SSC13-X-2

NASA's GRAIL Spacecraft Formation Flight, End of Mission Results, and Small-Satellite Applications

Christine Edwards-Stewart
Lockheed Martin Space Systems Company
P.O. Box 179, Denver, CO 80127   303-977-5302
christine.m.edwards@lmco.com

ABSTRACT

The Gravity Recovery and Interior Laboratory (GRAIL) mission was composed of twin spacecraft tasked with precisely mapping the gravitational field of Earth's Moon. GRAIL science collection required that the two spacecraft operate in the same orbit plane and with precise relative separation and pointing, which evolved through the primary and extended mission Science phases. Because of the relatively small size of the GRAIL spacecraft compared to other exploration missions, and the implementation of formation flight operations, lessons learned from this mission are applicable to future small-satellite missions. A description of the formation flight approach that was implemented on the GRAIL spacecraft will be accompanied by a presentation of flight results and discussion of small-satellite applications.

INTRODUCTION

The GRAIL project was a NASA Discovery Program mission consisting of two spacecraft developed and operated by the Lockheed Martin Space Systems Company. The project was managed by the Jet Propulsion Laboratory (JPL) and was led by Principal Investigator Maria Zuber at the Massachusetts Institute of Technology (MIT). On December 31, 2011, and January 1, 2012, New Year's Eve and New Year's Day, the twin GRAIL spacecraft entered lunar orbit to begin the mission of investigating the Moon 'from crust to core' by developing a high-resolution gravity map. The two spacecraft, named Ebb and Flow and commonly referred to as GRAIL-A and GRAIL-B, weighed 133 kg each. They flew in formation with a separation of 175–225 km in a low-altitude polar orbit with an average altitude of 55 km during the primary mission. The mission was extended in late 2012; and in order to increase science fidelity, the orbital altitude was decreased to as low as 11 km with a separation of 40 km. During the primary and extended science missions that were completed in 2012, high-precision spacecraft-to-spacecraft range measurements enabled the mapping of the global lunar gravity field to unprecedented resolution. Measurements were collected using an inter-spacecraft link between two on-board payloads. When linked, the payloads utilized the signal carrier phase to measure the range between GRAIL-A and GRAIL-B payloads within a few micrometers. Figure 1 shows an artist portrayal of the GRAIL spacecraft, with a gravity map overlaid on the Moon.

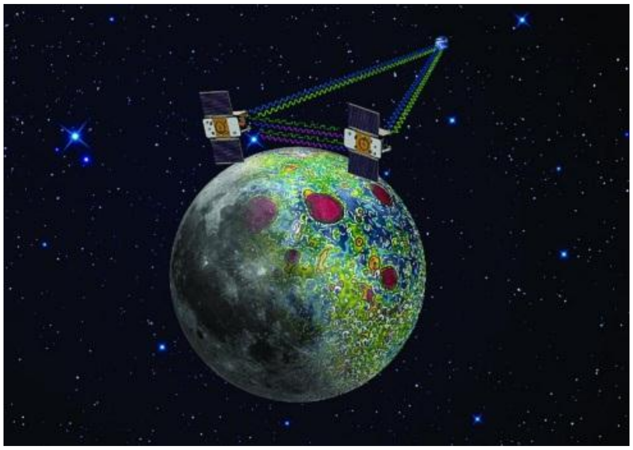


Figure 1: Artist Portrayal of GRAIL Spacecraft with Lunar Gravity Map[1]

Figures 2 and 3 show orbital timelines of both GRAIL missions. During each Science Phase, the spacecraft payloads could be pointed at each other to make ranging measurements while still maintaining a power positive attitude. During the remaining phases, the spacecraft were put into a Sun-pointing mode, and the spacecraft team performed activities to prepare for the next science phase of the mission. This document will focus on the science phase operations. More information on the other phases can be found in Reference 2.

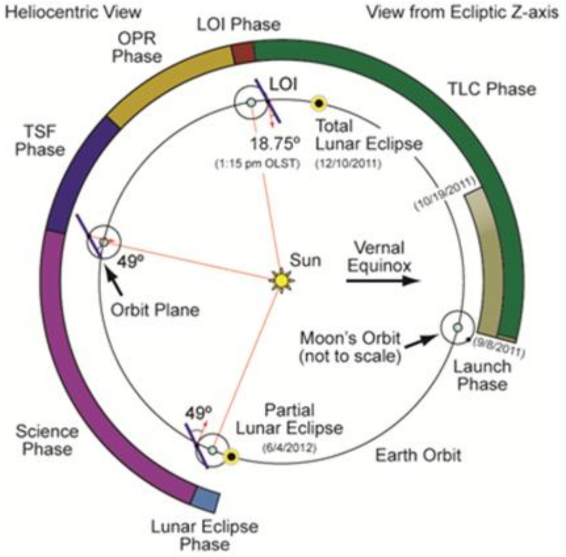


Figure 2: Primary Mission Phases[1]

