vehicle (LV), and a modified version of the JPL science instrument (*sans*

[1] 978-1-4577-0557-1/12/$26.00 ©2012 IEEE

GPS). A summary of these project elements is provided in Section 3.

Driving criteria for project conception and proposal "win" strategy were as follows:

(1) Propose a mission within the Discovery Program cost cap, with financial headroom.

(2) Judiciously utilize heritage designs and mature spacecraft development processes from JPL and LM.

(3) Architect the mission with limited and clean interfaces and robust technical resource margins.

(4) Reduce risk by early payload prototyping.

(5) Enlist a strong team of experienced key personnel, including persons who worked on GRACE and the Mars Reconnaissance Orbiter (MRO) and a "who's who" of gravity scientists.

(6) Define measurement requirements on the basis of instrument capability.

(7) Include an unprecedented education and public outreach (E/PO) program, with flight cameras dedicated to student use, under the leadership of America's first woman in space, Dr. Sally Ride.

As proposed and selected by NASA, GRAIL has six science investigations. The first four are required for minimum mission success (the "science floor") and the remainder to achieve full mission success (the "baseline mission"). GRAIL's science investigations are 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 mass concentrations (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 a possible lunar core [6].

These investigations were proposed as the level-1 requirements constituting the contractual agreement with NASA. *A key success factor for the project is that the level-1 requirements remained unchanged through the entire project development cycle.* The level-1 requirements were deconstructed into specific measurement requirements, which were based on the capability of the instrument and spacecraft performance, and throughout the mission development and execution were similarly unchanged.

3. Project Elements

The GRAIL project consists of the following elements: spacecraft, payload, launch system, and mission operations system. Figure 1 diagrams the two spacecraft. Figure 2 shows the spacecraft installed in the LV payload fairing. Figure 3 shows the GRAIL launch.

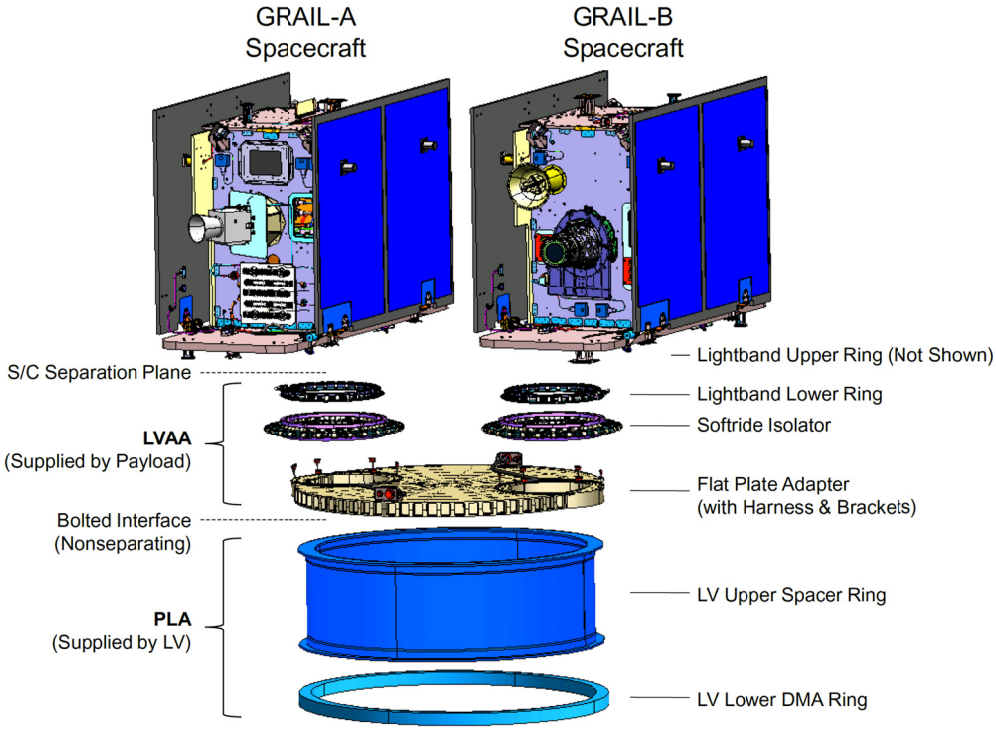

Figure 1—GRAIL's twin spacecraft.

