Operating the Dual-Orbiter GRAIL Mission to Measure the Moon's Gravity

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NASA's mission to measure the Moon's gravity and determine the interior structure, from crust to core, has almost completed its 3-month science data collection phase. The twin orbiters of the Gravity Recovery and Interior Laboratory (GRAIL) mission were launched from Florida on September 10, 2011, on a Delta-II launch vehicle. After traveling for nearly four months on a low energy trajectory to the Moon, they were inserted into lunar orbit on New Year's Eve and New Year's Day. In January 2012 a series of circularization maneuvers brought the orbiters into co-planar near-circular polar orbits. In February a distant (75-km) rendezvous was achieved and the science instruments were turned on. A dual-frequency (Ka and S-band) inter-orbiter radio link provides a precise orbiter-to-orbiter range measurement that enables the gravity field estimation. NASA's Jet Propulsion Laboratory in Pasadena, CA, manages the GRAIL project. Mission management, mission planning and sequencing, and navigation are conducted at JPL. Lockheed Martin, the flight system manufacturer, operates the orbiters from their control center in Denver, Colorado. The orbiters together have performed 28 propulsive maneuvers to reach and maintain the science phase configuration. Execution of these maneuvers, as well as the payload checkout and calibration activities, has gone smoothly due to extensive pre-launch operations planning and testing. The key to the operations success has been detailed timelines for product interchange between the operations teams and proven procedures from previous JPL/LM planetary missions. Once in science phase, GRAIL benefitted from the payload operational heritage of the GRACE mission that measures the Earth's gravity.

I. Introduction

THE Gravity Recovery and Interior Laboratory (GRAIL) project[1] has nearly completed its prime mission with the collection of almost three months of gravity data at the Moon. The science objective of increasing the understanding of the interior of the Moon from crust to core, by precise measurement of gravity field, is within reach. The flight team and the twin orbiters have performed almost flawlessly since the launch on September 10, 2011. The two orbiters were inserted into lunar orbit on New Year's Eve and New Year's Day 2011/2012. During January and February 2012 the orbits were circularized and the flight formation for gravity data collection was established. Mission operations, conducted at Jet Propulsion Laboratory (JPL) in Pasadena and Lockheed Martin (LM) in Denver, have proceeded smoothly largely due to an extensive pre-launch mission operations system development program.[2] Because the prime mission was only nine months and the mission timeline was busy from the start, containing 33 baseline propulsive maneuvers, the flight team was trained for all mission phases before launch. This paper provides a mission overview and highlights the operations experiences of the prime mission. NASA approved a six-month extended mission in March 2012 that will provide an additional three months of gravity data collection in the fall of 2012. The extended mission science phase will be conducted at a lower altitude than the prime mission enabling even higher resolution gravity measurements.

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II. Mission Overview

The GRAIL prime mission is only nine months long, the last three months are the gravity data collection months.[3] Nearly four months were required to reach the Moon on a low energy trajectory, and then two months to circularize the orbit and establish the science formation. A mission timeline is shown in Fig. 1, including the baseline 33 propulsive maneuvers. The primary mission was designed to avoid the lunar eclipses in December 2011 and June 2012. Survival of the lunar eclipses was not a spacecraft design requirement.

The twin orbiters were launched side-by-side on a Delta II 7920H launch vehicle from the Cape Canaveral Air Force Station on September 10, 2011 at 9:08 a.m. EDT. Postponed due to weather (high winds aloft) on the opening launch day, the launch occurred two-days into the defined launch period, September 8 through October 19, 2011. Two daily, instantaneous launch windows were available, one at 93- and one at 99-degree azimuth. Due to high winds aloft at the first opportunity on September 10, the launch occurred at the second opportunity, 39 minutes later.

Each orbiter performed three of five planned maneuvers in the trans-lunar cruise phase to target for the Lunar Orbit Insertion (LOI) burn. The first maneuver was not necessary due to the accurate launch vehicle injection. The fifth maneuver was not needed because orbit determination and maneuver execution errors from the fourth maneuvers were within specification. The LOI maneuvers, performed 25 hours apart on December 31 and January 1, placed the two orbiters into 11.5-hour, nearly co-planar orbits.

In January 2012, during the orbit period reduction (OPR) phase, seven propulsive maneuvers on each orbiter reduced the orbit period to just under two hours. In February, during the transition to science formation (TSF) phase, the orbits were phased and the distant rendezvous was established. In the baseline design the science phase was to begin on March 8 when the solar beta angle was 49 degrees. This was a spacecraft design requirement as the solar panels lie in the plane of the orbit when the orbiters are in their science configuration. As it turned out there was sufficient power, and acceptable thermal conditions, at 43-degree beta angle to allow the gravity mapping to begin on March 1, a week earlier than planned.

Originally a decommissioning phase was to follow the three-month science phase, but with the approval of an extended mission, this phase was postponed. Analysis by Lockheed Martin in the fall of 2011 based on the measured performance of the flight system showed that the orbiters could survive the lunar eclipse. This enabled the extended mission proposal and the opportunity to obtain another three months of gravity data collection. The extended mission science phase will be conducted in September, October and November 2012.

