SSC12-II-5

Small Spacecraft Design for the GRAIL Mission

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ABSTRACT

On September 10, 2011, two identical spacecraft were launched from the Kennedy Space Center Space Launch Complex-17B on their 4-month, low-energy trajectory to the moon. The primary objective of the Gravity Recovery and Interior Laboratory (GRAIL) mission was to collect a global gravity map of the moon with a resolution approximately 1000 times better than existing knowledge. Lockheed Martin had the responsibility of designing, developing, assembling, testing, launching, and operating the twin spacecraft. With a dry mass of 200.6 kg each, these GRAIL spacecraft were among the lightest ever to be selected for a NASA Discovery-class mission.

This paper discusses some of key trade studies performed and the resulting design features of these two small spacecraft. Among the areas of discussion are the following:

- Spacecraft architecture and its significant heritage from Experimental Small Satellite #11 (XSS-11)
- Increasing the delta-v capability required for the lunar orbit insertion
- Solar array sizing for the science collection phase
- Mounting position for the Ka-band antenna, one of the key components of the science instrument
- Launch configuration trade study: stacked design vs. side-by-side design
- Spacecraft similarity trade study: mirror image buses vs. identical buses with a rotated science orientation
- Limited redundancy approach and its associated fault protection

This paper also discusses some of the on-orbit performance during GRAIL's primary mission including:

- Spacecraft performance and anomalies
- Science results from the primary mission
- Analysis performed to justify and gain approval for a 6-month extended mission

Not only have the GRAIL spacecraft returned a wealth of scientific data, but they paved the way for future Lockheed Martin small satellite applications including an entry in NASA's Rapid Spacecraft Development Office (RSDO) catalog.

INTRODUCTION

GRAIL is a two-spacecraft lunar gravity mapping mission led by Dr. Maria Zuber of the Massachusetts Institute of Technology (MIT). The project was managed by the Jet Propulsion Lab (JPL) under the leadership of David Lehman, Project Manager. The primary payload was the Lunar Gravity Ranging System (LGRS) developed by JPL. Lockheed Martin's responsibility was the design, development, assembly, test, launch, and operations of the twin spacecraft.

The GRAIL mission proposal was submitted to NASA in June 2007 and awarded in November 2007. One of the basic mantras of the GRAIL proposal was high value science for both low cost and low implementation risk. Several of the spacecraft design features were specifically chosen to minimize mass and other resources. The twin spacecraft launched on September 10, 2011 and successfully completed their primary missions on May 29, 2012. The spacecraft have just begun their extended missions which will extend through December 7, 2012.

SCIENCE OVERVIEW

A NASA Discovery-class mission, GRAIL will unlock the mysteries of the moon by mapping the lunar gravitational field globally to unprecedented accuracy and resolution. In essence, it will peer deep inside the moon to reveal its internal structure and thermal history. Knowledge acquired about the moon from GRAIL will be extended to understand the broader evolutionary histories of the other rocky planets in the inner solar system: Earth, Venus, Mars, and Mercury. The moon is a linchpin for understanding how the terrestrial planets evolved.

Per the GRAIL project-level documentation, the mission has two primary goals:

- Determine the structure of the lunar interior, from crust to core;
- Advance understanding of the thermal evolution of the moon;

and one secondary goal:

- Extend knowledge gained from the moon to the other terrestrial planets.

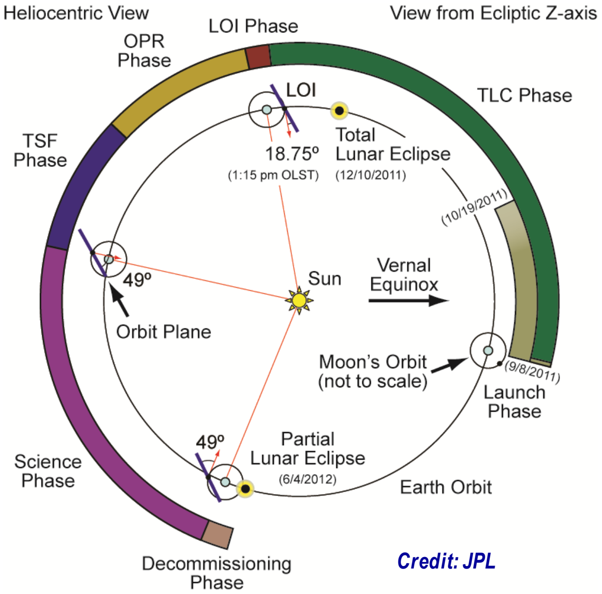
GRAIL was implemented using an Lockheed Martin-designed spacecraft and a JPL-provided science payload derived from the very successful Gravity Recovery and Climate Experiment (GRACE) mission. GRAIL placed twin spacecraft (referred to as GR-A, or *Ebb*, and GR-B, or *Flow*) in a low-altitude (~55 km), near circular, polar lunar orbit to perform high-precision range-rate measurements between them using a Ka-band payload. Subsequent analysis of the spacecraft-to-spacecraft range-rate data provided a direct measure of the lunar gravity. The GRAIL science team then utilized the gravity data collected and executed the following six investigations:

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
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

Science investigations 1 through 4 are considered the science floor, or threshold requirements. When added to the science floor, investigations 5 and 6 yield the full science, or baseline requirements.