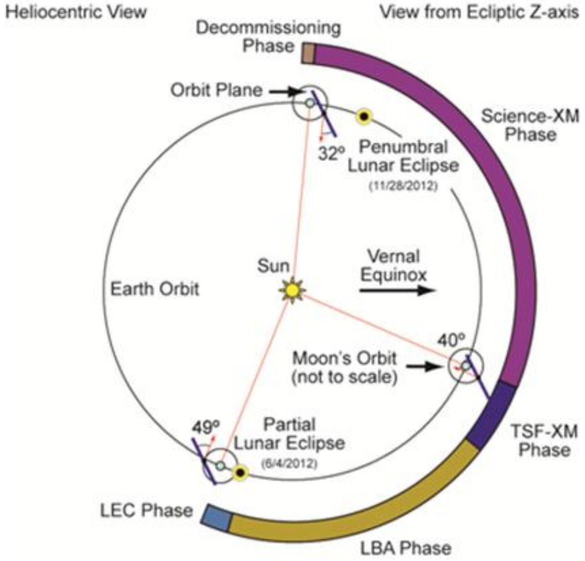
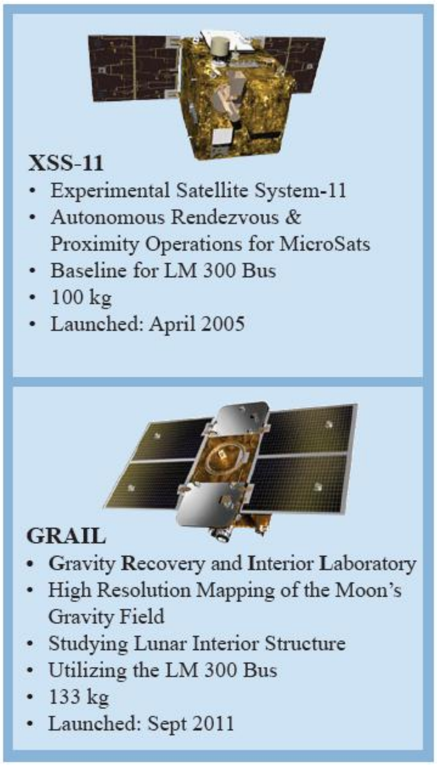


Figure 3: Extended Mission Phases[1]

The next section discusses how the GRAIL spacecraft design was matured from previously-developed small-satellite technology. Then follows a discussion of the formation-flight applications of the GRAIL mission that provided lessons learned for future small-satellite missions.

OVERVIEW OF GRAIL DESIGN EVOLUTION FROM SMALL-SATELLITE TECHNOLOGY

The GRAIL spacecraft was adapted from the platform of a previously-flown small satellite, the XSS-11, which weighed just 100 kg and had dimensions of roughly one meter by one meter. The XSS-11 was recognized with the 2007 AIAA Technical Achievement Award for the successful design, development, integration, and on-orbit tests of autonomous rendezvous and proximity operations technologies. This successful small-satellite mission provided a foundation for compact integrated avionics, streamlined verification and testing philosophies, and coordinated flight operations, and became the baseline for the Lockheed Martin (LM) 300 bus. For the GRAIL spacecraft, the LM 300 bus was also implemented. Figure 4 illustrates the evolution of the XSS-11 design to GRAIL.



XSS-11

- Experimental Satellite System-11
- Autonomous Rendezvous & Proximity Operations for MicroSats
- Baseline for LM 300 Bus
- 100 kg
- Launched: April 2005

GRAIL

- **G**ravity **R**ecovery and **I**nterior **L**aboratory
- High Resolution Mapping of the Moon's Gravity Field
- Studying Lunar Interior Structure
- Utilizing the LM 300 Bus
- 133 kg
- Launched: Sept 2011

Figure 4: Evolution of GRAIL from XSS-11 Small-Satellite Design[8]

SMALL-SATELLITE FORMATION FLIGHT APPLICATIONS

Formation Flight Approach

The twin GRAIL spacecraft were flown in a formation designed to establish a link between to two primary payloads. This formation design required high-precision control of not only position and velocity states, but also spacecraft attitude. The spacecraft attitude control mode that allowed the establishment of the payload-to-payload link is referred to as Orbiter Point mode. Figure 5 illustrates how the spacecraft flew in formation with the primary science instrument, the Lunar Gravity Ranging System (LGRS), measuring range using the K_a-band inter-spacecraft link. The spacecraft body-frame coordinates are also illustrated in Figure 5, with each LGRS pointing towards the other spacecraft along the –Z axis.