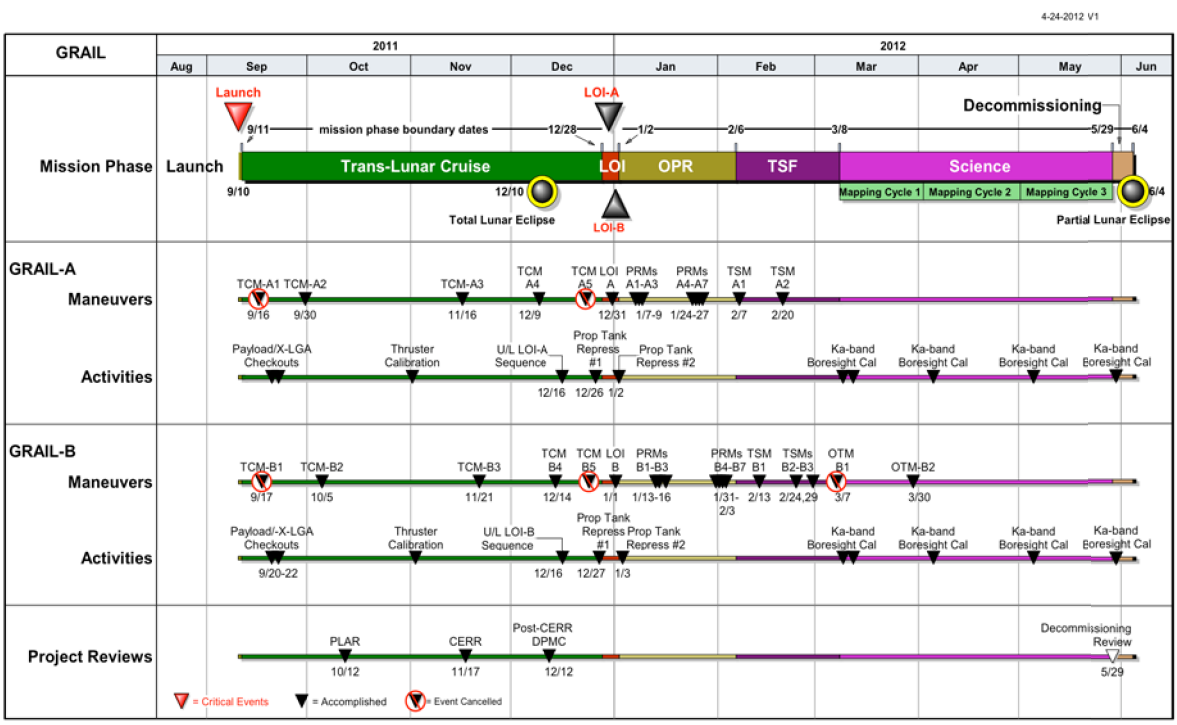

Figure 1. GRAIL prime mission timeline including 33 planned maneuvers to set up science formation at the Moon.

III. Orbiter Description

The GRAIL-A (GR-A) and GRAIL-B (GR-B) orbiters, renamed Ebb and Flow after insertion into the lunar orbit, are nearly identical with heritage from past spacecraft built by LM.[4] The orbiters are shown in Figs. 2 and 3. The main structure and propulsion system are based on the design used on XSS-11, and the avionics and flight software are based on heritage from Mars Reconnaissance Orbiter. The orbiters are three-axis stabilized with reaction wheels and hydrazine warm-gas thrusters for attitude control, and a star tracker and an inertial measurement unit (IMU) for attitude determination. The IMU propagates the attitude when the star tracker is off-line. Sun sensors provide attitude information in safe mode. A 22N hydrazine main engine operating in blow-down mode provides the thrust for all maneuvers except the small orbit trim maneuvers that are performed with the ACS 1N thrusters. The main engine is aligned in the –X direction, providing thrust in the +X direction. Accelerometers in the IMU are used for main engine burn cutoff and maneuver reconstruction. There are two low gain antennas (LGA), one on the +X and one on the –X side of the orbiter for communication to the ground. The science payload is a GRACE-heritage lunar gravity ranging system (LGRS) that transmits and receives an inter-orbiter Ka-band signal to measure the relative velocity of the two orbiters and an S-band inter-orbiter signal for time correlation between the two orbiters. The science payload includes an Ultra-Stable Oscillator (USO) that provides a steady reference signal for all data, and a Radio Science Beacon to provide one-way X-band signal to the ground for precision orbit determination. The launch mass of each orbiter was 306 kg, including 106 kg of propellant.

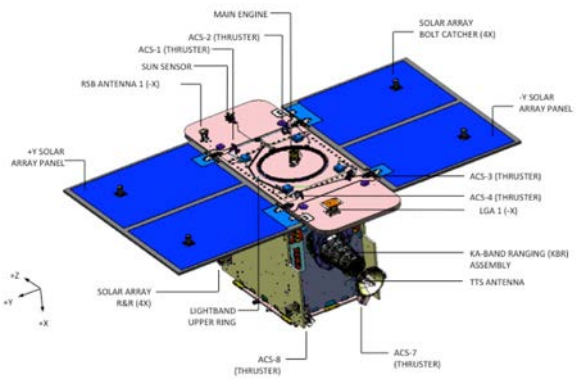

Figure 2. Orbiter –X view.

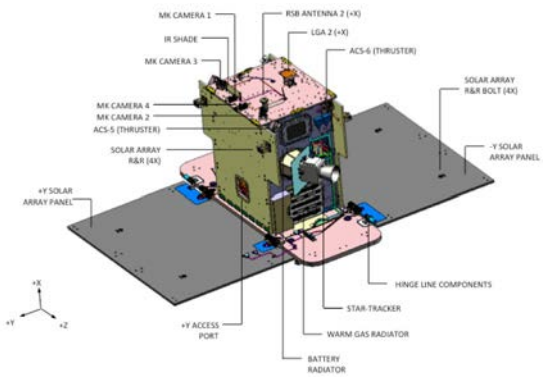

Figure 3. Orbiter +X view.

IV. Ops Organization

The flight operation organization consists of the eight teams shown in Fig. 4. All teams were located at JPL except the Spacecraft Team (SCT) that was located at Lockheed Martin in Denver. The SCT included the real-time operations staff that commanded the orbiters and provided real-time direction to the DSN station operators. Two teams at JPL utilized the Multi-mission Ground System Support (MGSS) services: the Mission Planning and Sequence Team (MPST) and the Data Management Team. The MPST members were dedicated to the GRAIL mission. The DSN scheduling function and the MOS/GDS configuration management function were also provided by MGSS. All MGSS services were funded by the GRAIL project. The Science Data System (SDS) Team performed the Level 1 science data processing and provided near-real-time assessment of science payload health.

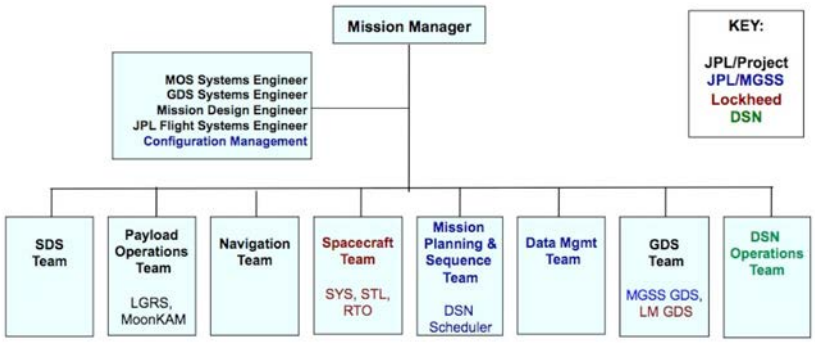

Figure 4. Flight Team organization comprised of eight teams.