MISSION DESIGN OVERVIEW

GRAIL's mission design for the primary 9-month duration was developed by JPL. There were seven unique mission phases as depicted in Figure 1.



Credit: JPL

Figure 1. Heliocentric View of the Primary Mission

Launch Phase

The 42-day launch period spanned from September 8, 2011 and to October 19, 2011. GRAIL was launched on the third day of this period after two days of weather delays. The GRAIL spacecraft separated from the Delta-II second stage shortly after the completion of the trans-lunar injection burn. The GR-A and GR-B separation events occurred approximately eight minutes apart. Initial acquisition occurred over the Goldstone DSN complex followed by the solar array deployments.

Trans-Lunar Cruise (TLC) Phase

The TLC trajectory was designed with a low-energy transfer to the moon via the Sun-Earth Lagrange point #1. Compared to an Apollo-like direct trajectory, the low-energy trajectory had the advantage of longer launch period, lower spacecraft delta-v, and longer TLC duration. For GRAIL, the extended TLC duration was beneficial because it allowed time to complete spacecraft out-gassing and it enabled the payload ultra-stable oscillator to reach a constant temperature prior to the start of science. Five trajectory correction maneuvers were executed per S/C during TLC.

Lunar Orbit Insertion (LOI) Phase

The GR-A and GR-B LOI maneuvers were executed about a day apart on Dec 31, 2011 and Jan 1, 2012, respectively. The burns successfully captured the spacecraft into near-polar, elliptical orbits about the moon with a period of about 11.5 hours.

Orbit Period Reduction (OPR) Phase

The purpose of the OPR phase was to reduce the orbit period from 11.5 hours to about 1.9 hours and to align both spacecraft in the same orbit plane. OPR phase included seven delta-v maneuvers per S/C.

Transition to Science Formation (TSF) Phase

The primary activity during TSF was the fine-tuning of the orbital conditions necessary for the collection of gravity science data. At the end of TSF phase, the attitude was changed from a sun-pointed orientation (which it had maintained throughout the mission) to an orbiter-to-orbiter attitude where each spacecraft points its Ka-band antenna at the partner probe.

Science Phase

At the start of the Science phase the GRAIL spacecraft were in a near-polar, near-circular orbit with a mean altitude of approximately 55 km. During the subsequent 82-day Science phase, the moon rotated slightly more than three times underneath the GRAIL orbit. The collection of gravity data over one complete rotation (27.3 days) was referred to as a mapping cycle. A separate drift was intentionally set up to vary the range between the two spacecraft from 84 km to 216 km. This technique maximized the probability of satisfying the different science investigations.

In addition to the Ka-band spacecraft-to-spacecraft range data, S- and X-band gravity measurements were made using the Doppler data via tracking of the spacecraft by the ground stations of the Deep Space Network (DSN). The purpose of these measurements is the determination of the absolute position of the two spacecraft. While the inter-spacecraft Ka-band ranging provides an accurate measurement of the relative spacecraft range, it does not provide a very accurate absolute position relative to the moon. The Science phase was successfully completed on May 29, 2012.

Decommissioning Phase

The Decommissioning phase was scheduled to follow the end of the Science phase and provided for the orderly disposal of the two spacecraft. The original Decommissioning approach was to allow the twin probes to impact the moon prior to the partial lunar eclipse on June 4, 2012. However, the recently approved extended science mission (discussed later in this paper) caused the Decommissioning phase to be delayed until December 2012.

SPACECRAFT DESIGN PROCESS

As illustrated in Figure 2, the Lockheed Martin spacecraft design process is iterative, consisting of four primary steps: analyze requirements, perform trade studies, define design, and verify solutions. This simple but powerful process was used successfully on GRAIL to design and maintain a spacecraft configuration that was able to meet the unique needs of a lunar gravity mapping mission.

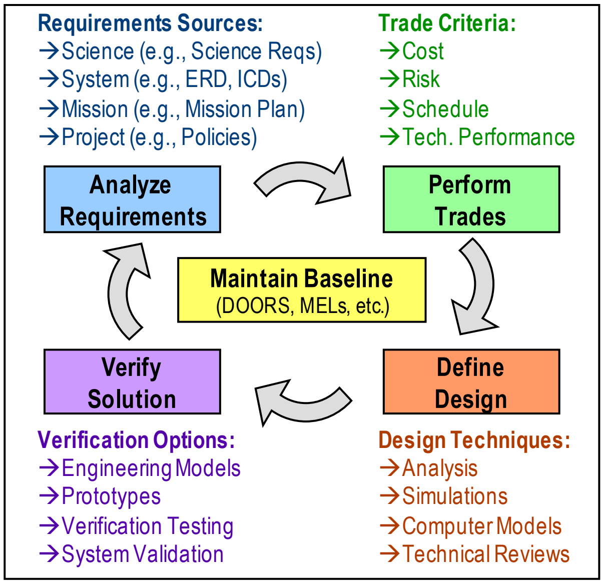


Figure 2. Interactive Spacecraft Design Process

Step 1. Analyze Requirements

The requirements derivation process was critical to spacecraft development. Missed, incomplete, or incorrect requirements would have adversely affected design, complexity, test, and verification. Requirements derivation and flow-down for GRAIL began with systems engineering performing requirements analysis to decompose higher-level requirements to lower levels. This process required support from all subsystem teams to ensure complete allocation. Tabletop reviews were conducted with representatives from each subsystem to ensure all affected areas were identified. After the reviews, any changes were documented to maintain traceability and control.

