# GRAIL Description

Mission Overview

The GRAIL mission placed two spacecraft (GRAIL-A and GRAIL-B), flying in formation, into orbit around the Moon to study its internal structure. By very precisely measuring the distance of one orbiter relative to the other, the orbital perturbations caused by the Moon could be observed. Combining this with the orbiter position as determined from Earth-based observations, the mass distribution on the Moon could be determined.

The GRAIL spacecraft were launched side-by-side on a single Delta II vehicle during a 26-day launch window that opened on September 8, 2011. The actual launch was two days later. The mission timeline was constructed to ensure continuity in operations by avoiding lunar eclipses on December 10, 2011, and June 4, 2012, when spacecraft power from the solar panels would be interrupted. The Goldstone DSN complex acquired initial spacecraft signals and confirmed solar array deployment.

The trans-lunar cruise phase consisted of a 3.5-month low-energy transfer via the Sun-Earth Lagrange point 1 (EL1). Compared to a direct trajectory, this low-energy transfer reduced spacecraft fuel requirements (by approximately 130 m/s), allowed more time for spacecraft check-out and out-gassing, and increased the number of days available in the launch window each month.

Both spacecraft approached the Moon under the South Pole where they each executed a 41-minute Lunar Orbit Insertion (LOI) maneuver to put them into an elliptical orbit with a period of 11.5 hours. The LOIs for the two spacecraft were separated by one day. Each LOI was simultaneously visible from the Goldstone and Canberra DSN complexes.

A series of four maneuvers were then performed to reduce the orbits to nearly circular with a mean 55-km altitude and 113-minute period. Further maneuvers positioned the spacecraft to the desired initial separation distance, which then drifted between 65 km and 225 km.

The 90-day Science Phase was divided into three 27.3-day nadir-pointed mapping cycles. Two daily 8-hour DSN tracking passes acquired science and “E/PO MoonKam” data. Following the Extended Mission Phase (August 29 - December 12, 2012), there was a 6-day decommissioning period, after which the spacecraft impacted the lunar surface.

For more information on the GRAIL mission, see Roncoli and Fujii, 2010.   
  
Mission Phases

The GRAIL Mission was divided into eight phases: Launch, Cruise, Orbit Insertion, Transition to Science, Science, Hiatus, Extended Mission, and Decommissioning.

Launch  
The Launch Phase extended from the start of the countdown to the initial acquisition, by the DSN, of the orbiters in a safe and stable configuration.

The twin orbiters were launched from Cape Canaveral Air Force Station, Florida, on a Delta II Heavy shortly after the opening of the launch window in September 2011. There were at least 21 launch opportunities within this 26-day window. The Goldstone DSN complex acquired the initial signal, as well as confirmation of solar array deployment.

Mission Phase Start Time: 2011-09-10

Mission Phase Stop Time: 2011-09-10  
  
Cruise  
The Cruise Phase extended from after DSN initial acquisition of the orbiters in a safe and stable configuration until the first Lunar Orbit Insertion (LOI) maneuver.

The orbiters followed a low-energy trajectory to the Moon, which took them near the Sun-Earth Lagrange Point 1 (EL1). The low-energy trajectory minimized the velocity change (dV) required for insertion into lunar orbit. During the 112-day cruise, several maneuvers were executed on each orbiter to adjust the trajectory.

One maneuver placed the orbiter on the low-energy trajectory and another separated the Lunar Orbit Insertion (LOI) maneuvers for each orbiter by about a day. The remaining maneuvers were used to fine tune the trajectory.

The low-energy transfer was chosen to reduce the spacecraft fuel requirements (by ~130 m/s), to allow more time for spacecraft check-out and out-gassing, and to increase the number of days available in the launch window each month.

Mission Phase Start Time: 2011-09-10

Mission Phase Stop Time: 2011-12-31  
  
Orbit Insertion  
This phase included the propulsive maneuvers to insert the two spacecraft into lunar orbit. The maneuvers were separated by about 25 hours, with the GRAIL-A maneuver occurring on December 31, 2011, and the GRAIL-B maneuver occurring on January 1, 2012.