V. Trans-Lunar Cruise Phase and Lunar Orbit Insertion

The focus of the operations activity during trans-lunar cruise was to perform the trajectory correction maneuvers (TCMs) on schedule and prepare for the critical LOI maneuvers. GRAIL's maneuver planning process, developed and validated pre-launch, provided the timelines to build, test, and uplink the maneuver sequences. TCM-1s were not needed due to the accurate launch vehicle injection. TCMs 2, 3 and 4, on both orbiters were all performed within specification and established accurate flight paths[5] leading to the LOI targets (Fig. 5).

A. Early Payload Checkout

Because the first TCMs were not required the flight team was able to add a checkout activity not in the pre-launch mission plan. On September 22, at a separation distance of 500 km, the two orbiters were pointed to each other and the lunar gravity ranging systems (LGRS) were turned on. Each orbiter received the Ka and S-band signals from the other and thereby demonstrated that the science payload was functioning as expected. Two days prior to this orbiter-to-orbiter link checkout a payload thermal checkout was performed. The LGRS and MoonKAM on both orbiters were powered for six hours in order to calibrate the spacecraft thermal model. The inter-orbiter ranging test proved to be invaluable, greatly facilitating performance assessment in the early stages of science mapping.

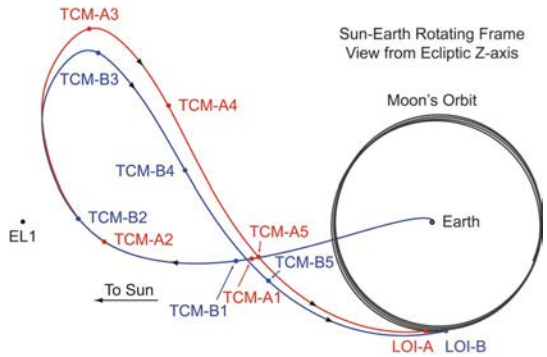

Figure 5. Trans-lunar cruise trajectories in Sun-fixed coordinate system.

B. Trajectory Correction Maneuvers

Six TCMs were performed on schedule and produced the desired LOI target conditions so that the contingency-TCM-5s were not needed. TCM-4s were performed in 15% pulse-mode, as they were small maneuvers, 0.25 m/s. TCM-A4 was cutoff by the backup timer because the thrust uncertainties were large thereby affecting the burn duration. As duty cycle maneuvers were not part of the pre-launch mission plan, there was no unit level data available. Despite the early cutoff, 98% of the desired thrust was achieved and the LOI target was reached.

As part of the critical event readiness process for LOI, the GRAIL navigation team developed a set of detailed "Go/No-Go" criteria for TCM-5. For both orbiters, TCM-4 accuracies met the defined periapsis requirement for initial lunar orbit as shown in Fig. 6. This requirement was not just based on entering lunar orbit, but also setting up the correct orbital starting point for the orbit-period-reduction and transition-to-science-formation maneuvers.

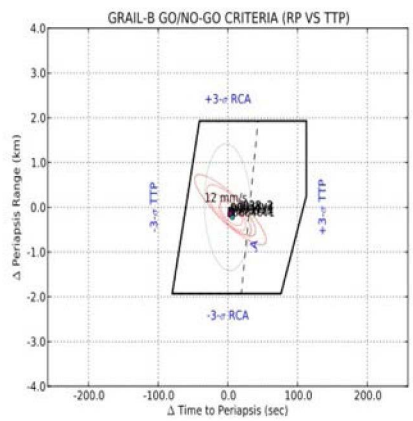

Figure 6. GRAIL-B TCM-B5 "Go/No-Go" criteria satisfied by final orbit determination solution.

C. LOI Maneuver Planning

Once TCM-2s were executed, the final LOI maneuver design was started assuming nominal flight performance for the deterministic TCM-3s. Two sequence development passes were scheduled, allowing for an update after TCM-3 in case of large execution errors. Since the TCM-3s were nominal, the second pass was not required. A contingency LOI sequence was built for both orbiters in the event the propellant tank re-pressurization did not occur. The re-pressurization did occur but on a delayed schedule as described below. All LOI command products were tested extensively with both nominal test cases, and those with anomalies before being approved for flight. Additional risk reduction testing was added during cruise to further minimize any risks associated with LOI.

D. In-flight Training for LOI

The Trans-Lunar Cruise timeline also accommodated additional team training in preparation for LOI. Originally slotted as an Operational Readiness Test, this evolved into a set of full flight team tabletop activities. During this training, the flight team was presented various mission anomalies associated with the LOI and OPR phase timelines,

and was asked to formulate operational responses to recover from each situation. The anomalies addressed included a failed propellant tank re-pressurization, a propellant tank over-pressurization, and an accelerometer failure resulting in a timer cutoff for LOI. The last two mock anomalies, both on the same orbiter, produced a much shorter capture orbit period for this vehicle.

E. Propellant Tank Re-pressurization

Tank re-pressurizations were planned for December 23. The helium supply is separated from the propellant tank by a high-pressure latch valve and a pyro valve. The latch valve is upstream of the pyro valve. On December 23 the GR-A pyro valve was fired. The pressure reading on the propellant tank unexpectedly decreased by 60 psi, instead of increasing a small amount due to high-pressure helium in the line between the two valves. The GR-B re-pressurization and GR-A latch valve opening was delayed to investigate the cause of the anomalous pressure reading. This behavior had been noted on previous LM missions, such as Mars Odyssey, as a zero-bias shift in the pressure transducer caused by the pyro shock. Once this was confirmed with reasonable certainty, the flight team proceeded with the re-pressurization events: firing the GR-B pyro on December 24, cycling the GR-A latch valve on December 26, and cycling the GR-B latch valve on December 27. GR-B showed a 37-psi downward shift after the pyro event. Calibration curve zero-point values in flight software were updated for both pressure transducers.