To develop the conceptual design, the systems engineering team used the requirements contained in all applicable sources including GRAIL's environmental requirements document (ERD), JPL project policies, the launch vehicle interface control document (ICD), the mission plan, and the instrument ICDs. See Table 1 for some of the major driving requirements on the spacecraft.

Table 1: Spacecraft Key Driving Requirements

Key Requirement	Value	Source
Spacecraft Dry Mass, each	≤ 226.0 kg	Launch Vehicle
Science Data Downlink	≥ 3.6 MB/day	Science
CM to Ka Antenna Boresight	≤ 3.0 cm	Science
Thermal-induced Structural Motion	≤ 15.0 μm/orbit	Science
Ka Antenna Temperature Stability	≤ ±3.0 °C/orbit	Science
Formation Flying Attitude Control	≤ 1.0 mrad/axis	Science
Articulating Components	Not Allowed	Science
Total Mission Delta-V	≥ 850.0 m/sec	Mission Design
Mission Lifetime	≥ 9 months	Mission Design
Science Orbit Mean Altitude	≥ 55.0 km	Mission Design
Solar Array Power (end of life)	≥ 700 W at 1AU	Mission Design

Step 2. Perform Trade Studies

The spacecraft development process requires numerous trade studies early in the lifecycle to choose design options that meet the mission requirements while staying within the resources of the Discovery program. All told, nearly 30 trade studies were performed by the GRAIL spacecraft team to drive out the final configuration of the flight system. Listed below are some of the most critical trades.

Spacecraft Architecture.

One of the earliest decisions for the development team was the question of spacecraft architecture. Normally, the team endeavors to make extensive use spacecraft heritage to keep down the design cost and to reduce risk. There were numerous spacecraft bus options to consider as the GRAIL point of departure. These bus options included previous NASA missions under the Discovery program office (e.g., Genesis, Stardust) and Mars program office (e.g., Mars Odyssey, Mars Reconnaissance Orbiter). There was an additional bus option from an AFRL mission known as Experimental Small Satellite #11 (XSS-11). This XSS-11 bus was a lightweight design with a low coefficient of thermal expansion that resists mechanical distortions during environmentally-induced temperature changes.

The various bus options were assessed against the key driving requirements. Table 2 shows the color-coded results of the trade (green=compliant; yellow=minor change required; red=major design obstacle). The table illuminates the XSS-11 bus as the most applicable point of departure. Of course, this is not meant to suggest that the XSS-11 bus would fly unchanged. The GRAIL team was fully aware that design changes would be required to implement some of the unique aspects of the lunar gravity mission. Many of these design changes are discussed later in this paper.

Table 2: S/C Architecture Trade Results

Key Requirement	Value	Stardust	Genesis	Odyssey	MRO	XSS-11
Spacecraft Dry Mass, each	≤ 226.0 kg	G	Y	Y	R	G
Science Data Downlink	≥ 3.6 MB/day	G	G	G	G	G
CM to Ka Antenna Boresight	≤ 3.0 cm	G	R	G	G	G
Thermal-induced Structural Motion	≤ 15.0 μm/orbit	G	G	G	Y	G
Ka Antenna Temperature Stability	≤ ±3.0 °C/orbit	G	Y	G	G	G
Formation Flying Attitude Control	≤ 1.0 mrad/axis	Y	R	Y	Y	G
Articulating Components	Not Allowed	G	G	Y	Y	G
Total Mission Delta-V	≥ 850.0 m/sec	R	R	G	G	Y
Mission Lifetime	≥ 9 months	G	G	G	G	G
Science Orbit Mean Altitude	≥ 55.0 km	G	R	G	G	G
Solar Array Power (end of life)	≥ 700 W at 1AU	Y	R	G	G	Y

Delta-V Capability.

XSS-11 had an innovative warm gas system to provide precision control necessary for its mission which was necessary for the tight formation flying requirements of the lunar orbit. However, the total delta-v capability was one area where the XSS-11 spacecraft bus was not adequate for GRAIL. Because it was designed for Low Earth Orbit, the total delta-v capability of XSS-11 was about 200 m/sec short of the 850 m/sec required by GRAIL to capture into lunar orbit. There were two options considered for increasing the delta-v:

A. Mounting two XSS-11-like buses on a common propulsion stage. The single propulsion module would complete the lunar orbit insertion and then individually release the two spacecraft into their final formations around the moon. In this option, the bus changes to XSS-11 would be minimized, but an entirely new propulsion module would need to be developed.

B. Increasing the delta-v capability of each spacecraft. This would entail separating each spacecraft from the launch vehicle individually, and flying each bus to the moon independently. Each vehicle would perform its own trajectory correction maneuvers and lunar orbit insertion burns. In this option, the XSS-11 fuel tank would be replaced with a larger one (with a capacity of 106 kg of hydrazine) and the bus would be stretched by approximately 12 cm to accommodate it.

The trade matrix for the two options is shown in Table 3, with green shading used to depict the preferred option for each parameter. Option B was the clear winner and was selected early in the development as the final implementation.