Figure 2—Spacecraft in launch vehicle payload fairing.

Figure 3—GRAIL launch, September 10, 2011.

The flight system is made up of the spacecraft and the payload. The two spacecraft, provided by LM, 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 twin 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. structure, propulsion, avionics, and software were built in-house by LM; hardware for remaining subsystems hardware was provided by subcontractors.

The payload consists of a science instrument, the Lunar Gravity Ranging System (LGRS), and an E/PO camera, the Moon Knowledge Acquired by Middle school students (MoonKAM), on each spacecraft. LGRS is provided by JPL, which built some assemblies in-house, procured others from suppliers, and integrated and tested the whole. As mentioned above, the two LGRS are required to communicate with each other. MoonKAM is provided by Ecliptic Enterprises, using the mature RocketCam product. Each spacecraft has an independent MoonKAM, made up of a digital video recorder and four fixed camera heads.

GRAIL's launch system is a Delta II Heavy rocket, unit 7920H-10. It includes, as mission-unique equipment, a special payload adapter assembly. The rocket is provided by United Launch Alliance (ULA).

The mission operations system (MOS) is distributed. Its foundation is the multimission capabilities at JPL and LM, including NASA's Deep Space Network (DSN). It is supplemented by a science data system, with MIT and JPL elements, and data will ultimately be submitted for archive to NASA's Planetary Data System. 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 project organization employed to achieve these deliveries is described in Section 4.

4. PROJECT MANAGEMENT

Per the NASA Discovery Program paradigm, GRAIL is a PI-led mission. Dr. Zuber is responsible for the success of the mission in all respects, and she leads the GRAIL science team. As a "hands-on" PI, she participated in a prominent way in all aspects of project development, including risk management, reviews, and financial decision making. She selected JPL to perform project management, deliver the payload, lead the MOS, and perform systems engineering, safety and mission assurance, and business functions; JPL also performs gravity modeling activities. JPL in consultation with Dr. Zuber selected LM to deliver the flight systems, including fabrication of the spacecraft and system integration and test and launch site support. NASA's Kennedy Space Center (KSC) provided launch services, including launch site operations and successful launch of the ULA Delta II Heavy. NASA's Goddard Space Flight Center (GSFC) provided the Deputy PI, Dr. David Smith (who has subsequently joined MIT), and performs gravity modeling work. SRS directs the E/PO program. NASA oversight was conducted by the Discovery and New Frontiers Program Office, located at NASA's Marshall Space Flight Center, with direction from the NASA Headquarters Science Mission Directorate.

The GRAIL project organization chart is depicted in Figure 4.

The staffing was designed with the following outcomes in mind: a) designate a larger-than-the-norm number of staff as proposed key personnel, all of whom brought substantial flight project experience to the team; b) include several veterans of the heritage projects, GRACE and MRO; and c) retain all key personnel until their areas of responsibility were completed. As of launch, only two of 16 proposed key personnel were no longer on the project, the Chief Engineer (responsible for system architecture and trade studies, who left after its completion at the project Critical Design Review [CDR]) and the Payload Manager (who departed after delivering the payload). They were supported by qualified staff at JPL and LM, augmented by contractor support staff when the need arose. Under the heading of "Team Competency," one participant noted: "Have never seen a program with as high a percentage of talent-level at all levels of the organization—huge effect on small team efficiency" [7].

GRAIL's guiding philosophy was *low*-risk implementation, so proactive risk management was integral to project success. Monthly Risk Board meetings included the PI, Project Manager (PM), most key personnel, and relevant support staff. Before life-cycle reviews, the meetings were extended to walk through every risk. At least twice during project development, special risk identification sessions were convened by the Project Systems Engineer. Culturally, anyone on the project could recommend a risk, and most were proactive in this regard. Risk identification was continually encouraged by all members of the GRAIL leadership team. The project Risk List was tied to the project Liens List, discussed below. An important point to note is that *GRAIL used risk management as a value-added*