F. Lunar Orbit Insertion

The LOI sequences were activated on December 26 and 27 following the tank re-pressurizations. The sequences had been uploaded to both orbiters on December 16. Adjustments to fault protection were made in the days leading up to the critical event. On New Year's Eve and New Year's Day the two orbiters performed as expected, burning their main engine for about 38 minutes while pitching about an axis normal to the orbit plane to keep the thrust vector aligned with the velocity vector to reduce the gravity losses (Fig. 7). The burns imparted a delta-V of about 190 m/s while expending about 24 kg of propellant. The burn durations were shorter than expected (71 seconds on GR-A and 25 seconds on GR-B) because of higher tank pressure than predicted due to more heating from the gas generator. The gas-generator duty cycle was higher than predicted due to propellant movement in the tank shifting the orbiter center-of-mass and causing a higher than predicted ACS-thruster duty cycle. However, the maneuver accuracy was well within specification for pointing and magnitude. The targeted orbit period was achieved to within 4 minutes, and the desired inclination to within 0.03 degrees.

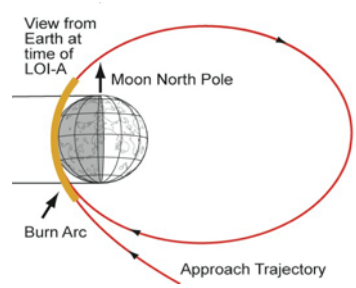

Figure 7. LOI Geometry – GRAIL approaching Moon from the South.

VI. Orbit Circularization

After the orbiters were captured in their 11.5-hour orbits, a second propellant tank re-pressurization was performed, and the flight team began to prepare for Orbit Period Reduction phase maneuvers (Fig. 8). Maneuver Cluster 1 consisted of three maneuvers, each a day apart with the same magnitude and the same burn direction, to reduce the orbit period to about 3.8 hours. These maneuvers were performed on schedule on January 7-9 for GR-A and January 13-15 for GR-B. Cluster 2 consisted of four daily maneuvers to reduce the period to 1.9 hours. These were performed on schedule on January 24-27 for GR-A and January 31 to February 3 for GR-B. Maneuver performance was within specification in all cases.

On January 10, the day after GR-A completed its Cluster 1 maneuvers, its star tracker locked on a bad attitude solution for 10 minutes after the Moon passed though the field-of-view (FOV). The initial response was to adjust flight software parameters used in determining when an attitude quaternion was valid. But, on January 16 more extended star tracker outages were seen. Normally the tracker will see 7-9 valid stars in the field, but with the Moon obscuring much of its view, the tracker got "stuck" on a bad solution by misidentifying the only two stars in its view. Initially the problem was avoided by commanding the tracker to standby mode in real time each orbit when the Moon was near the FOV. When the star tracker is in standby mode the onboard gyro propagates the attitude quaternion. The longer-term

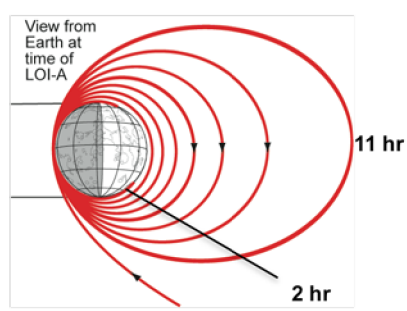

Figure 8. OPR Phase periapsis maneuvers circularize the orbits.

solution was to create an "overlay sequence" (aka "mini-sequence") that put the tracker in standby mode each orbit during the Moon view. The "overlay sequence" runs in parallel with the "background sequence" that manages DSN contacts and other routine activities. The star tracker overlay sequence was used in OPR phase and TSF phases on both orbiters whenever the orbit geometry required it. In the science phase, with the orbiter nadir-pointed, the star tracker never sees the Moon as the tracker is mounted on the orbiter looking 40 degrees above the local horizontal.

VII. Transition to Science Formation

At the completion of the OPR phase, both orbiters were in low, near-circular polar orbits with GR-B lapping GR-A every three days. Now the flight team's task was to bring the orbiters to their final science orbits,[6] with GR-B leading GR-A. Five Transition-to-Science Maneuvers (TSMs) were required to place the orbiters into the science formation. In pre-launch planning this phase was considered to be the most demanding because of the large uncertainties in maneuver times meant the maneuvers could be at any time of day (Fig. 9). However, because the maneuvers achieved the targeted orbital parameters with high accuracy the resulting maneuver times were very tractable.

On February 7, TSM-A1 adjusted GR-A's orbit eccentricity and argument of periapsis so that no eccentricity correction maneuvers would be required in the science phase. Then on February 13, when GR-B was 30 minutes ahead of GR-A, TSM-B1 placed GR-B into the same orbit as GR-A. The two orbiters were now "in synch" but too far apart for science data collection.

The next three maneuvers brought the orbiters to within 75 km to start the science phase: TSM-A2 on February 20 put GR-A in the science orbit (period=113.6 minutes) and started a drift to reduce the separation distance. TSM-B2 on February 24 slowed the drift rate. TSM-B3 on February 29 stopped the drift when the orbiters were 75 km apart but also imparted a slow positive drift rate targeted for a separation distance of 225 km on March 30, at the end of the first mapping cycle.

Contingency maneuvers were prepared for TSM-B2 and TSM-B3 on GR-A in the event that GR-B was not able to make these maneuvers. These contingency, "pop-up", maneuvers would have avoided the orbiters passing each other if the GR-B maneuver was missed.

On March 1 the orbiters were commanded from "Sun-point" to "Orbiter-point" attitude mode (Fig. 10). The first Orbital Trim Maneuver (OTM) scheduled for March 7 was not required due to the accuracy of the targeted orbit after TSM-B3.

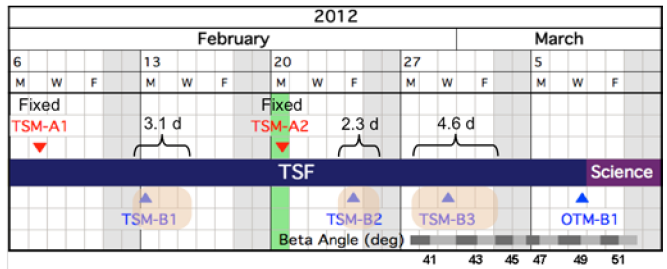

Figure 9. TSF phase a priori maneuver time uncertainties due to maneuver execution errors.

