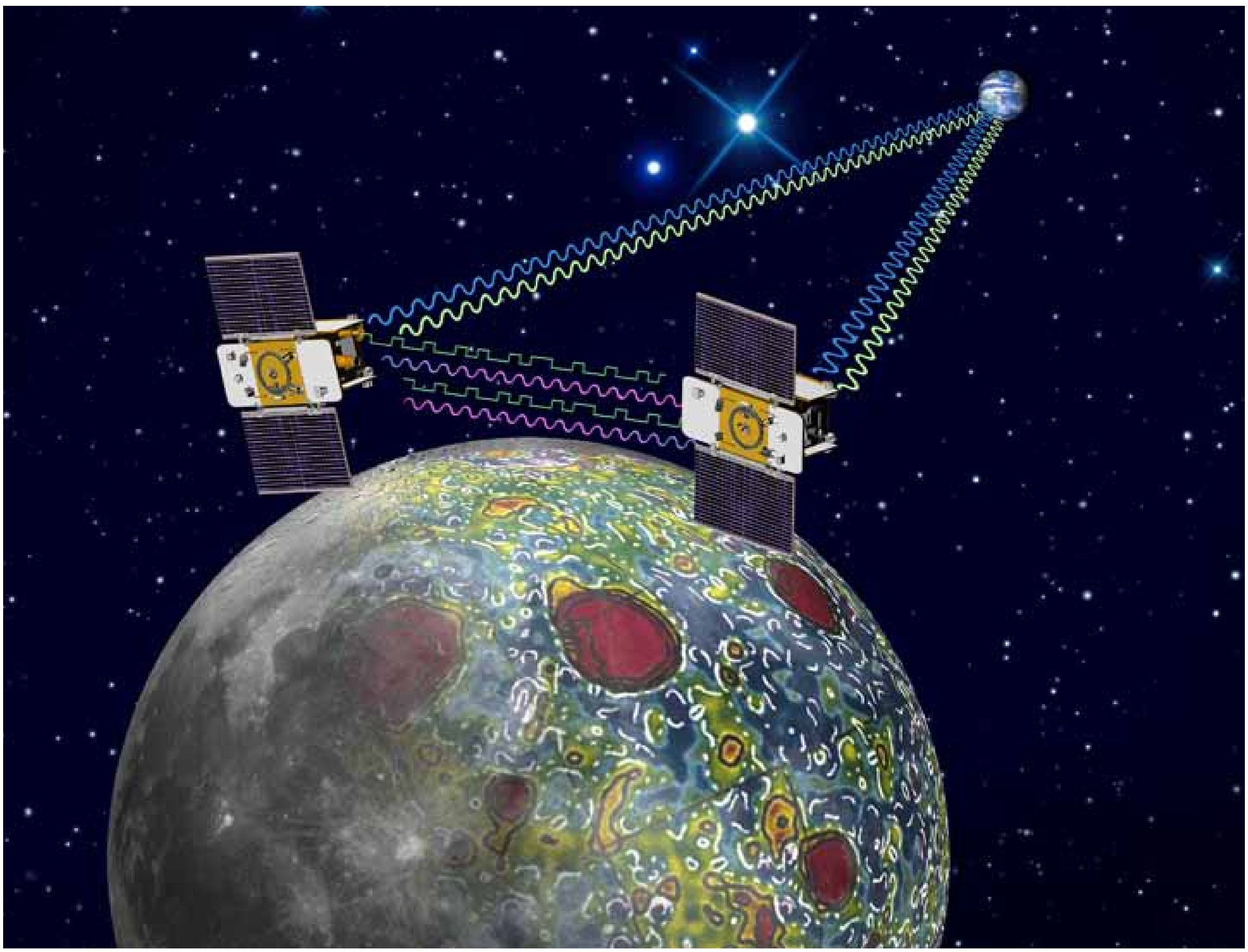
National Aeronautics and Space Administration

PRESS KIT/AUGUST 2011

Gravity Recovery and Interior Laboratory (GRAIL) Launch



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Media Contacts

Dwayne Brown NASA Headquarters, Washington, DC	Policy/Program Management	202-358-1726 dwayne.c.brown@nasa.gov
DC Agle Jet Propulsion Laboratory, Pasadena, Calif.	GRAIL Mission	818-393-9011 agle@jpl.nasa.gov
Caroline McCall Massachusetts Institute of Technology, Cambridge, Ma.	Science Investigation	617-253-1682 cmccall5@mit.edu
Gary Napier Lockheed Martin Space Systems, Denver, Colo.	Spacecraft	303-971-4012 gary.p.napier@lmco.com
George Diller Kennedy Space Center, Cape Canaveral, Fla.	Launch Operations	321-867-2468 george.h.diller@nasa.gov