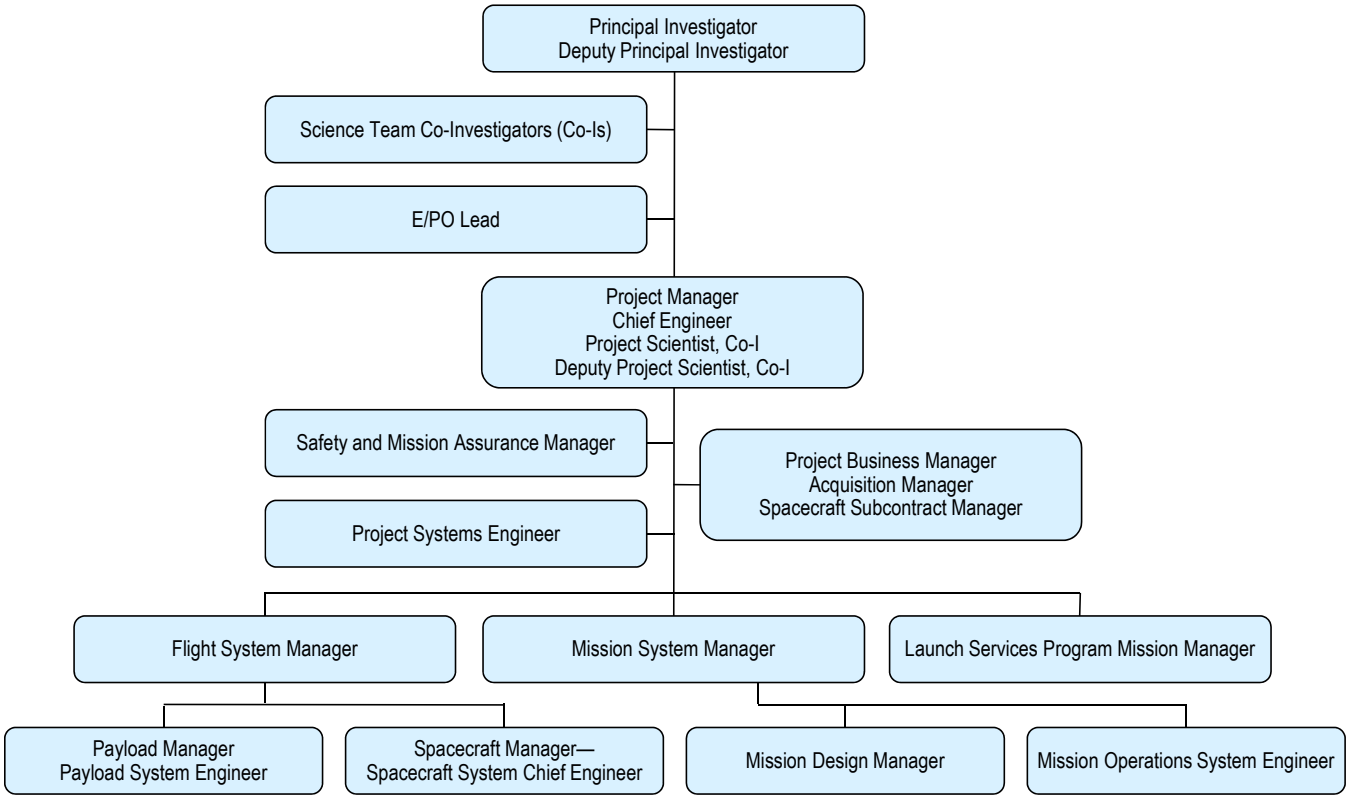

Figure 4—GRAIL organization chart.

technique for managing the work to go, instead of doing the minimum to meet an Agency reporting requirement.

Similarly, Safety and Mission Assurance (SMA) held a full-partner role on the project. In addition to the traditional responsibilities for requirements compliance, oversight, and discipline area support, the SMA team was heavily involved in independent assessment of, and implementation support for, the critical technical issues and anomalies experienced over 3 ½ years of development. (More details are provided in Section 6.)

Finally, Business Management not only took care of the "housekeeping" aspects of NASA and institutional budgeting, funding, and reporting, but also provided value-added scheduling expertise and contract management, a contribution elaborated in sections 7 and 8. Most innovative was the Technical, Schedule, and Cost (TSC) Control Board, chaired by the PI, which decided all top-level technical and schedule changes and reviewed and approved all requests for use of project cost reserves. Only the PI could approve release of cost reserves, a practice which had a powerful effect on encouraging team leads to solve their own problems and bring forward only requests that were truly needed, well justified, and reasonable in amount relative to the scope of the problem. Not all requests were approved. On the other hand, the PI would make periodic calls for staff to propose ideas for risk-reduction activities, and value-added investments were usually supported. (Since GRAIL is single-string, risk reduction was continually kept in mind.) Liens were conservatively bookkept at 100% likelihood of occurrence, and earned value management (EVM) was implemented throughout Phase C/D per NASA policy.