Table 3: Trade Matrix for Increased Delta-V

Trade Parameter	Option A	Option B
Ease of Launch and Cruise Operations	1 S/C operations	2 S/C operations
Number of Separation Mechanisms	2 Lightbands, 1 LV system	2 Lightbands
Number of Propulsion Modules	2 mono-prop, 1 bi-prop	2 mono-prop
Maximum Use of Heritage	Requires new propulsion stage	Larger fuel tank and minor bus stretching
Simplicity of Integration and Test	2 S/C plus prop stage	2 S/C
Solar Array Deployment	Deploy while joined	Independent deployments
Control vs. Non-Control S/C During Cruise and LOI	GR-A master, GR-B slave	Each S/C is independent
Overall Risk	Higher	Lower
Overall Cost	Higher	Lower

Solar Array Sizing.

As shown previously in Table 2, the XSS-11 solar arrays were undersized for the GRAIL power requirements. The solar array power production was increased by about 60% (from ~500W on XSS-11 to ~800W on GRAIL) simply by increasing the size of the two solar arrays. Fortunately, the baselined solar array mechanisms had ample margin to accommodate the larger arrays without any changes. Furthermore, there was ample volume available in the launch vehicle fairing.

Ka-band Antenna Mounting.

The next major design decision was the mounting orientation of the Ka-band antenna. The Ka-band antenna is the component of the LGRS instrument that points from one spacecraft to the other during the gravity measurement process. Through minute frequency changes and precision time-tagging, the Ka-band signal is converted to a change in range between the two spacecraft, which is later converted into a measurement of the lunar gravity. Due to the micron-level precision of the orbiter-to-orbiter ranging measurements, spacecraft-induced error sources must be minimized. One such error source is Ka-band antenna displacement along the line-of-sight to the partner spacecraft caused by attitude control errors in pitch and yaw. The magnitude of the displacement is proportional to the distance between the boresight of the Ka-band antenna and spacecraft center of mass (CM).

The original spacecraft design had the Ka-band antenna mounted inside the main bus above the fuel tank, approximately 50 cm from the CM. A small hole was cut in the spacecraft side panel to afford an appropriate view to the other spacecraft to enable the ranging measurements. See Figure 3 for an illustration of the original antenna mounting.

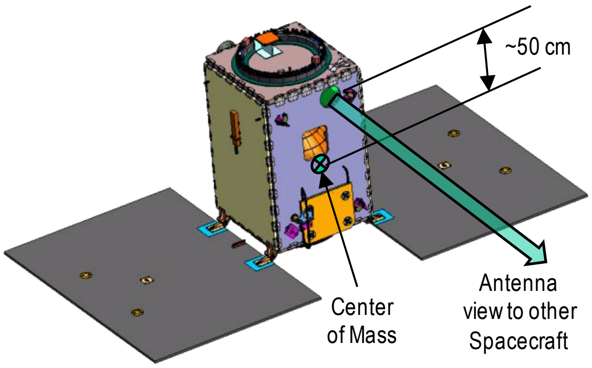


Figure 3: Ka-band Antenna ~50 cm from CM

It became apparent during the early development that this configuration would cause unacceptable errors in the gravity measurements. The design team realized that the Ka-band antenna had to be relocated nearer to the spacecraft CM. Unfortunately, the interior of the bus was almost completely consumed by the larger fuel tank. The solution was to mount the Ka-band antenna on the exterior panel of the spacecraft on the opposite side, very close to the predicted CM. The revised mounting is depicted in Figure 4.

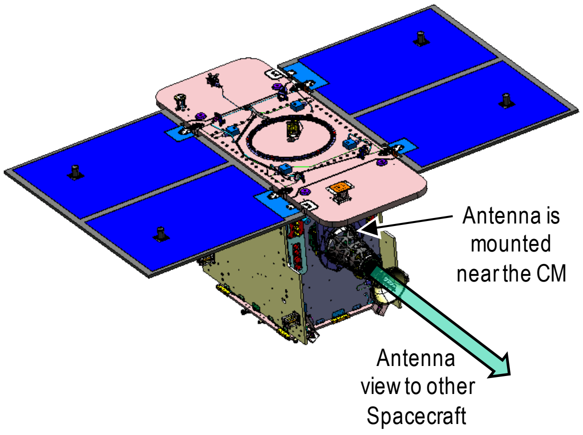


Figure 4: Revised Antenna Mounting Near the CM

Launch Configuration.

Early in the development lifecycle, the twin GRAIL spacecraft were designed to be launched in a stacked configuration within the Delta-II fairing as shown in Figure 5.

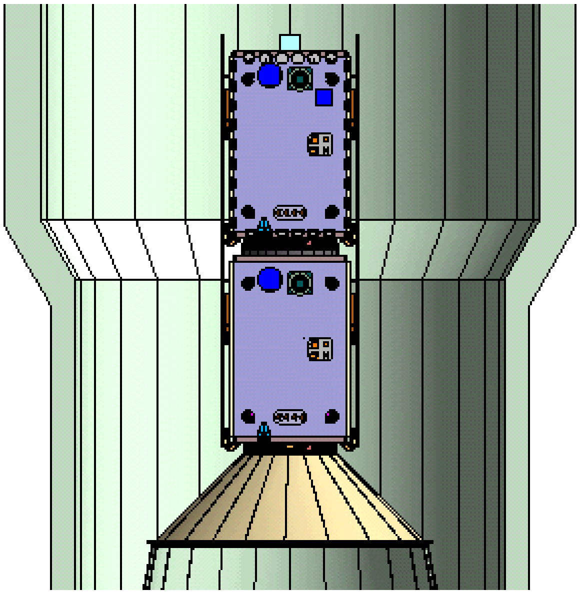


Figure 5: Original Stacked Launch Configuration

However, as the design team members began further analysis on this launch configuration they identified a number significant drawbacks. As a trade option, a side-by-side configuration was considered as illustrated in Figure 6.