For more information

http://www.nasa.gov/grail

http://grail.nasa.gov

Contents

Media Services Information

NASA Television Transmission

In continental North America, Alaska and Hawaii, NASA Television's Public, Education, Media and HD channels are MPEG-2 digital C-band signals carried by QPSK/DVB-S modulation on satellite AMC-3, transponder 15C, at 87 degrees west longitude. Downlink frequency is 4000 MHz, horizontal polarization, with a data rate of 38.86 MHz, symbol rate of 28.1115 Ms/s, and 3/4 FEC. A Digital Video Broadcast (DVB) compliant Integrated Receiver Decoder (IRD) is needed for reception. Note: Effective Wednesday, Sept. 1, 2010, at 2 p.m. Eastern, NASA TV is changing the primary audio configuration for each of its four channels to AC-3, making each channel's secondary audio MPEG 1 Layer II.
For digital downlink information for NASA TV's Media Channel, access to NASA TV's Public Channel on the web and a schedule of programming for GRAIL activities, visit **http://www.nasa.gov/ntv**.

Media Credentialing

News media representatives who wish to cover the GRAIL launch must contact NASA/Kennedy Space Center Public Affairs in advance at 321-867-2468.

News Conferences

Two GRAIL pre-launch news conferences will be held at the Kennedy Space Center Press Site. The GRAIL "mission" news conference will be held on Sept. 6, 2011, at 1 p.m. EDT. The second, the GRAIL "science" news conference, will be held on Sept. 7, 2011 at 10 a.m. EDT. The news conferences will be televised on NASA TV.

Launch Status

Recorded status reports will be available beginning two days before launch at 321-867-2525 and 301-286-NEWS.

Internet Information

More information on the GRAIL mission, including an electronic copy of this press kit, news releases, status reports and images, can be found at **http://grail.nasa.gov** and **http://www.nasa.gov/grail**.

Quick Facts

Mission Name

GRAIL is an acronym for Gravity Recovery And Interior Laboratory.

Spacecraft

The two spacecraft (GRAIL-A and GRAIL-B) are mirror twins.

Structure
Main structure: 3.58 feet (1.09 meters) high, 3.12 feet (0.95 meters) wide, 2.49 feet (0.76 meters) deep

Power
Total solar array power at 1 AU: 763 watts

Power: Four panels of silicon solar cells mounted on satellite's top and side exterior surfaces

Batteries: 10 nickel-hydrogen cells providing up to 16 amp-hours of 28-volt power

Instruments
Microwave ranging instrument, accelerometer, star camera

Mass
Launch: 677 pounds (307 kilograms)
Dry: 443 pounds (201 kilograms)
Fuel/He: 234 pounds (106 kilograms)

Launch Vehicle

Type: Delta II 7920H-10C (also known as a Delta II Heavy)
Height with payload: 124 feet tall (37.8 meters) and 8 feet (2.4 meters) in diameter
Mass fully fueled: 622,662 pounds (282,435 kilograms)

First Stage:
— Main engine (RS-27A) and nine (46-inch, or 1.2 meter) strap-on solid rocket motors
— LOX and RP-1 (kerosene), liftoff thrust of 207,000 pounds
— Each solid rocket motor produces 136,400 pounds of thrust

Second Stage:
— Aerojet AJ10-118K second stage engine
— Burns Aerozine-50 and nitrogen tetroxide oxidizer
— Vacuum-rated thrust: 9,645 pounds

Launch Site: Space Launch Complex 17B, Cape Canaveral Air Force Station, Fla.

GRAIL Mission Milestones and Distances Traveled

Launch period: Sept. 8 – Oct. 19, 2011 (42 days).
Launch location: Pad SLC-17B, Cape Canaveral Air Force Station, Fla.
Moon Arrival Date:
GRAIL-A: Dec. 31, 2011
GRAIL-B: Jan. 1, 2012

Science Orbit Altitude: 34 miles (55 kilometers)

The distances travelled by GRAIL-A and GRAIL-B to the moon are similar but not the same. Also, the distance travelled to the moon changes (decreases) as a function of launch date. The distance the spacecraft will have travelled for a Sept. 8 launch is much larger than the distance travelled on an Oct. 19 launch.