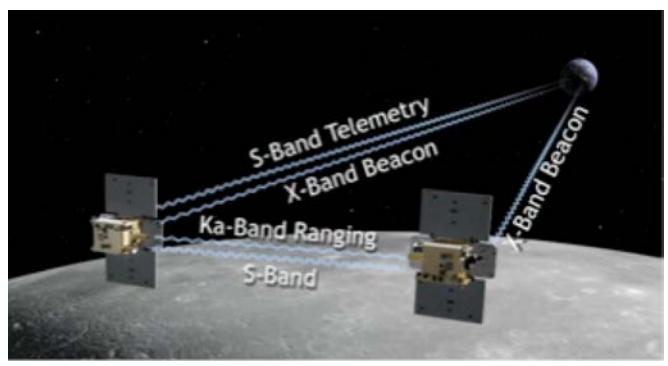

Figure 10. Orbiters in their science formation in Orbit-point attitude mode (not to scale).

VIII. Science Phase

Science data collection began a week ahead of schedule on March 1, 2012, with the GRAIL orbiters in a near-polar, near-circular orbit with a mean altitude of 55 km. Favorable power and thermal conditions permitted staying in continuous Orbiter-point attitude on March 1 with a solar beta angle of 43 degrees rather than the planned March 8 at 49-degree beta angle. The flight team had a plan to allow brief daily intermittent orbiter pointing for payload checkout this week, but it was not required. During the 82-day science phase, the Moon rotates three times underneath the GRAIL orbit, resulting in three mapping cycles of 27.3 days. From the start of Mapping Cycle 1 to the start of Mapping Cycle 2, the mean separation distance drifted from 75 to 216 km. A small Orbit Trim Maneuver (OTM), the first maneuver using only the attitude control thrusters, was executed near the end of Mapping Cycle 1 to change the separation drift rate and bring the orbiters closer together again to approximately 65 km at the end of Mapping Cycle 3 (end of the science phase). The data collected at the shorter separation distances enable

determination of the higher-order gravity coefficients that describe shorter-wavelength and shallow structure, while that collected at the longer distances favors determination of the lower-order coefficients that describe longer-wavelength and deeper structure.

Since data continuity is critical for the gravity experiment, GRAIL utilized a double data-transmission strategy: all science and engineering data were transmitted to the ground twice, on two consecutive DSN passes. This avoided extra effort on the part of the flight team to retrieve missing data. With the excellent performance of the flight system, this strategy enabled the capture 99.992% of available science data over the first two mapping cycles, March 1 to May 1. (This paper went to print midway through the third mapping cycle.)

A. Initial Gravity Measurements

A typical ground track on March 2 and the corresponding inter-orbiter range residuals along that track as measured by the Ka-band dual one-way tracking is shown in Fig. 11. The bottom portion of the figure shows the topography along the track and the orbit altitude. The figure clearly shows that the gravity measurement is more sensitive at lower orbit altitudes. The altitude varies between 24 and 86 km on this orbit.

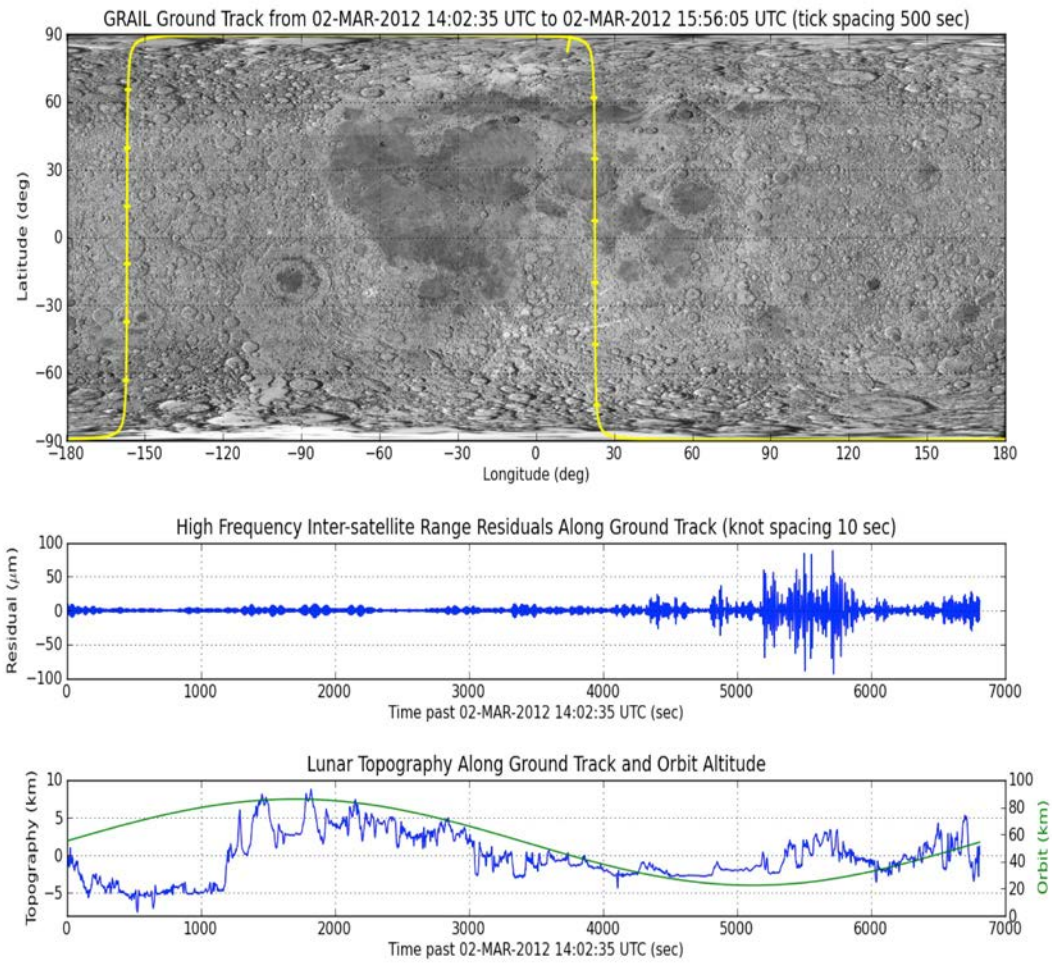

Figure 11. Inter-orbiter Ka-band range residuals from GRAIL match the ground track topography from the LOLA instrument on the Lunar Reconnaissance Orbiter, and are more sensitive at lower altitudes.