Oversight of GRAIL, provided by the Discovery Program Office at NASA's Marshall Space Flight Center under direction of the NASA Headquarters Science Mission Directorate, was characterized by open communication. The interactions represented a useful and value-added aspect of the GRAIL mission and contributed positively to successful implementation.

5. DESIGN

Per the NASA instructions, the Conceptual Design Phase (Phase A) had a specified start date and a specified end date, resulting in an intensive six-month study. The goal for the GRAIL team was not only to complete the required conceptual design, management plan, and cost proposal (as a Concept Study Report [CSR], aka step-2 proposal), but also to get an early start on Phase B. This was particularly important for GRAIL because the mission needed to be launched either prior to or after major eclipses at the Moon, spaced on average every 6 months, which preliminary analysis indicated would likely render the solar panels and electrical power subsystem inoperable. Team win strategy dictated the former option, which would provide an attractive launch date for NASA (earlier than the AO's not-later-than date) and provide commensurate cost savings (no standing army). The flip side of this aggressive strategy was that Phase B/C/D would be constrained to 45 months, which translated into a one-year Phase B.

During Phase A, the project completed the following activities, as specified by NASA: conceptual design, management plan, Phase B work plan, network schedule, and parametric cost estimate. Additionally, JPL established a Gravity Recovery Instrument for Planets (GRIP) testbed for early system analysis using GRACE residual hardware and GRAIL prototype electronics. A first pass was made at a project element Inheritance Review (IR), but this was not conducted in depth, as would become evident the following year. By the time of the NASA site visit in August 2007 preliminary versions of all Phase B gate products were completed and exhibited to the Agency source evaluation team. This not only impressed the evaluators but also meant far less work for the project team to do in Phase B.

As proposed, GRAIL performed to a one-year Preliminary Design Phase (Phase B). This included, per NASA's project management requirements, preliminary design, implementation plan, project technical/schedule/cost baseline, and specified gate products and control plans. It also included demonstration of technology maturation for the new elements within the payload, which included the Time Transfer System within the LGRS. JPL required an internal independent institutional review of the project's readiness to initiate preliminary design, the Project Mission System Review (PMSR), early in Phase B. This was scheduled very early (April 1–3, 2008) so as to identify quickly any requisite course correction and to get everyone on a common work plan. The early PMSR proved challenging due to the late start at JPL and LM of staffing up personnel beyond the study team, but it had the unexpected benefit of forcing early teambuilding.

Following PMSR, design progressed in two waves. First was a battery of IRs. In most instances design heritage was confirmed and decision to proceed granted. However, in the case of the flight reaction wheels, the review exposed serious concerns about a foreign-manufactured product, and a difficult but necessary decision was made to change to another supplier, who would need to modify its existing product line. Later in Phase B, LM proposed to reverse its "buy" approach for avionics, to complete development from an existing internal research and development (IRAD) program and be able to maximize reuse of MRO flight software; this alternative was subjected to the IR process prior to receiving the go-ahead for further development.

The second wave was a series of Preliminary Design Reviews (PDRs) for the instrument assemblies and the payload as a whole, for the spacecraft subsystems, for portions of the MOS, and for some cross-cutting areas (e.g., Requirements Review). Between the IRs and the PDRs, 38 internal reviews were conducted during the one-year Phase B.

Design maturity was facilitated by several factors. First, GRAIL was conceived as a capabilities-driven mission, with requirements taken as-is from the heritage designs and modified only where absolutely necessary (and then only to the smallest extent possible). This provided a flight system design with very large technical margins (notably mass and power), which allowed the project team to expend margins to solve technical problems and surprises instead of devising elegant work-arounds. Second, as proposed, the Formulation Phase key personnel included both a Project Systems Engineer (responsible for systems engineering processes and staff, and serving as the Engineering Technical Authority) and a Chief Engineer (dedicated to maintaining the project architecture and conducting and closing all trade studies). Third, the small number of technology developments received the necessary resources and attention during Phase B. These included elements of the LGRS, with engineering model assemblies tested in the GRIP testbed; MRO-lite avionics, starting late and requiring a plan for transitioning from an IRAD effort to a flight manufacturing job; and reaction wheels, also starting late and needing a fast-track design team.