Both spacecraft approached the Moon under the South Pole where they each executed a 41-minute Lunar Orbit Insertion (LOI) maneuver to put them into an elliptical orbit with a period of about 11.5 hours. Each LOI was simultaneously visible from the Goldstone and Canberra DSN complexes.

Mission Phase Start Time: 2011-12-31

Mission Phase Stop Time: 2012-01-01  
   
Transition to Science  
Once in lunar orbit, and after checkout of the orbiter systems, several maneuvers were performed on each orbiter to reduce the orbit period and lower the altitude to the science orbit. These maneuvers were grouped into two clusters, with each cluster spanning about a week; clusters alternated between GRAIL-A and GRAIL-B. Each maneuver cluster used the same maneuver design, which reduced the workload on the operations teams. The orbit period was reduced to 113 minutes.

A series of maneuvers was then performed to establish the proper spacecraft formation at the start of the Science Phase. These maneuvers positioned the spacecraft to the desired initial separation distance, which would then drift between 65 km and 225 km.

Mission Phase Start Time: 2012-01-01

Mission Phase Stop Time: 2012-03-01  
  
Science  
The 90-day Science Phase was divided into three 27.3-day nadir-pointed mapping cycles. Two daily 8-hour DSN tracking passes acquired science and “E/PO MoonKam” data.

The Science Phase of the mission was conducted from a near-circular, near-polar orbit with a mean altitude of 55 km. There were three different mapping cycles during the Science Phase, each covering a sidereal month (27.32 days). The first mapping cycle started while the science orbit had low periapsis altitudes with an orbiter separation distance of approximately 85 kilometers. Over the course of the first mapping cycle, and into the second mapping cycle, the periapsis altitudes of the science orbit increased, and the mean separation distance slowly drifted to 225 kilometers. A small Orbit Trim Maneuver (OTM) was performed during the second mapping cycle to decrease the separation drift rate. Following this OTM to the end of the third mapping cycle, the periapsis altitudes decreased, and the mean separation between the orbiters slowly drifted from 225 km back to 65 km.

During the Science Phase, data were stored onboard and downlinked as bandwidth became available. Each orbiter received an average of twelve hours of tracking coverage per day.

Mission Phase Start Time: 2012-03-01

Mission Phase Stop Time: 2012-05-29  
  
Hiatus  
In the Hiatus Phase the beta-angle, which determines the amount of sunlight on the solar panels and controls the amount of energy available to the spacecraft, dropped below its threshold. Science operations were suspended and the two spacecraft executed a series of maneuvers to re-position themselves for beta-angles above the threshold prior to the start of the Extended Mission.

Mission Phase Start Time: 2012-05-29

Mission Phase Stop Time: 2012-08-29  
  
Extended Mission  
GRAIL proposed (and NASA approved) an Extended Mission, since there was sufficient fuel in the two spacecraft to acquire additional science data. The mean spacecraft altitude was lowered by about a factor of 2 to increase the sensitivity of the gravity measurements, and GRAIL defined a new set of science objectives. As in the Science Phase, the spacecraft separation distance was variable. DSN coverage was comparable.

Mission Phase Start Time: 2012-08-29

Mission Phase Stop Time: 2012-12-12  
  
Decommissioning  
Science data were collected during the Decommissioning Phase as in the Extended Mission phase. After final calibrations, the Decommissioning Phase ended with impact of the spacecraft on the lunar surface.

Mission Phase Start Time: 2012-12-12

Mission Phase Stop Time: 2012-12-18  
  
Mission Objectives

The Moon is the most accessible and best studied of rocky, or 'terrestrial', bodies beyond Earth. Unlike Earth, however, the Moon's surface geology preserves the record of nearly the entirety of 4.5 billion years of solar system history. Orbital observations combined with samples of surface rocks returned to Earth show that no other body preserves the record of geological history so clearly as the Moon.