During Orbiter Point mode, each spacecraft determined where its partner spacecraft was located through the use of an on-board configuration file, which was called the ephemeris file. The ephemeris file contained the coefficients of a Chebyshev polynominal that represented the dual-spacecraft system's elliptical orbits. The coefficients for the spacecraft executing the file were first in index, with the other spacecraft coefficients second, to allow a consistent flight software algorithm to be used on both spacecraft without additional parameters. These coefficients were provided as an input to flight software, which used the polynomials to determine the Cartesian position and velocity vectors of both spacecraft in the inertial frame, for a given time span.[5] Chebyshev polynomial representation of Navigation SPICE kernel "truth" vectors has an extensive heritage with successful use on Spitzer Space Telescope, the Mars Reconnaissance Orbiter (MRO), and other spacecraft programs.[6] On GRAIL, the algorithm used Chebyshev coefficients from both spacecraft trajectory fits to arrive at Earth-relative epoch J2000 frame spacecraft position and velocity vectors, which formed the basis for spacecraft-to-spacecraft relative reference vectors, which were further resolved into attitude quaternions.[5]

For nominal orbital operations, the inertial aligned vector was defined as the orbiter-relative unit vector, and the inertial planar vector was defined as the spacecraft zenith position unit vector. The orbiter-relative inertial vector was defined as the vector from the center of mass of one spacecraft to the center of mass of the other spacecraft, as illustrated in Figure 6. Since the body aligned vectors were parameterized, the operations team was able to align the spacecraft center of mass with the phase centers of the two K_a-band instruments, allowing for alignment of antenna signals that were the basis for the scientific measurements.[5]

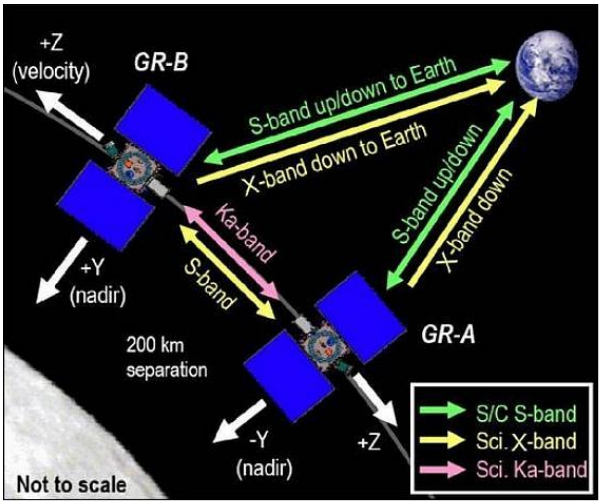


Figure 5: Attitude of the GRAIL Spacecraft during Science Phase[1]

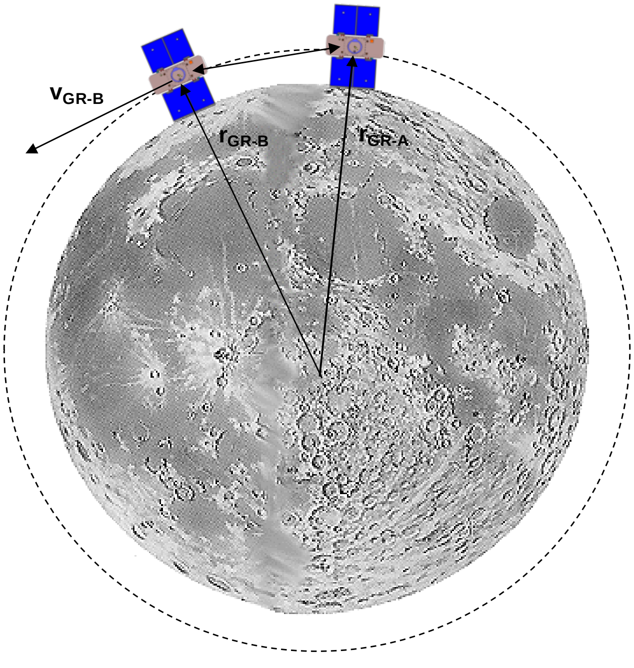


Figure 6: Spacecraft Vectors[5]