Completion of Phase B required generation of many gate products, presentation of the project PDR to a NASA Standing Review Board (SRB) on November 11-14, 2008, management approvals, and NASA approval to proceed to Implementation. While GRAIL's Phase A/B design activity was exemplary in many respects (the SRB report indicated, "Instrument is above PDR level. Spacecraft system is at PDR level"), the following were open concerns that constituted liens against Phase C development: a) rigor of the risk management approach, b) maturity of the gravity modeling effort, c) planned late completion of the MOS PDR, and d) maturity of fault protection [8].

6. DEVELOPMENT

With a solid preliminary design and implementation plan, including substantial schedule and cost reserves, it might be expected that GRAIL's Phase C development would go smoothly. However, some areas turned out not to be as effectively planned as thought, and "unknown unknowns" surfaced, so the healthy reserves proved to be a critical success factor.

A 12-month final design activity led to the project CDR on November 9-13, 2009. Similarly to Phase B, this NASA life-cycle review was preceded by 28 internal reviews (including an E/PO peer review) and the generation of many NASA- and JPL-required gate products.

Because the avionics and the reaction wheels were lagging the remainder of Flight System development, they constituted the worry items on the project for Phase C. For avionics, the challenges and problems prior to project CDR were developing a parts procurement program that met the need dates, while the important accomplishments included significant design progress. For reaction wheels, the issues were in the electrical design area due to changes being made in the underlying technology. The final trouble area during this time span was electronic parts; both JPL and LM were late in ordering long-lead electrical, electronic, and electromechanical parts and in some cases ordered custom parts with lengthy deliveries when standard parts could have met the form, fit, and function requirements. In the spirit of not overanalyzing the problem or pointing fingers, the PM simply spoke across the table to the project Acquisition Manager and directed, "Solve the parts problem." A Tiger Team was quickly established, and after ten weeks of daily meetings and with the aid of additional parts engineering and procurement staff, the situation was brought under control, albeit with some financial and schedule impact.

With these caveats, GRAIL successfully passed project CDR. The SRB noted, "Instrument is above CDR level. Spacecraft system is at CDR level (with full closure of avionics subsystem CDR [via delta-CDR held December 15, 2009].…" The key watch items at that point were two science goals that might not be met, late parts deliveries, avionics development, reactions wheels development, and MOS maturity [9]. But an unpleasant surprise was about to emerge.

Very soon afterwards (viz, before the report out to NASA Headquarters), the project was informed that the previously provided LV loads for the Delta II Heavy were incorrect, in fact substantially too low. This was determined by examination of data from a recent Delta II liftoff (the Gamma Ray Large Area Space Telescope [GLAST]). The launch loads issue promptly became the first crisis for the project team, because it meant that the final-designed flight system would be shaken to pieces by the launch environment, in which case, as the PM described it, "We don't have a project!"

Following the by now common use of tiger teams, GRAIL suited up another, this time with significant representation beyond JPL and LM. Members included ULA, KSC, and (eventually) Moog CSA Engineering. Starting work in December 2009 and working through the holidays, the team presented multiple conceptual designs at an independent assessment on January 28, 2010 and received approval for a dual-SoftRide load attenuation system approach. LM subcontracted with Moog CSA for SoftRide and on a rush schedule successfully completed PDR on May 5, 2010 and CDR on June 11, 2010.

The pace of activity picked up on all fronts heading towards the end-of-Phase-C life-cycle review, the System Integration Review (SIR), which was held on June 21-23, 2010. Of greatest significance was that the SIR was held one week ahead of the CSR/step-2 proposal date for the SIR, meaning that every one of the calendar days originally hypothesized to be available for system integration, test, and launch operations were in fact still available, plus an additional margin of seven. Having 65 days of schedule reserve would prove invaluable through Phase D.

The SRB was particularly impressed that "payload is in terrific shape, and on time!" and that "A key post-CDR issue, launch loads, has been successfully mitigated." The only liens identified were a reaction wheels test failure that occurred a week before SIR, avionics delivery issues, and behind-schedule flight software [10].