B. Solar Flare on March 7

An X-class solar flare on March 7, the largest seen since 2003, raised the proton flux levels in the vicinity of the Earth (Fig. 12) and affected the orbiters in several areas: 1) The USO on both orbiters saw frequency shifts, 2) the GR-B GPA rebooted, 3) the GR-B MoonKAM experienced an over-current condition on the 12V power supply that powers the four camera heads, and 4) the GR-A MoonKAM DVC had a communication interrupt with the orbiter C&DH. The spacecraft fault protection turned off the GR-B MoonKAM and power cycled the GR-A MoonKAM. The flight team, to protect the GR-A MoonKAM, turned it off and turned on the USO Heater #2 to prevent the USO survival heater from cycling.

The GR-A and GR-B MoonKAMs were powered on again on March 13 and 14, respectively, but another 12V power supply over-current event on GR-B on April 2 caused spacecraft fault protection to again power it off. Space weather was quiet at this time and apparently was not the cause of the over-current. After this event the USO heater #2 was turned on and the MoonKAM was left off until Mapping Cycle #2 was complete to ensure minimum thermal disturbance to science data collection. The GR-B MoonKAM was turned on again on April 30.

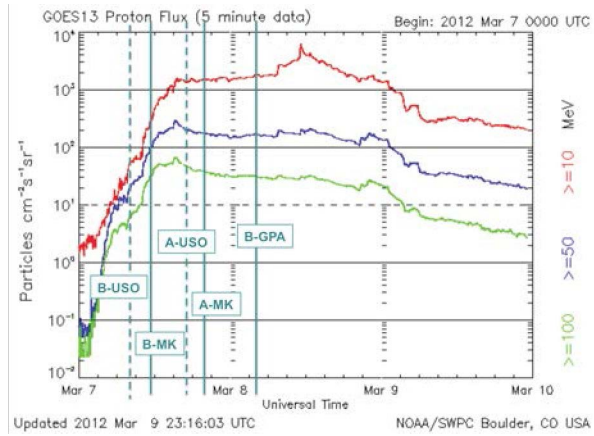

Figure 12. Proton flux levels following solar flare of March 7 and times of orbiter events.

C. Ka-band Boresight Calibrations

Before the start of science phase, an updated Ka-band boresight vector was uplinked to each orbiter. These vectors (from the orbiter center-of-mass to the Ka-band horn phase center) were determined from a computed center-of-mass and the nominal Ka-band phase center. Attitude control algorithms use the Ka-Band boresight vector to point the orbiters to one another. Also, knowledge of these vectors is key to the science data reduction in determining the motion of the center-of-mass due to gravity, since the dual one-way range measurement is only measuring the range changes between the phase centers.

Ka-band boresight calibrations were performed multiple times in the science phase in order to update these vectors. The boresight vector changes over the mission due to center-of-mass migration resulting from propellant usage. Two calibrations were performed at the beginning of the first mapping cycle and single calibrations were performed at the end of each mapping cycle. Each calibration consisted of six 6-degree slews about the orbiter X-axis and then six slews about the Y-axis. The calibration was performed twice in the orbit to demonstrate repeatability. The boresight-vector analysis requires a good knowledge of the gravity field since gravity errors will be seen in the Ka range residual. Therefore accurate determination of the boresight vector had to wait until the LGRS data provided an improved gravity field.

Fig. 13 shows the Ka range residuals from the March 9 calibration for the slews performed near apoapsis (88-km altitude). The figure shows that the measured-versus-computed residuals are more closely matched with the 25-day gravity field compared to the 15-day field. Fig. 14 shows the Ka range residuals for the March 9 calibration for the slews performed near periapsis (23-km altitude), using the 15-day gravity field. The

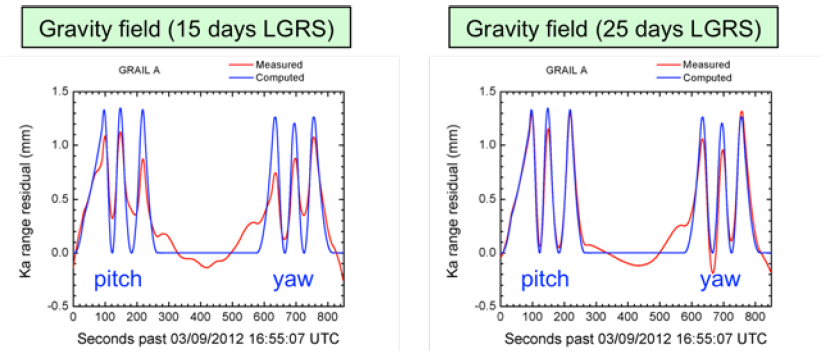

Figure 13. Ka-band range residuals from the March 9 Ka-band calibration performed near apoapsis using two different gravity field models.

slews cannot be distinguished because the gravity field errors have a more dominant effect on the range residuals. And the same is true using the 25-day LGRS gravity field. Later, when an even better gravity field is produced, the periapsis calibration data can be reanalyzed to determine an accurate boresight vector that will be used in later gravity data processing. The result of the first two calibrations (March 8 and 9) showed that the vectors computed before the start of science phase met specifications and vector updates onboard were not necessary.

D. TTS Direct-to-Earth Calibrations

When the Earth is near the orbiter orbit plane, it is possible for the DSN to receive Time Transfer System (TTS) S-band signals directly. A special Radio Science Receiver was set up at DSS-24 (Goldstone) to receive the signal that provided a correlation between LGRS-time and UTC. These calibrations were not included in the pre-launch mission plan, but were added during flight as an initiative to reduce timing errors in science data. The LGRS was powered on briefly in mid-January 2012 for the initial calibration. Additional calibrations were added every two weeks during science phase. These calibrations enhanced the science data quality by providing more accurate time tags on the Ka-band ranging data.

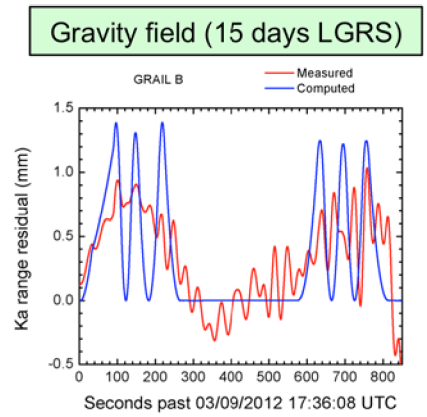

Figure 14. Ka-band range residuals from the March 9 Ka-band calibration performed near periapsis using the 15-day gravity model.