For contingency scenarios, payload thermal constraints drove a secondary design to mimic the nominal orbiter point attitudes. This contingency design was to be utilized in the event of a spacecraft anomaly or in the event that faulty polynomial coefficients were uplinked. Limiting the long-term drift of the contingency solution was paramount, and the GRAIL solution was to model the orbit as a circular orbit representing a mean of the actual elliptical orbit. Since the contingency orbit approximation was non-evolving, it was possible to utilize a single arc to fully represent a single orbit, and use a modulus function to maintain epoch continuity within the span of the arc. The modulus function modified the input for the time, the spacecraft clock kernel (SCLK), to ensure it remained within the start and stop times of the single available arc, as illustrated in Figure 7. This contingency pointing mode also aligned each spacecraft with its respective inertial velocity vector. This is in contrast to the nominal pointing mode which aligned each spacecraft payload with the spacecraft-to-spacecraft inertial vector. The difference between the nominal and contingency modes was on the order of 3 degrees. The contingency approach maintained essentially the same Moon-relative attitude without any knowledge of the other spacecraft, allowing for contingency ephemeris updates on a single orbiter. However, since contingency pointing no longer referenced the other spacecraft, science collection was not guaranteed.[5]

The attitude control state that used this contingency modulus function was named Velocity Point, and flight results of this mode are discussed in the Lessons Learned section of this paper.

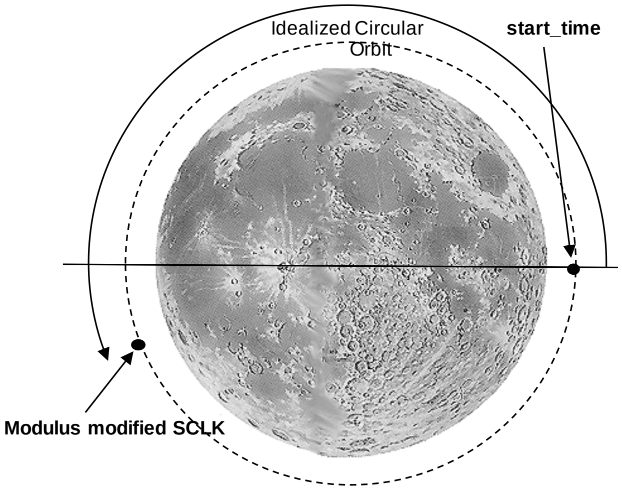


Figure 7: Contingency Orbit Representation with Modulus Function SCLK Progression[5]

Adjusting the Formation for Extended Mission

During the extended mission, the geometry of the Sun location, with respect to the spacecraft orbit around the Moon, was different than that of the primary mission, leading to the need for swapping the GRAIL-A and GRAIL-B positions in the formation, as illustrated in Figures 8 and 9. GRAIL-B led GRAIL-A in the orbit during primary mission, and vice versa in extended mission.