7. ATLO

NASA describes Phase D as System Assembly, Integration and Test, and Launch. JPL and LM use the term Assembly, Test, and Launch Operations (ATLO), but the meaning is the same.

GRAIL entered ATLO with a schedule baseline of 40 days' schedule margin for LM Colorado activities (flight system assembly, integration, functional test, environmental test, and transportation to the launch processing facility) and 25 days' margin for KSC/ULA Florida activities (Launch System assembly and integration, launch-vehicle-to-spacecraft integration, fueling, and launch). These planned margin days excluded second-shifts, weekends, and holidays. In practice, work-to-ship was tight, and work-to-launch was relatively routine, with judicious application of cost reserves to support second-shift and overtime augmentations.

A critical success factor was LM and JPL's extensive experience in ATLO, especially the fact that John Henk, the LM Program Manager, had an ATLO background. The JPL/LM team knew from the school of hard knocks what items required special attention, how long tests and other actions actually took to perform, where margin would be best placed, and what flexibilities existed in the ATLO flow. Per plan, there were sufficient spares to keep making forward progress, and hardware could be swapped from GRAIL-A to GRAIL-B or from flight spare or testbed status to test out the flight and ground software. Full-functionality ATLO test units (ATUs) were used temporarily while flight units were completing unit test; then penalty (regression) testing was performed at the spacecraft level. Workmanship tests were performed on both spacecraft, whereas performance and stress tests were, in some cases, divided between the two. The project fully completed its proposed no-excuses Incompressible Test List tests, as well as the highest-priority optional Risk-Reduction Tests (RRTs). As appropriate, RRTs were performed on simulator workstations (SoftSim), on the GRAIL Testbed, or on a spacecraft.

Challenges during ATLO included late delivery of avionics (due to a myriad of small and irritating causes), hence the ATUs approach; late completion of flight software acceptance testing (largely due to competition for resources with the Juno project); and behind-schedule closeout of verification and validation (V&V) paperwork (test reports, analyses, second-set-of-eyes review, and final recording in the archiving tool); in the case of avionics, until the final flight units arrived, requirements could be tested but the official run for record could not be performed. Using the GRAIL "teaming for success" approach, JPL and LM brought on additional staff, redeployed existing staff, and had one organization's persons perform activities on behalf of the other—what was important was getting the job done, not rigid lines of organizational authority. It became quite common for JPL to volunteer to help in an area or for LM to request help (and vice versa); this provided quick staffing to combat problems, minimizing schedule and cost impacts while reinforcing team spirit. The nonhierarchical and collaborative nature of the GRAIL team was a key factor in solving the project's technical and schedule problems.

8. Contract Collaboration

JPL issued a subcontract to LM for GRAIL, split by phases. Phase C/D was executed as a cost-plus-fixed-fee-plus-incentive-fee arrangement, with final contractor fee dependent upon in-flight performance and actual costs as compared to target costs. Phase A had been firm-fixed-price (FFP), with both JPL and LM providing supplemental bid and proposal/IRAD investments. (JPL institutional investment was applied to the GRIP testbed [see Section 5 above] and LM's to MRO-lite avionics development.) Phase B was cost plus fixed fee, as is the current Phase E operations phase. Contract changes were limited in number and significance and were quickly processed, so the project requirements were controlled, the incentive approach never changed, and the subcontract baseline was always clear. EVM was implemented during Phase C/D as a trailing indicator; it was not a first alarm of problems but did assist in bounding the schedule and cost consequences.

Contract surveillance was conducted using a combination of insight and oversight techniques, founded on a philosophy that JPL involvement must be value-added and reflective of the project's risk-management program. During Phase A JPL and LM management agreed that each organization would use its proven spaceflight development practices. In other words, JPL would not force LM to do things the JPL way, nor would LM pressure JPL to work to LM procedures. The surveillance approach centered on the following:

(1) Document Submittals—per JPL's Standard Subcontract Data Requirements List/Data Requirements Descriptions (SDRL/DRDs), with some items negotiated to allow LM equivalents and/or to be delivered in place (referred to as "engineering submittals").

(2) Reviews—Monthly Management Reviews (MMRs) in Denver (with pre- or post- working sessions on business status, technical issues, etc.); mutual participation in each other's many peer reviews.