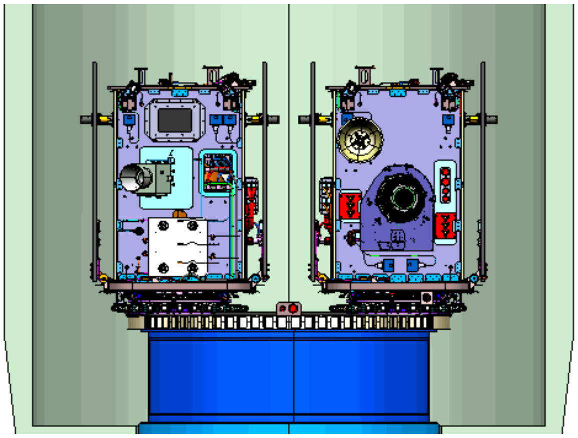


Figure 6: Alternate Side-by-Side Configuration

The analysis of the side-by-side configuration revealed numerous advantages over the stacked design (see Table 4). The only two notable disadvantages were: a) additional harnessing by the Delta-II launch vehicle provider to provide individual separation signals for GR-A and GR-B, and b) additional dynamic analysis by Lockheed Martin required to confirm that the two spacecraft would not re-contact one another during the deployment sequence. Since neither of these disadvantages was deemed to be prohibitive, the side-by-side configuration was adopted as the new baseline.

Table 4: Advantages of Side-by-Side Configuration

Subsystem	Advantages of Side-by-Side Configuration
Command & Data Handling	• Eliminates C&DH hardware modifications required to perform the GR-A to GR-B separation
Power & Harness Subsystems	• Launch umbilical design identical for GR-A & GR-B • Solar array aspect ratio is easier to change • Eliminates Power hardware modifications required to perform the GR-A to GR-B separation
Flight Software	• Eliminates changes to heritage launch sequences • Eliminates flight software modifications required to perform the GR-A to GR-B separation
Structure	• Less strengthening of the vehicles required • Vehicles will be identical except for payload • Reduced load factors on Delta-II
Mechanisms	• Can use XSS-11 heritage separation system
Telecom	• Eliminates GR-A antenna obstruction during launch
Thermal	• GR-A payload deck can be used as radiator • Payload thermal control can be more similar
Assembly, Test, and Launch Ops	• Reuse of test products, equipment, and processes • Expands flexibility and reduces handling risk • Enables real parallel assembly and test operations • Easier system-level environmental test operations

Spacecraft Similarity.

The gravity measurement technique on GRAIL (inherited from GRACE) requires that the two Ka-band antennas be precisely pointed at one another with one antenna pointed forward and the other pointed aft. Furthermore, GRAIL's orbit requires that the normal vector of fixed solar arrays be precisely aligned with the orbit normal in the sunward direction.

This unique formation flying orientation led to the next spacecraft design trade which centered on the similarity of the two spacecraft. The two options identified by the design team were:

A. Mirror Image Spacecraft. This option (depicted in Figure 7) entails designing a left-looking GR-A spacecraft shown on the right side and a mirror image GR-B spacecraft that looks to the right. Notice that the green conical Ka-band antennas are actually mounted on different panels on the two spacecraft.

B. Identical Spacecraft. This option (illustrated in Figure 8) uses an identical design for each spacecraft, but the two GRAIL orbiters fly in orientations that are 180° rotated from one another. In other words, GR-A operates with its +Y axis pointed at zenith, while GR-B flies with its +Y axis at nadir.