Distance travelled to the moon (launch to lunar orbit insertion) for a launch on Sept. 8:
GRAIL-A = 2,594,378 miles (4,175,246 kilometers)
GRAIL-B = 2,663,793 miles (4,286,959 kilometers)

Distance travelled to the moon for a launch on October 19:
GRAIL-A = 2,243,336 miles (3,610,300 kilometers)
GRAIL-B = 2,305,784 miles (3,710,800 kilometers)

Distance spacecraft travel in lunar orbit (from lunar orbit insertion to end-of-mission):
GRAIL-A = 13,193,550 miles (21,232,961 kilometers)
GRAIL-B = 12,800,869 miles (20,601,001 kilometers)

Program

The GRAIL mission totals about $496.2 million, which includes spacecraft development and science instruments, launch services, mission operations, science processing and relay support.

Moon Facts

The actual Earth–moon distance ranges from about 223,700 to 251,700 miles (360,000 to 405,000 kilometers), depending on the moon's position in its orbit.

The mean radius of the moon is 1,080 miles (1,737.4 kilometers); the diameter is 2,159.1 miles (3,474.8 kilometers).

Total mass of the moon is 81 quintillion tons (74 sextillion kilograms). The surface temperature at the equator during the day is as high as 273 degrees Fahrenheit (134 degrees Celsius) and at night is as cold as minus 244 degrees Fahrenheit (minus 153 degrees Celsius).

Gravity at the surface of the moon is 1/6 that of Earth. The moon's magnetic field is less than 0.01 that of Earth's.

The orbital speed of the moon is 2,287 mph (3,680 kilometers per hour).

At the closest distance, it would take 135 days to drive by car at 70 mph (113 kilometers per hour) to the moon.

The moon is actually moving away from Earth at a rate of 1.5 inches (3.8 centimeters) per year.

The moon's widest craters are 1,553 miles (2,500 kilometers) in diameter.

From Earth, we always see the same side of the moon.

If Earth did not have its moon, Earth would spin three times as fast, making a day last only 8 hours instead of 24.

The age of the oldest moon rock collected by astronauts is 4.5 billion years old. The rocks collected during NASA's Apollo program weigh in at 842 pounds (382 kilograms).

The moon's highest mountains are 5.6 miles high (9 kilometers).

The lunar day (or the time from sunrise to sunrise) on the moon is approximately 708 hours (29.5 days).

The surface area of the moon is 23,559,000 square miles (37,914,000 square kilometers). It has almost the same surface area as the continent of Africa.

If you weighed 120 pounds, you would weigh only 20 pounds on the moon.

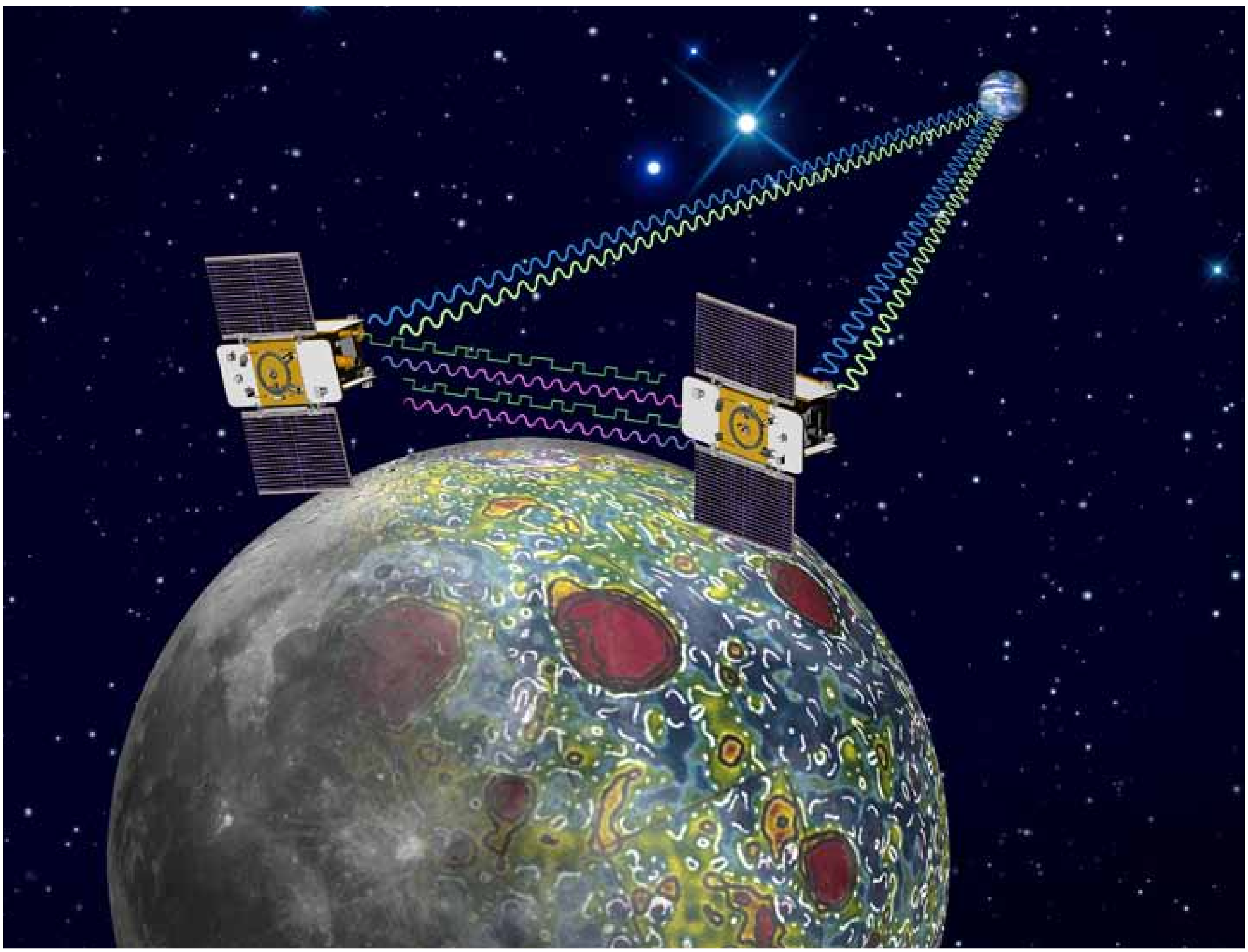
The moon has no significant atmosphere or clouds, and no known active volcanoes.