(3) People—colleague-to-colleague telecons; JPL representatives on site at LM during key activities (working within contractual restrictions to prevent

unauthorized technical direction or contract changes). People saw themselves as "the GRAIL team" and operated in a quasibadgeless manner.

The principal surveillance tools changed in importance over time, but the most important tools were the personal interactions. A "24-hour rule" allowed LM a short period of time to troubleshoot an issue prior to notifying JPL. LM management could get involved and the issue could be triaged without pressure from the customer, but LM was obligated to provide a candid report to JPL the very next day, even if the concern was not yet under control. Tools emphasized over time were

(1) Early—completion of trade studies, drawings, procurement specs (tangible indicators of progress).

(2) Middle—delivery of hardware elements and software modules (direct impact on project critical path).

(3) Late—weekly ATLO schedule updates, daily status telecons (keeping everyone current in a very dynamic environment).

In the project's Lessons Learned, LM described JPL's "streamlined" and "embedded" surveillance practice as "significant to team cohesion and performance" [11]. More information regarding contract collaboration is available in a recent conference presentation [12].

9. REVIEWS

It was GRAIL's lot to become the first JPL flight project implemented under the then-new NPR 7120.5D SRB process. This had some advantages (e.g., exempt from the new Joint Confidence Level requirement, which went into effect after its project PDR, GRAIL was able to influence the developing practices to some extent). As detailed below, it also had some disadvantages (the project had to deal with an immature schedule assessment activity). Impacts of the new process were felt primarily in the area of reviews and secondarily in the area of gate products and control plans.

Reviews are intended to serve the project first and the external customers and stakeholders second. In practice, GRAIL derived the greatest benefit from internal peer reviews and Technical Interchange Meetings (TIMs), whereas the NASA life-cycle reviews and the JPL institutional reviews largely benefitted other parties. The self-imposed reviews were informal shirt-sleeve working sessions, with review teams including non-project personnel. The results were summarized at the external reviews. Unique to GRAIL was a series of Gravity Modeling Peer Reviews, which tied together lunar gravity knowledge, spacecraft and LGRS error sources, and evolving scientific models, including GRACE experience. The chief benefit GRAIL received from the external reviews was that, as envisioned in the CSR, they served as control milestones for managing the project, a forcing function to make sure the project team completed critical-path work on time (including prereviews, gate products, and open-paper closure).

External reviews were centrally managed by the project office (except launch campaign reviews, which were managed by KSC). A project Review Captain (RC) led the preparation effort for each of the project-managed reviews, beginning with the PMSR, supported by documentation, information technology, logistics, and scheduling personnel. The preparation activity included coordination of prereviews (some required by the institution, others self-initiated), interaction with the SRB (for the NASA life-cycle reviews), outline reviews (invented by GRAIL), dry runs (review practice sessions), and support services for multiple sites. (Some reviews were held by videocon, others by a call-in capability using the Meeting Place application.) In parallel, much attention was paid to commissioning and managing NASA- and JPL-required gate products and control plans, including negotiating, assigning, tracking, reviewing, obtaining signatures, and submitting.

SRB interactions began well in advance of each life-cycle review with regular telecons involving the PM, RC, SRB Chair, SRB Review Manager, and other personnel as appropriate (e.g., NASA Program Executive, NASA Mission Manager, Project Business Manager). Telecons covered negotiation of the Terms of Reference (ToR), which took a very long time due to evolving Agency instructions; top-level agenda for the review with specific required subjects and special topics; prereview documentation delivery schedule (for gate products and advance copy presentation slides); support to SRB independent cost and schedule assessments; SRB members' participation in prereviews; and more.

Most activities went relatively smoothly, but there was a continuing major difficulty involving the SRB's Independent Schedule Assessment (ISA). Because the ISA construct was new to NASA and had not been tested out on any flight project before, GRAIL became the "guinea pig" for the new process. As attempted on GRAIL, the ISA included parametric schedule assessment, health-checking of the project's schedule, and a Schedule Risk Assessment. The immaturity of these methods was demonstrated by the fact that GRAIL completed project PDR and project CDR on or ahead of the originally proposed dates, ultimately launching on day 3 of its 30-day launch window, yet the ISA conclusion after each of those reviews was that GRAIL was less than 50% likely to make launch on time. Additionally, during Phase C/D the ISA conclusions were repeatedly negative while actual EVM data was consistently highly positive. The difference of opinion would not have mattered so much had the project team not been required to devote an extraordinary number of non-value-added work-hours to supporting requests for information, reconciliation telecons, and comparisons of how JPL and LM institutional scheduling practices (part of their certified EVM systems) matched up to the ISA consultants' practices.