E. Orbiter Angular Momentum Accumulation

The placement of reaction wheel desaturation maneuvers ("desats") during science phase was a key consideration, since thruster firings interrupt the science data arc. Desats were commanded from an onboard "background sequence" near the North Pole where ground track coverage is the densest. Solar pressure produced the dominant torque on the orbiters in the first and third mapping cycle. But in the second cycle, where the orbiters are in full-Sun orbits (solar panels perpendicular to the Sun), the gravity-gradient torque became the dominant torque. Due to uncertainties in the orbiter mass properties, larger than expected gravity-gradient torque was evident late in the first mapping cycle and caused the flight team to create special "overlay sequences" (executing in parallel with background sequence) to insert additional desat maneuvers. This avoided the triggering of autonomous desat maneuvers, which may not have occurred over the poles, resulting in the loss of unique science measurements.

F. Possible Telecommunications Multi-path Effects on Uplink and Downlink

It is believed that multi-path effects from signals reflecting off the Moon's surface, both uplink and downlink, are responsible for GRAIL link issues experienced with DSN communications. First seen on February 13 and 14, after TSM-B1, when both orbiters were in low orbits and the Earth was near 90 degrees on the low gain antenna (LGA), occasional problems with one-way S-band telemetry lockups were experienced. Later, in the science phase, problems were seen occasionally on both the uplink and the downlink when the Earth angle was at 60-90 degrees to the LGA. Also periods of noisy Doppler residuals were seen when in two-way lock. To mitigate these effects the project made sure the station operators were aware of the schedule when this geometry would occur and they were given instructions to make repeated attempts to re-acquire the signal when telemetry lock was dropped or when two-way Doppler residuals were large; and they were provided with frequent updates to the best-lock frequencies. While this was an occasional nuisance for the prime mission, there was a concern that with the lower altitudes in the extended mission, and with the need to keep the eccentricity correction maneuvers on schedule, uplink problems could jeopardize the mission. As a result, an investigation was initiated to see if periods of poor uplink/downlink performance could be predicted and therefore avoided. The investigation revealed that the Apollo missions also experienced link issues thought to be due to reflected signals off the Moon's surface. There are theories that there could be "hot spots", craters that focus the radiation, causing the signals to fade or amplify.

G. GRAIL Navigation Benefits from the New Gravity Field

In early April the Science Team delivered to the Navigation Team a spherical harmonic gravity field model of degree and order 270, based on 30 days of LGRS data. After a brief checkout period the Navigation Team adopted this field (truncated to degree and order 200) for its operational processes. From April 16 on it was used in the production of the orbital ephemerides that were delivered twice weekly to the SCT. With this field's better

predictive capabilities the ephemeris delivery frequency was reduced to once a week. The new field noticeably reduced the solution differences from one orbit determination solution to the next. However, with the new field it was still necessary to add the periapsis impulses within the orbit determination analysis to get the best data fit. The size of these impulses was reduced markedly.

H. E/PO Imaging

Each GRAIL orbiter carries a camera with four imaging heads to support the Education and Public Outreach (E/PO) activity led by Sally Ride Science. Middle school students request images of particular spots on the Moon and supervised students at University of California San Diego prepare commands to capture the images and have them downloaded. The cameras are aligned with the orbit plane, two looking nadir, one looking forward and one backward. The forward and backward looking cameras are separated by 60 degrees. One nadir camera has 5.4-degree FOV; the others have 44-degree FOVs. The initial image set was taken in the OPR phase on January 18-19 by GR-A. The cameras were turned on for the science phase on March 5. The GR-A cameras operated throughout the science phase except for March 7-13. The GR-B cameras operated in Mapping Cycle #1 (except March 7-14) and Mapping Cycle #3 but were off during Mapping Cycle #2 (See Section B). Thus far, GRAIL E/PO activity involves 3116 student operations centers at 2853 unique schools. Fig. 15 shows a sample MoonKAM image from a 44-degree FOV camera.

Figure 15. Sample MoonKAM image.

IX. Science Results

The most accurate global gravity model of the Moon to date has been developed from the first month of GRAIL science data. The measurement uncertainty is improved by one order of magnitude on the near side and more than two orders of magnitude on the far side. A much more detailed lunar gravitational landscape is revealed, particularly over the lunar far side, showing the gravity signals of numerous craters and basins not seen before. At the current resolution of the field nearly all craters larger than 25-km diameter display gravity signals indicative of the processes of formation.

GRAIL is revealing gravity details that correlate with the lunar topography obtained from by the Lunar Orbiter Laser Altimeter (LOLA) measurements from the Lunar Reconnaissance Orbiter (LRO) mission. Fig. 16 compares the LOLA topography with the GRAIL gravity data in the region of Tycho, a prominent 86-km diameter complex crater on the Moon's nearside. This preliminary GRAIL gravity model is to degree and order 270, corresponding to a spatial resolution of 20 km.

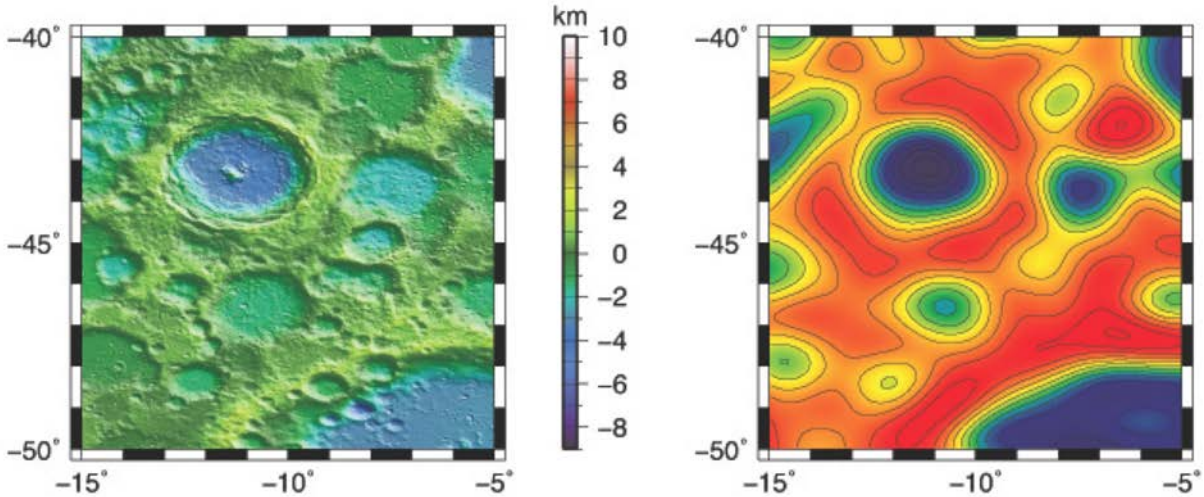

Figure 16. Tycho, a prominent 86-km diameter complex crater on the Moon's nearside, is shown in LOLA topography (left) and GRAIL gravity (right). Tycho is in the upper left of each figure. In the gravity map reds correspond to mass excesses and blues to mass deficits.