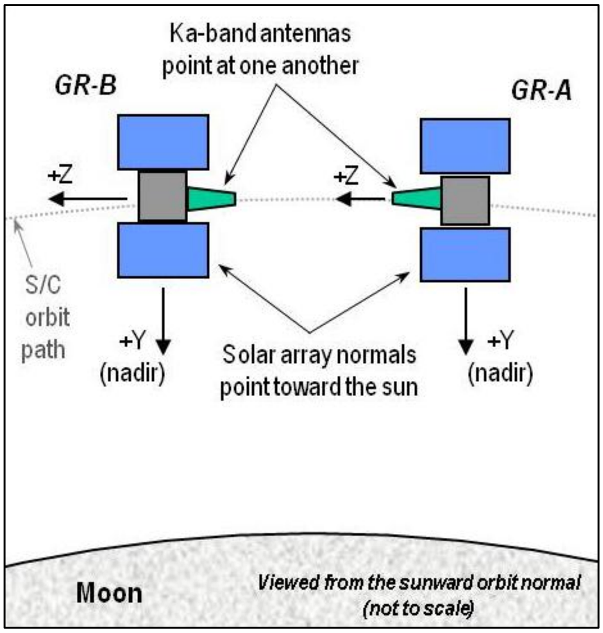


Figure 7: Science Collection with Mirror Image S/C

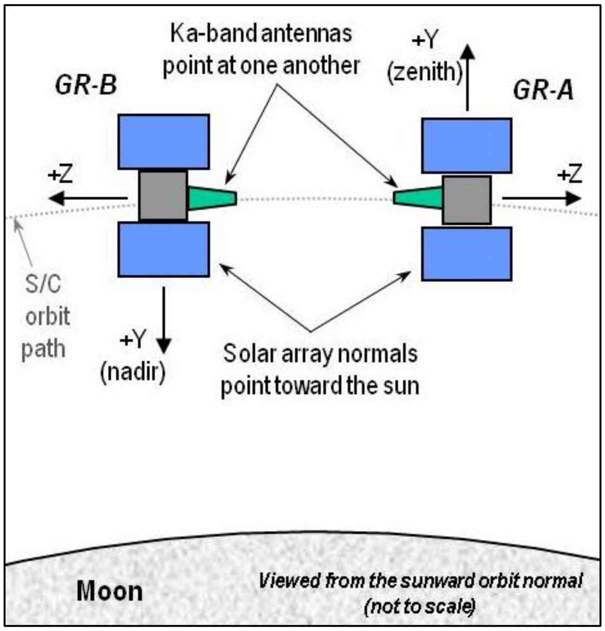


Figure 8: Science Collection with Identical S/C

The trade matrix for this decision is shown in Table 5 with green shading shown to depict the most favorable option for each criterion. From a pure design standpoint, either option was satisfactory because each met the spacecraft requirements. However, from an implementation perspective including cost and schedule, there was a clear advantage to identical spacecraft.

Table 5: Spacecraft Similarity Trade Matrix

Trade Parameter	Option A	Option B
Harness Design for Payload	Different	Identical
Flight Parameters	Identical	Minor mods
Additional Structural Drawings	7	0
Interchangeability	No	Yes
Payload Brackets	Different	Identical
Ballast Mass Impacts	5.6 kg	0 kg
Nadir Thermal Designs	Identical	Different
Number of Thermal Models	2	1
Ground Support Equipment	Minor mods	Identical
System-level Acceptance Tests	Different	Identical

The word "identical" is a slight misstatement because there are a few minor differences between the two spacecraft. These are necessitated by the 180° rotation in the science orientation. The design differences are:

- Ka-band antennas have a 2° cant in opposite directions
- Star trackers are canted in opposite directions
- Camera heads are mounted on different sides of the payload panel
- Thermal radiators/blankets are different on the nadir and zenith panels
- Minor differences in some flight software parameters

Redundancy.

One unique aspect of GRAIL was the extremely short mission duration of 9 months. With limited exceptions, all spacecraft and payload components had previously demonstrated much longer in-flight performance on other missions. Moreover, the GRAIL ERD specified benign radiation conditions at the moon. Based on all these factors, GRAIL was proposed as a single-string mission consistent with the XSS-11 baseline. XSS-11's single-string approach is not uncommon for the AFRL, especially for a technology demonstration mission. However, this strategy is rare for a NASA Discovery-class mission. Fortunately, NASA lauded the single-string approach as an innovative cost-reducing measure and concurred with the project assessment that it would not significantly increase GRAIL's mission risk.

Fault Protection.

With only rare instances of component redundancy, the GRAIL Fault Protection (FP) required some changes to work in a single-string application. As with previous Lockheed Martin spacecraft in this family, the FP consists of three tiers: component-level, performance-level (aka subsystem-level), and system-level (aka high level FP). Generally, faults are detected and resolved at the lowest possible level, and then elevated to higher levels only if necessary. At the top of the hierarchy are Safe Mode and other executive FP functions.

It may seem that component-level FP has minimum utility on a single-string platform, but that is not the case. While it is true that a component swap is not possible, there are other prudent steps such as power-cycling the component or resetting its interface to the flight computer. Furthermore, component-level FP is critical for detecting the fault even it cannot be resolved at that level. As faults are elevated to higher levels, responses such as Safe Mode, warm computer resets, and cold computer reboots are possible.

The requirement to reduce thermal perturbations during GRAIL science collection necessitated two key changes to system-level FP. The first was a change in the Safe Mode attitude during Science phase. Rather than having the spacecraft slew directly to a sun-pointing attitude, the Safe Mode was altered to allow the spacecraft to remain in its science orientation pointing at the other orbiter. The second change to Science phase Safe Mode was a change in the power load-shedding response. Normally, all payload elements are powered off during a Safe Mode entry, but this response would adversely affect the thermal stability of the instruments. The decision was made to leave the payload components powered on during Safe Mode except in extreme cases.

All of these FP changes were tested extensively as part of the flight software acceptance test program. The successful complete of the test program provided extreme confidence to the team that the necessary FP safeguards were in place for GRAIL.

Step 3. Define Design

With all the key trade studies resolved, the system and subsystem engineers began further definition of the baseline designs. This was accomplished through use of analyses, detailed simulations, computer modeling, and technical reviews. GRAIL's successful Preliminary Design Reviews at the end of Phase-B provided the confidence that the design was sound. The Critical Design Reviews at the end of Phase-C served as the final definition of the spacecraft design.