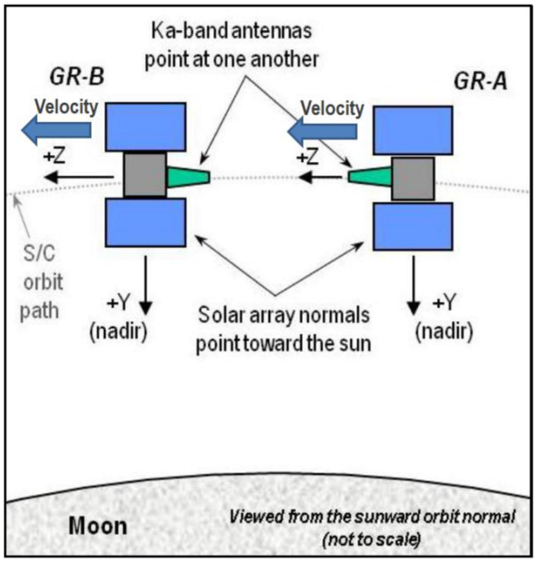


Figure 8: Formation during Primary Mission Science Phase

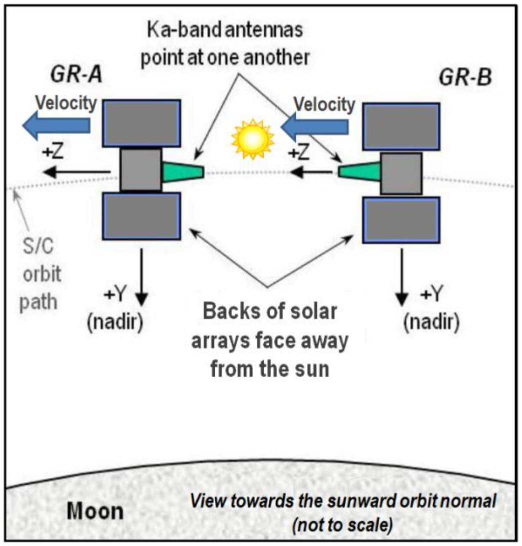


Figure 9: Formation during Extended Mission Science Phase

Trajectory Maintenance Maneuvers

During the extended mission, the goal was to fly at lower altitudes to obtain even higher resolution gravity map data than that of the primary mission. To achieve this goal, orbit maintenance maneuvers were needed weekly to prevent the orbit from decaying and the spacecraft from impacting the Moon's surface. With this ambitious maneuver schedule, several changes to the operations design were identified to avoid unusual attitudes that could have been introduced with the original Orbiter Point approach. These attitudes stemmed from the dependency each spacecraft had on the other spacecraft in terms of defining its pointing vector (the inertial spacecraft-to-spacecraft vector). If the trajectory of one spacecraft was altered, while the other trajectory was not, orbiter-point attitudes suddenly required very large offsets from nadir to maintain payload-to-payload pointing. These large nadir offsets were thermally undesirable, because they would expose vulnerable parts of the spacecraft bus to the lunar environment. To address this issue, the maneuver timing was adjusted to mitigate excursions in the formation flight attitude, as discussed in the next section. Also, a contingency operation was introduced for commanding the spacecraft into a different attitude mode than Orbiter Point, in case one spacecraft failed to execute a maneuver and could not maintain the desired formation with the other spacecraft. [5]

While developing the operations approach for extended mission, the team performed simulations of the maneuvers that would be performed weekly to maintain the desired orbits. Because Orbiter Point was the only mode in which gravity could be measured, the approach was to maintain Orbiter Point around the maneuver and the slews to the burn attitude to maximize science data acquisition. Also, the plan was to continue to separate the timing of each spacecraft's maneuver by at least one orbit—just over two hours. This timing separation was used in the primary mission and helped to minimize operational complexity, because the flight team could focus on the execution of one spacecraft burn first and then shift to the other spacecraft's burn. However, simulations showed that this separation of the maneuver timing led to off-nominal spacecraft attitudes, because one spacecraft would try to track the other spacecraft while it was in a different orbit. Figure 8 shows the resulting attitude excursion by showing the star tracker assembly (STA)-to-Moon angle, which usually remains constant while the spacecraft are flying in formation in the Orbiter Point mode. In this simulation, the spacecraft gradually slewed up to eight degrees off the usual attitude. [5]

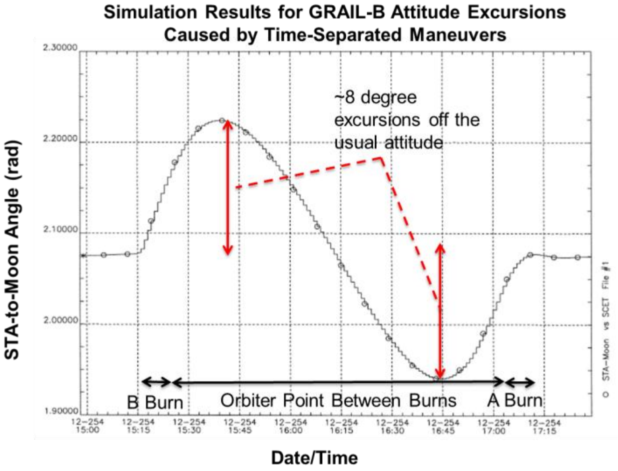


Figure 8: Simulation of Attitude Excursions[5]

To avoid these attitude excursions and develop a new operations approach for the extended mission maneuvers, a trade study was performed. The options for solving this problem are shown in the Table 1. These options were incorporated into a Pugh Matrix trade study (Table 2). The Pugh Matrix is a systems engineering trade study technique that helps a team identify a solution that meets various and sometimes conflicting stakeholder needs.[7]

In this case, the attitude control team needed to maintain pointing requirements, the spacecraft team needed to minimize the operations impact, and the science team needed to maximize science data collection. Based on the trade study results, the best solution was to perform the maneuvers at the same time. Implementation of this solution had minimal attitude excursions, acceptable impacts to operations, and low impact to science acquisition when the maneuvers were performed within a minute of each other. When the nearly-simultaneous maneuvers were implemented on a weekly basis in the extended mission, the flight results performed as expected, and the attitude excursions were successfully avoided. [5]

Table 1: Options Considered in the Trade Study[5]