X. Extended Mission

On the basis of competitive review, NASA has approved an extended mission for GRAIL, through December 2012, that will enable collection of higher resolution gravity data by flying at an even lower altitude. The mission timeline is shown in Fig. 17. In late May, when the prime mission is complete, periapsis raise maneuvers will circularize the orbits (84-km altitude) for the low activity Low Beta Angle phase. For ten weeks after the lunar eclipse passage on June 4 the orientation of the orbit plane relative to the Sun does not allow for operation of the LGRS payloads while in orbiter-point configuration. A second three-month science phase will begin on August 30 when the solar beta angle reaches 40 degrees. In the science phase, weekly eccentricity correction maneuvers (ECMs) on both orbiters will maintain the 23-km mean altitude orbits. There will also be a weekly OTM on one orbiter, a day after the ECMs, to control the orbiter separation distance. The extended mission contains 45 baseline maneuvers. The altitude variation about the mean will be constrained to ±12 km. By operating at the lowest orbit the flight team can safely support, the resolution of the gravity field measurement will be increased by over a factor of two. The orbiters will impact the Moon about two and a half weeks after the final maneuvers that will occur shortly before the penumbral lunar eclipse on November 28.

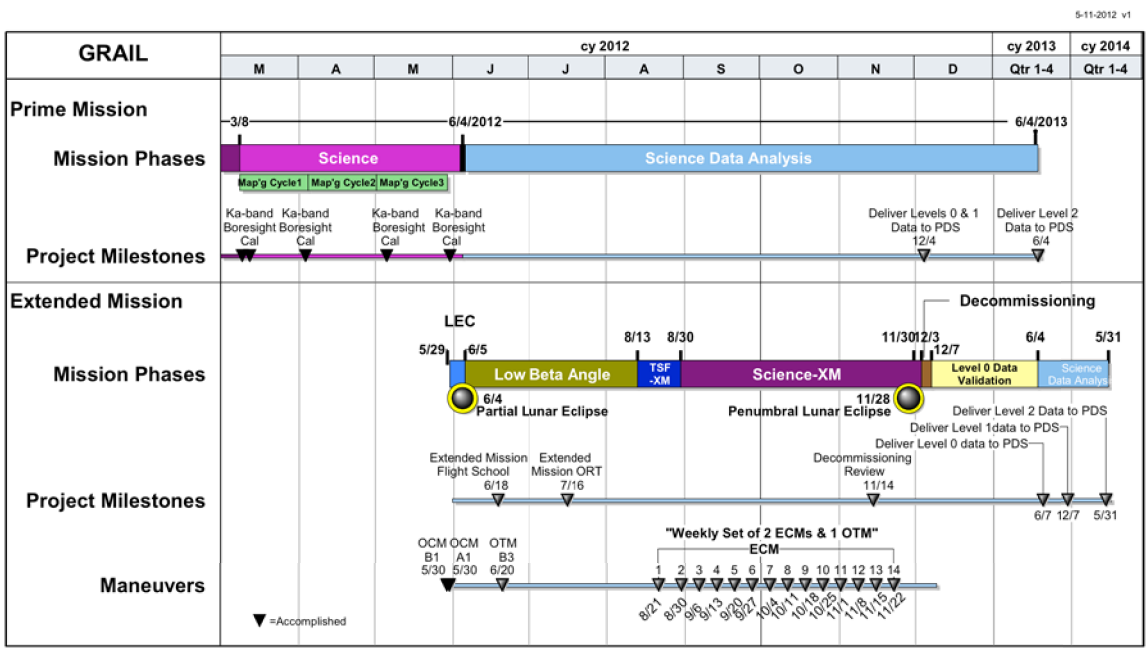

Figure 17. Extended mission timeline.

XI. Conclusion

The GRAIL mission is on track to satisfy all prime mission requirements. The performance of the orbiters and payload has been nearly flawless and the conduct of the flight team has been excellent. It is clear that the detailed operations planning and careful operations system validation before launch have paid big dividends. The prime mission has executed the mission timelines for activities almost exactly as they were laid out in the pre-launch mission plan. Flight experience gained in the prime mission puts the flight team in a good position for completing a challenging extended mission where the science payoff is even greater.

Appendix A
Acronym List

ACS	Attitude Control System
C&DH	Command & Data Handler
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DSN	Deep Space Network
E/PO	Education and Public Outreach
ECM	Eccentricity Correction Maneuver
FOV	Field of View
DVC	Digital Video Controller (MoonKAM)
GDS	Ground Data System
GPA	Gravity Processing Assembly
GR-A	GRAIL-A Spacecraft (Ebb)
GR-B	GRAIL-B Spacecraft (Flow)
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
IMU	Inertial Measurement Unit
LGA	Low Gain Antenna
LGRS	Lunar Gravity Ranging System
LM	Lockheed Martin Space Systems Company (Denver)
LOI	Lunar Orbit Insertion
LOLA	Lunar Orbiter Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
MK	MoonKAM
MoonKAM	Knowledge Acquired by Middle School Students
MOS	Mission Operations System
MGSS	Multi-mission Ground System Services
MPST	Mission Planning and Sequence Team
OPR	Orbital Period Reduction
OTM	Orbit Trim Maneuver
RSB	Radio Science Beacon
SCT	Spacecraft Team
TCM	Trajectory Correction Maneuver
TLC	Trans-Lunar Cruise
TSF	Transition to Science Formation
TSM	Transition to Science Maneuver
TTS	Time Transfer System
USO	Ultra-stable Oscillator

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