Step 4. Verify Solution

The design solutions were routinely verified using engineering models, hardware prototypes, verification tests, and a comprehensive system validation program. All verification events were tracked in the Dynamic Object Oriented Requirements System (DOORS) to track compliance with the requirements. The final spacecraft design is shown in detail in Figure 9 and Figure 10.

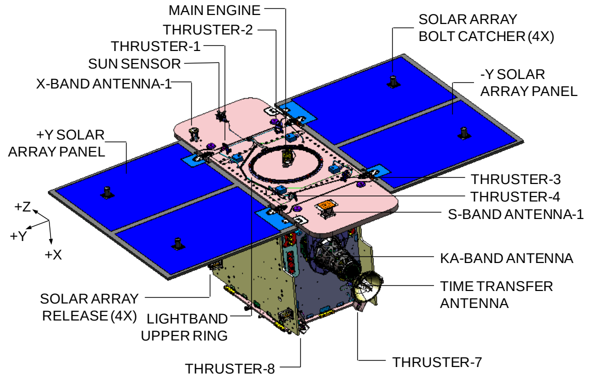


Figure 9: Final Spacecraft Design (bottom view)

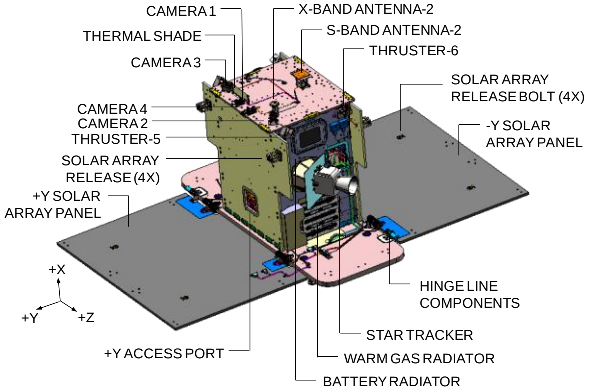


Figure 10: Final Spacecraft Design (top view)

PROGRAMMATIC MILESTONES

As with all planetary missions, rigorous adherence to the key project milestones was critical to make the launch period. All milestones during the spacecraft development lifecycle occurred on their originally scheduled dates as baselined in the June 2007 proposal to NASA. This schedule performance bolstered the project's confidence and kept the external oversight to a minimum. The key milestones were:

- Jan 15, 2008 Lockheed Martin begins Phase-B
- Nov 11, 2008 Preliminary Design Review
- Nov 09, 2009 Critical Design Review
- Jun 21, 2010 System Integration Review
- Nov 09, 2010 Environmental Test Readiness Review

- May 05, 2011 Pre-Ship Review
- Sep 10, 2011 Launch (third day of the launch period; first two were scrubbed due to weather)
- Oct 12, 2011 Post-Launch Assessment Review
- Dec 31, 2011 GR-A Lunar Orbit Insertion
- Jan 1, 2012 GR-B Lunar Orbit Insertion
- May 29, 2012 Primary Mission Completed

PRIMARY MISSION S/C PERFORMANCE

GRAIL's primary mission ended on May 29, 2012. The performance of both GR-A and GR-B was outstanding. In all, 28 delta-v maneuvers were successfully executed between the two orbiters. There were no major anomalies in flight, and only a handful of minor issues. Some of the noteworthy minor anomalies were:

- Mis-modeling of –X panel temperatures
- Bias shift on the low pressure transducers during the repressization pryo event
- Uplink errors due to an apparent multi-path condition caused by the lunar surface
- Single event upset susceptibility by the commercial camera system

None of the anomalies resulted in any loss of science data and there were no Safe Mode entries on either S/C.

PRIMARY MISSION SCIENCE RESULTS

According to a JPL/NASA press release on May 29, 2012, the GRAIL spacecraft completed their primary mission earlier than expected. The press release states:

> *The GRAIL mission has gathered unprecedented detail about the internal structure and evolution of the moon. This information will increase our knowledge of how Earth and its rocky neighbors in the inner solar system developed into the diverse worlds we see today.*
>
> *"GRAIL delivered to Earth over 99.99 percent of the data that could have been collected, which underscores the flawless performance of the spacecraft, instrument and the Deep Space Network," said Zuber.*

In summary, the science threshold requirements (i.e., science objectives 1 through 4) have been achieved. Science analysis continues on objectives 5 and 6, and the team is optimistic that these requirements will be satisfied based on current data quality assessments.

EXTENDED MISSION

Under the leadership of Maria Zuber (MIT) and David Lehman (JPL), the GRAIL project submitted an extended mission proposal to NASA on February 20, 2012. About a month later, NASA approved the extension at the full funding level. The extended mission design, which includes a partial lunar eclipse on June 4, 2012, is depicted in Figure 11.