There are two high tides and two low tides every day on every beach on Earth because of the moon's gravitational pull.

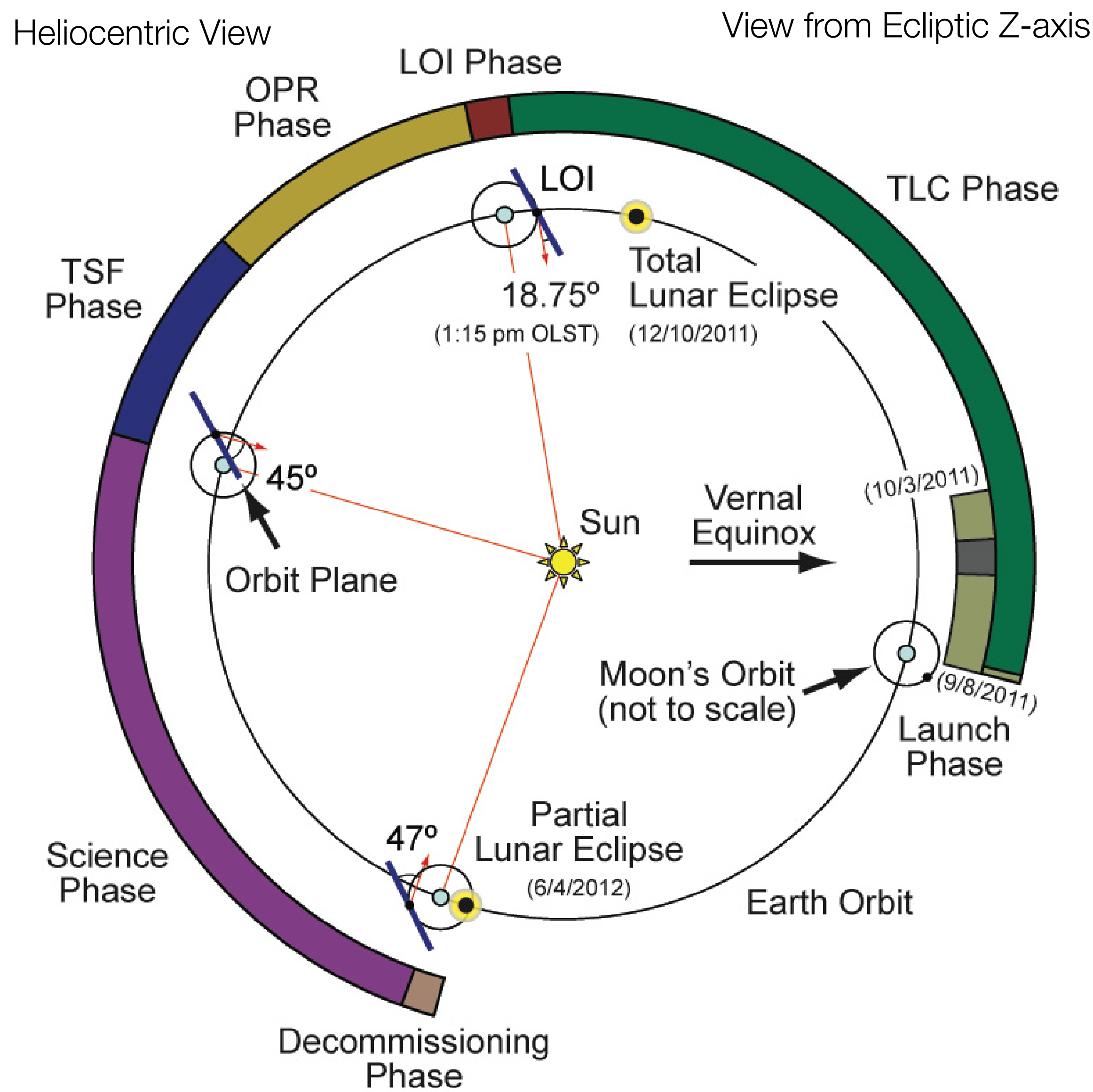
Why GRAIL?