Option #	Option Description
Option 1	Do Nothing: Perform maneuvers with timing separation of one-orbit like in Primary Mission, and accept attitude excursions
Option 2	Perform maneuvers at the same time, potentially avoiding attitude excursions
Option 3	Make each spacecraft point as if the other spacecraft is still in the same orbit
Option 4	Command the spacecraft out of Orbiter Point around the maneuvers

Table 2: Pugh Matrix Trade Study[5]

Option	Meet Attitude Error Requirements?	Operations Impact	Science Impact
Option 0: Do nothing	**No**	**Low**	**Low to Medium**
Option 1: Perform Burns at the Same Time	**Yes**	**Low to Medium**	**Low**
Option 2: Two Ephemeris Files for Before and After the Burns	**Yes**	**High**	**Medium**
Option 3: Take Spacecraft Out of Orbiter Point Around Burns	**Yes**	**High**	**Medium to High**

Contingency Operations for a Missed Maneuver

As introduced in the previous section, if the weekly spacecraft maneuvers were separated by hours, then the spacecraft attitude would shift away from an approximate nadir orientation to track the other spacecraft. Similarly, if a maneuver was missed because one of the spacecraft suffered an anomaly, then the two spacecraft would point towards each other while they were in different orbits after the true trajectories were updated with ephemeris file uplinks. This continuation of Orbiter Point mode with the spacecraft in different orbits would result in the spacecraft slewing off the usual attitude with respect to the Moon.

The spacecraft would not immediately attempt to point at each other in the event of a missed maneuver. Each spacecraft would continue pointing as if the maneuvers were successful until they received new ephemeris files. For the spacecraft that missed the maneuver, this situation would lead to an increase in magnitude of attitude oscillations around nominal orbiter point and a long-term drift away from nominal orbiter point. These deviations from a nominal attitude would not be due to the spacecraft executing slews, but instead due to its outdated knowledge of its true position. The spacecraft would adjust its attitude as if it successfully completed the burn, when in reality it would still be in its old orbit. Simulations revealed that both the short-term oscillations and the long-term drift would not cause the spacecraft to slew significantly for seven days, or until the on-board ephemeris expired. Therefore, no immediate threat to spacecraft safety would exist. [5]

However, with the uplink of updated ephemeris files after a missed maneuver, the two spacecraft would then point the payloads at each other, causing each spacecraft to slew off a nominal (approximately nadir) attitude to follow the other spacecraft. These slews would be single axis and could be large, reaching up to ± 25 degrees with respect to a nominal attitude. Figure 9 shows the instrument-to-Moon angle and is a good representation of the off nominal slews, because the instrument is mounted perpendicular to the axis of rotation. The magnitude of these slews could point the payload at the Moon and potentially cause thermal issues. Additional analysis would be required to determine if the spacecraft would remain in a safe state while in this scenario. This would add additional work to the operations team already attempting to recover from a spacecraft anomaly.[5]

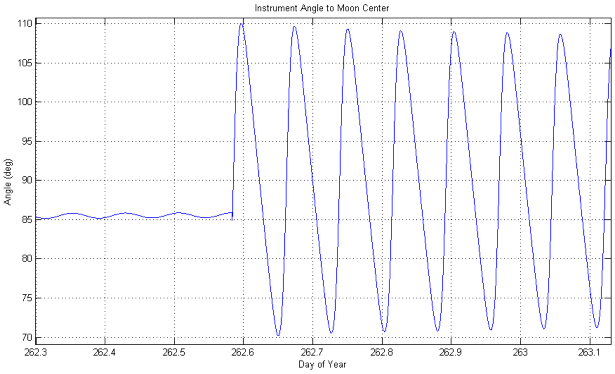


Figure 9: GRAIL-A Instrument Angle to Moon Center[5]

The operations team decided that, in the event of a missed maneuver, both spacecraft would be commanded to velocity point, which would utilize the conic ephemeris and modulus function discussed in the Pointing Implementation Approach section. As discussed previously, no immediate threat to spacecraft safety would be introduced by remaining in orbiter point on an old ephemeris. Therefore, the velocity point command could be issued at any point between the missed maneuver and the time of the last valid on-board ephemeris. This would reduce the time pressure for responding to a missed maneuver and remove the need to supply updated ephemeris files. Velocity point would also prevent each spacecraft from slewing off a nominal attitude to follow the other spacecraft. Then the operations team would not have the additional workload of performing analyses and ephemeris builds while attempting to recover a spacecraft from safe mode. Once the formation was successfully re-established, nominal orbiter-pointing attitudes could be resumed. [5]