The structure and composition of the lunar interior (and, by Inference, the nature and timing of internal melting and heat loss) hold the key to reconstructing this history. Longstanding questions such as the origin of the maria, the reason for the nearside-farside asymmetry in crustal thickness, and the explanation for the puzzling magnetization of crustal rocks, all require a greatly improved understanding of the Moon's interior. Deciphering the structure of the interior will bring understanding of the evolution of the Moon itself and also extend knowledge of the origin and thermal evolution of the Moon to other bodies in the inner solar system. The Moon was once thought to be unique in developing a 'magma ocean' shortly after accretion; now such a phenomenon has been credibly proposed for Mars as well.

GRAIL Primary Mission science objectives were (1) to determine the structure of the lunar interior from crust to core and (2) to further understanding of the thermal evolution of the Moon. GRAIL accomplished these goals by performing global, regional, and local high-resolution (30x30 km), high-accuracy (less than 10 mGal, or 0.0001 m/s/s) gravity field measurements with twin, low-altitude (55 km) polar-orbiting spacecraft using Ka-band ranging instruments and radio tracking links to the Deep Space Network. For the Extended Mission, the objectives were refined to reflect the lower mean altitude (reduced by a factor of 2 from 55 km).   
  
Science Questions Addressed

The GRAIL Science Team conducted six lunar science investigations (Roncoli and Fuji, 2010):

1. Map the structure of the crust and lithosphere - Determine the Moon's global gravity field with global average Surface resolution of 30 km and with an accuracy of +/- 10 mGal.

2. Understand the Moon's asymmetric thermal evolution - Determine large regional gravity with global average surface resolution of 30 km and with an accuracy of +/- 2 mGal.

3. Determine the subsurface structure of impact basins and the origin of mascons - Determine small regional gravity that resolves basins and rings to a global average surface resolution of 30 km to a precision of +/- 0.5 mGal.

4. Ascertain the temporal evolution of crustal brecciation and Magmatism - Determine high-resolution local gravity fields with global average surface resolution of 30 km to a precision of +/- 0.1 mGal.

5. Constrain deep interior structure from tides - To constrain the deep interior from tides, determine the Love Number, k2, to an accuracy of 6 x 10^-4.

6. Place limits on the size of the possible inner core - To place limits on the size of a possible solid inner core, determine the Love Number, k2, to an accuracy of 2 x 10^-4 and determine the second degree and first-order gravity coefficients to an accuracy of 1 x 10^-10.

GRAIL's Extended Mission included six additional investigations:

1. Structure of impact craters

Utilize high resolution gravitational field to examine the structure of simple crater structure and central peaks.

2. Near-surface magmatism

Investigate the processes and extent of magmatism on the moon.

3. Mechanisms and timing of deformation

Develop a possible record and timing of faulting.

4. Cause(s) of crustal magnetization

Investigate sources of magnetization on the Moon.

5. Estimation of upper-crustal density

Examine variation of upper crustal density and porosity.

6. Mass bounds on polar volatiles

Study the relationship, if any, of neutron suppression regions to sub- surface structure.   
  
Science Instruments

To measure the inter-spacecraft range-rate, each spacecraft had a Ka-band Lunar Gravity Ranging System (LGRS), derived from the Earth-orbiting Gravity Recovery and Climate Experiment (GRACE) instrument. Timing and frequency within the LGRS were referred to its on-board Ultra-Stable Oscillator (USO), which also served as a frequency reference for the X-Band Radio Science Beacon (RSB) and a timing reference for the S-Band Timing Transfer Assembly (TTA) on each spacecraft. The RSB sent a one-way signal to DSN stations on the ground. The TTA synchronized timing between the two spacecraft LGRS units.

Also included on the spacecraft was an 'E/PO MoonKam' assembly that provided images and video of the lunar surface as part of the Education/Public Outreach and Student Collaboration segment of GRAIL.   
  
References

Roncoli, R.B., and K.K. Fujii, Mission Design Overview for the Gravity Recovery and Interior Laboratory (GRAIL) Mission, AIAA/AAS Astrodynamics Specialist Conference, Toronto, Ontario, Canada, 2010. doi:10.2514/6.2010-8383.