Additional information about the project's review activities, including practical examples and aids, is available in three IEEE papers [13].

In the midst of doing all of the necessary project development work in Phase C/D, and supporting all of the external reviews, GRAIL was subjected to a large number of audits. Auditors were from NASA (the NASA Office of Inspector General), other federal agencies (Government Accountability Office [GAO], Defense Contract Audit Agency [DCAA]), Caltech (JPL's parent organization), JPL, and LM. While the GRAIL team concurred with the importance of compliance and realized that each audit had a legitimate purpose, the sum of these audits (GAO's conducted annually) and their inappropriate timing had the effect of taking the project off-line during critical periods. It was not uncommon for different auditors to ask the same questions and request the same data. As a byproduct of GRAIL's technical, schedule, and cost success, the audit organization sometimes specifically sought out GRAIL or was steered to GRAIL by NASA Headquarters. NASA and the auditors were amenable to delaying audits until after a major project review, but the effort required of the project was significant. The Review Captain coordinated the NASA and federal agency audits with assistance from Caltech staff, providing data and answers to questions to the auditors without pulling key personnel off-line wherever possible.

10. Recommendations and Future Applications

Every project is unique, so what worked for GRAIL (and what didn't) is not a precise recipe for other space flight projects, whether sponsored by NASA or by another. However, it is recommended that other projects being conceived consider the positives and negatives in the GRAIL experience and select and tailor those items most applicable to the new mission concept.

Lessons to consider include

(1) Architect a sound concept from conception. Propose what you are going to launch, and launch what you proposed. Limit technology development; have limited and clean interfaces; and use capabilities-based requirements to gain large technical resources margins. Support this with healthy cost and schedule reserves.

(2) Do not change the original level-1 science requirements. Any change has a flow-down effect which gets only greater the further down in the project architecture it needs to be accommodated.

(3) Conduct a comprehensive formulation (pre-commitment) effort. Perform early prototyping of any open technology developments (or significant adaptations). Conduct penetrating inheritance reviews. Make it your goal to have no liens going into Implementation (post-confirmation Authorization to Proceed).

(4) Be agile in implementation (final design and development). Aggressively identify technical problems, and respond to them quickly.

(5) Recruit an excellent team, both key personnel and support personnel. Keep them on the project until their work is done. Consciously incorporate teambuilding events; a "badgeless" team will join together to overcome the tough times that are inherent in any project.

(6) Practice focused project management—not hands-off, but not micromanaging. Begin with an aggressive but achievable schedule. Use life-cycle reviews as control milestones for the entire project team; everyone has to deliver products compatible with their colleagues', and at the same time. Focus on "closing" (e.g., complete trade studies in Phase A, complete open paper in Phase D).

(7) Plan and execute value-added contract surveillance. No one gets to be a "watcher"; the contract monitors need to be embedded in the work activity.

(8) Watch the staffing. Late staff-up puts you behind schedule, as does losing personnel to other programs. Delayed staff-down costs money, and it exacerbates any behind-schedule position.

(9) Watch subcontracts. Place them early. Monitor performance (have some early warning indicators). Provide help as required. Move out early on electronic parts ordering; it is better to order a few parts and need to change them out than to fall off schedule trying to decide what to order.

(10) Enlist management's support in making external reviews nonintrusive and of maximum value. Obtain their help to minimize the number and impact of audits. Supporting non-project work can tie up project resources more than is healthy.

11. Summary

The GRAIL project successfully completed design and development on spec, on schedule, and on cost and is operationally healthy as it heads to the Moon. A review of what worked well and what did not work well from a project management perspective can provide valuable guidance to current and future NASA and other government projects.

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ACKNOWLEDGMENT

The authors acknowledge the contributions of the entire GRAIL project team at MIT, JPL, LM, KSC, GSFC, SRS, subcontractors, and supporting institutions, as well as the support provided by the NASA Science Mission Directorate and the NASA Discovery and New Frontiers Program Office. It is the success of their efforts that this paper strives to summarize.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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