LESSONS LEARNED FOR FUTURE SMALL-SATELLITE MISSIONS

GRAIL's Contribution to the Future of Small Satellites

The small-satellite community and NASA have shown interest in the development and innovation of formation-flight capabilities because of its application to swarm operations, distributed and networked satellites, and interferometry.[3] Also, the planet-finding and astronomy research goals for future Great Observatories (including the Terrestrial Planet Finder, the Stellar Imager, and the Laser Interferometer Space Antenna) hinge on distributing multiple apertures across a large distance while maintaining and sensing the desired separation with high-precision formation flight.[4] The implementation of formation flight and lessons learned from the GRAIL mission can pave the way for these potential future applications.

Reuse of Heritage Spacecraft Architecture and Low-Cost Solutions

Through the reuse of a heritage spacecraft's architecture, design costs were reduced. The LM 300 bus was implemented with modifications made to increase propellant tank and solar array sizing to meet the mission's delta-v and power requirements.[2] Another part of the XSS-11 heritage was the implementation of single-string redundancy. For Air Force Research Laboratory (AFRL) technology demonstration missions like the XSS-11, a single-string approach is common. For the 9-month GRAIL mission, NASA supported the single-string approach because most of the components had demonstrated longer lifespans on previous missions.[2] The project successfully implemented an innovative approach to single-string redundancy that enabled the execution of the mission at reduced costs.

Situational Awareness of How Small Satellites Can Affect Each Other in Formation Flight

During the operations development and preparation for the extended mission, the attitude control team learned how the activities of one spacecraft in formation flight could affect the other. This active approach towards the pursuit of situational awareness and the associated simulation testing led to the discovery that if the spacecraft did not perform coordinated maneuvers, then they would perform slow but significant slews to track each other while in different orbits. The discovery was made early enough that solutions could be developed and tested before the beginning of extended mission. As discussed in the previous section, the solutions were to perform maneuvers nearly simultaneously and to develop velocity-point contingency operations in case of missed maneuvers. Implementation of the Pugh Matrix, a systems engineering trade study technique, helped in one case to identify the solution that would meet multiple stakeholder needs. The conclusion from this set of activities is that future spacecraft teams who fly coordinated formations should proactively consider how one spacecraft can affect the other and perform simulation testing as early as possible to identify potential issues.[5]

Preparations for Changes in the Formation

For the swap of the GRAIL-A and GRAIL-B positions in the formation that was discussed earlier in this document, careful review of the on-board flight files was needed to ensure that the configuration parameters were correct for the change in formation. Updates were needed for the parameters of the inertial aligned vectors, which were introduced in the Pointing Implementation Approach section of this paper. Also, upon deeper investigation, a file that used the pitch rate of the spacecraft was identified and updated to have the opposite sign when the spacecraft swapped positions.[5] These activities showed that performing thorough investigations of the attitude control parameters was important before changing the formation configuration.

Flight Demonstration of Velocity Point

As part of decommissioning activities, both spacecraft were commanded to velocity point as an engineering test to validate the function. This test was performed after the last maneuver in the science phase and immediately before moving to a Sun-pointed attitude. Both spacecraft successfully completed at least one orbit in velocity point before the transition to Sun-point. Velocity point used a different alignment vector than nominal orbiter point, and small differences in spacecraft attitude were expected. Figure 10 shows the total attitude difference between the flight velocity point attitude and a predicted orbiter point attitude for the same dataset. The rising linear trend in the figure is the result of the Chebyshev polynomials in the ephemeris file used for this mode becoming outdated. This rise was expected, because the on-board file was expiring and was adequate for the test, as long as velocity point was executed within ten hours after the maneuver.

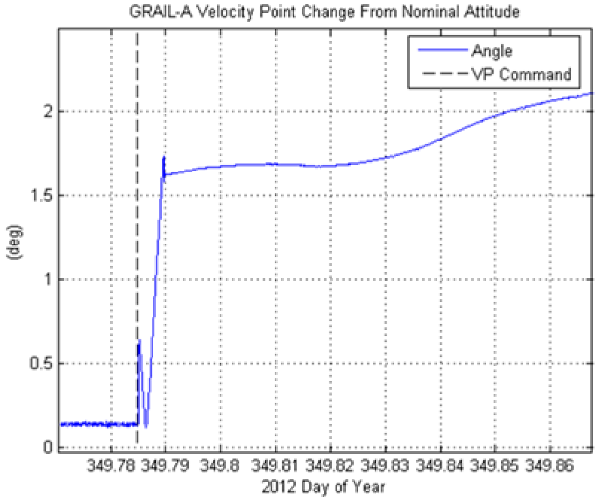


Figure 10: Change in Spacecraft Attitude between Velocity Point and Orbiter Point[5]