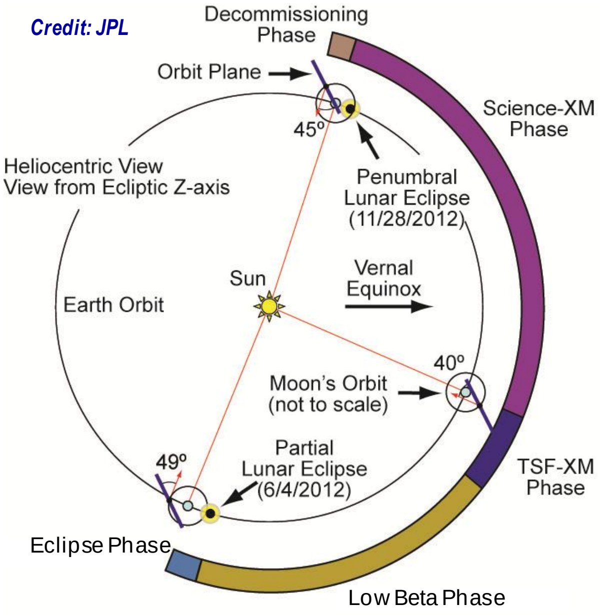


Figure 11: Heliocentric View of Extended Mission

The spacecraft systems and subsystems engineers thoroughly analyzed the extended mission design and concluded that there are no spacecraft limitations that would preclude its successful execution. There are three main areas where the team focused its analyses: a) lunar eclipse survival, b) low-altitude science operations, and c) the lengthened mission duration. Each focus area is discussed below. One key attribute of the extended mission is that it requires no mission-critical events. All such events (launch, orbit insertion, pyro events, and propulsion repressurizations) have already been successfully completed. In fact, there are no events required in the extended mission that were not routinely performed during the primary mission. In short, operations during the extended mission are low risk.

Lunar Eclipse Survival

Using the worst-case eclipse phasing data provided by the GRAIL mission design team, the spacecraft team collectively developed a baseline spacecraft configuration to use prior to and during the lunar eclipse. The goal was to use mission phases, operating modes, and other parameter settings that had been previously checked out during the primary mission. The thermal team performed a detailed assessment of the component temperatures to ensure that they will remain within acceptable ranges and satisfy payload derived stability requirements. The team also used its thermal model to calculate a worst-case heater power during the lunar eclipse. Using these average power loads and the baseline spacecraft configuration assumptions, the power subsystem performed detailed battery analysis of the lunar eclipse. Results show that the worst-case depth-of-discharge will be well below the limit allowed by FP. In fact, the eclipse depth-of-discharge will be only slightly higher than the LOI depth-of-discharge, the highest flight level to date.

Low Altitude Science Operations

There have been no spacecraft anomalies during the primary mission that jeopardize the completion of the extended mission. The complexity of the spacecraft operations during the low-attitude science operations will be no greater than the TSF phase, and therefore is within proven capabilities. All operational procedures and contingency plans are in place from the primary mission Science phase and are flight-proven. There are no changes to existing sequence designs, onboard command blocks, telemetry and command dictionaries, or ground software required for the extended mission.

Lengthened Mission Duration

Extending the mission by an additional six months poses no threats to any of the spacecraft components. This is because GRAIL's 9-month primary mission duration was already well below known life-limitations. All components were compared against their flight limits and shown to have adequate margin to complete the extended mission. The lone exception was the reaction wheels where additional vendor life-testing using the qualification model was funded in March 2012 and is expected to demonstrate an increased flight limit of 3.6 billion revolutions.

CONCLUSION

The GRAIL mission has been extremely successful, and the innovative design of the two lightweight spacecraft was a key contributor. A rigorous spacecraft design process which incorporated iterative improvements enabled an on-time and on-schedule development lifecycle. The on-orbit performance of these small orbiters exceeded all requirements and allowed the threshold science requirements to be achieved on May 29, 2012, far earlier than anticipated. Based on the success of the primary mission, GRAIL was recently awarded an extended mission by NASA which will run through December 2012.

ACRONYMS AND ABBREVIATIONS

AFRL	Air Force Research Laboratory
aka	also known as
CM	Center of Mass
DOORS	Dynamic Object Oriented Requirements System
DSN	Deep Space Network
ERD	Environmental Requirements Document
FP	Fault Protection
GR-A	GRAIL-A spacecraft, or Ebb
GR-B	GRAIL-B spacecraft, or Flow
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
ICD	Interface Control Document
JPL	Jet Propulsion Laboratory
LV	Launch Vehicle
LGRS	Lunar Gravity Ranging System
LOI	Lunar Orbit Insertion
MAVEN	Mars Atmosphere and Volatile Evolution
MEL	Master Equipment List
MGS	Mars Global Surveyor
MIT	Massachusetts Institute of Technology
mods	modifications
MRO	Mars Reconnaissance Orbiter
MTO	Mars Telecommunications Orbiter
NASA	National Aeronautics and Space Administration
OPR	Orbit Period Reduction
RSDO	Rapid Spacecraft Development Office
S/C	spacecraft
TLC	Trans-Lunar Cruise
TSF	Transition to Science Formation
XSS-11	Experimental Small Satellite #11
XM	Extended Mission

ACKNOWLEDGEMENTS

The author would like to acknowledge Dr. Maria T. Zuber (GRAIL Principal Investigator) and Dr. David E. Smith (GRAIL Deputy Principal Investigator) from the Massachusetts Institute of Technology.

The author would like to acknowledge David H. Lehman (GRAIL Project Manager), Tom L. Hoffman (GRAIL Deputy Project Manager), and the rest of the GRAIL team from the Jet Propulsion Laboratory.

Most importantly, the author would like to acknowledge John W. Henk (GRAIL Spacecraft Manager) and all the talented men and women at Lockheed Martin Space Systems Company that worked on the GRAIL program—your performance, commitment, and dedication were unparalleled! Congratulations on your remarkable achievements—***be proud!***

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