CONCLUSION

Operating during the year 2012, the GRAIL mission was an immense success with no emergency safe mode entries, and it created a gravity map of the Moon of unprecedented resolution. To obtain the gravity data, the spacecraft flew in formation with coordinated high-precision pointing and a design of an Orbiter Point mode. During the second half of 2012, the orbital altitude of the spacecraft was lowered to increase the resolution of the gravity data. Changes to operations were made to achieve and maintain formation flight at the lower altitudes, and lessons learned were documented to apply to future small-satellite and formation-flight missions. These lessons learned included:

1. The successful mission of GRAIL demonstrates technology and contributes lessons for the future of small satellites.
2. Reuse of spacecraft architecture and innovative approaches to redundancy can reduce costs for small-satellite missions.
3. Formation-flight operations require vigilance to maintain situational awareness.
4. Activities to change the spacecraft formation can benefit from careful planning, thorough investigations, stakeholder-inclusive trade studies, and early simulation testing.
5. In case the formation is broken during the mission, the implementation of a contingency mode, like velocity point, enables continued flight that does not depend on the location of the other spacecraft.

ACKNOWLEDGMENTS

The author would like to acknowledge other members of the GRAIL Attitude Control System (ACS) team—Dave Eckart, Ryan Olds, and Thomas Kennedy—for excellent teamwork, inputs, and analysis of the mission. Special thanks to Ralph Roncoli from JPL for his contribution of the graphics showing mission phases. Additional acknowledgements include Radek Uberna and Melissa Croswhite, both from Lockheed Martin, for advice on small-satellite applications. Also, the author acknowledges the other GRAIL teams at JPL, Lockheed Martin Space Systems Company, NASA's Goddard Space Flight Center, MIT, and Sally Ride Science for their collaboration in developing and flying a successful mission.

REFERENCES

1. Images Courtesy NASA/JPL-Caltech.
2. S. Spath, “Small Spacecraft Design for the GRAIL Mission,” 26th Annual AIAA/USU Conference on Small Satellites, Logan, UT, Aug. 2012.
3. H.J. Kramer and A.P. Cracknell, “An overview of small satellites in remote sensing,” International Journal of Remote Sensing, Volume 29, Issue 15, 2008, pp. 4285–4337.
4. H.P. Stahl and L. Feinberg, “Summary of NASA Advanced Telescope and Observatory Capability Roadmap,” IEEE Aerospace Conference, Big Sky, MT, March 2007.
5. C. Edwards-Stewart, D. Eckart, R. Olds, T. Kennedy, “Formation Flight Attitude Control Approach and Operations Results of the NASA GRAIL Spacecraft,” 36th Annual AAS Guidance and Control Conference, Breckenridge, CO, Feb. 2013.
6. A. Deprit, W. Poplarchek, and H.M. Pickard, “Compression of Ephemerides by Discrete Chebyshev Approximations,” AIAA and AAS Astrodynamics Conference, Palo Alto, CA, Aug. 1978.
7. S. Pugh, “Total Design: Integrated Methods for Successful Product Engineering,” Addison-Wesley Publishing Co. Inc., England, 1991.
8. B. King, “Small Satellites, Big Heritage: Mission Capable, Responsive Development, Assured Performance,” Lockheed Martin Corporation, 2012.

ABOUT THE AUTHOR

Christy Edwards-Stewart is an aerospace engineer at Lockheed Martin Space Systems Company in Waterton, CO and previously served as the primary attitude controller for the GRAIL-A spacecraft during its extended mission. Currently, she is a systems engineer and mission controller for the Mars Reconnaissance Orbiter (MRO) operations. Other previous positions at Lockheed Martin have included: Guidance, Navigation, and Control (GNC) operations lead for Mars Odyssey, launch support for the Jupiter-bound Juno spacecraft, GNC support for the comet flyby of the Stardust spacecraft, and Rendezvous, Proximity Operations, and Docking (RPOD) development for the Orion in Houston, TX. Also, she has been an innovator in developing how teams can utilize model-based systems engineering (MBSE) and 3-D virtual-reality environments for spacecraft development, production, and operations. Christy holds Bachelor and Master of Science Degrees in Aerospace Engineering from MIT, where she did research on the SPHERES small satellites in the Space Systems Laboratory (SSL). For outreach, she performs public speaking engagements about space exploration as a JPL Solar System Ambassador.