The Gravity Recovery And Interior Laboratory (GRAIL) will unlock the mysteries of the moon hidden below its surface. It will do so by creating the most accurate gravitational map of the moon to date, improving our knowledge of near-side gravity by 100 times and of far-side gravity by 1,000 times.

The high-resolution map of the moon's gravitational field, especially when combined with a comparable-resolution topographical field map, will enable scientists to deduce the moon's interior structure and composition and to gain insights into its thermal evolution — that is, the history of the moon's heating and cooling, which opens the door to understanding its origin and development. Accurate knowledge of the moon's gravity will also be an invaluable navigational aid for future lunar spacecraft. Finally, GRAIL will also help us understand the broader evolutionary histories of the other rocky planets in the inner solar system: Mercury, Venus, Earth and Mars. Indeed, the moon is a linchpin for understanding how the terrestrial planets evolved.



Mission Overview



This figure shows a timeline of the GRAIL mission phases from launch through the various mission phases. Since the relative position of Earth and the moon change over this entire period, it is simplest to illustrate the events relative to the sun, or heliocentric view.

The twin GRAIL spacecraft (called GRAIL-A and GRAIL-B) will be launched side-by-side on a single Delta II vehicle during a 42-day launch period that opens on September 8, 2011.

The GRAIL mission is divided into seven mission phases: Launch, Trans-Lunar Cruise, Lunar Orbit Insertion, Orbit Period Reduction,Transition to Science Formation, Science and Decommissioning.

Once launched, GRAIL will enter a three-and-a-half-month Trans-Lunar Cruise phase, which allows the two spacecraft to efficiently venture from Earth to the moon via the Sun-Earth Lagrange point 1. Lagrange point 1 is named for the Italian-French mathematician Joseph-Louis Lagrange. In 1764, he authored an essay for the Paris Academy of Sciences, defining points between bodies in space where the gravity between them balances the centrifugal force experienced at those points while orbiting with the bodies. This low-energy transfer was chosen to reduce the size of the rocket required to place GRAIL on its correct trajectory, allow more time for spacecraft check-out and increase the number of days available in the launch period.

Arrival at the moon occurs on a fixed date for both orbiters and is independent of the launch date. The year ends with the arrival of the GRAIL-A orbiter at the moon on Dec. 31, 2011, and the new year is ushered in with the GRAIL-B orbiter arriving at the moon on Jan. 1, 2012. Both spacecraft approach the moon under its south pole, where they execute a 38-minute Lunar Orbit Insertion maneuver to put them in an elliptical orbit with an orbital period of just over 11.5 hours.

A series of maneuvers is then performed to reduce the orbits to become nearly circular with a 34-mile (55-kilometer) altitude.

The 82-day Science Phase is divided into three 27.3-day mapping cycles. During the Science Phase, the moon will rotate three times underneath the GRAIL orbit. The collection of gravity data over one complete rotation (27.3 days) is referred to as a Mapping Cycle.

Following the Science Phase, a five-day decommissioning period is planned, after which the spacecraft will impact the lunar surface in approximately 40 days.

Mission Phases

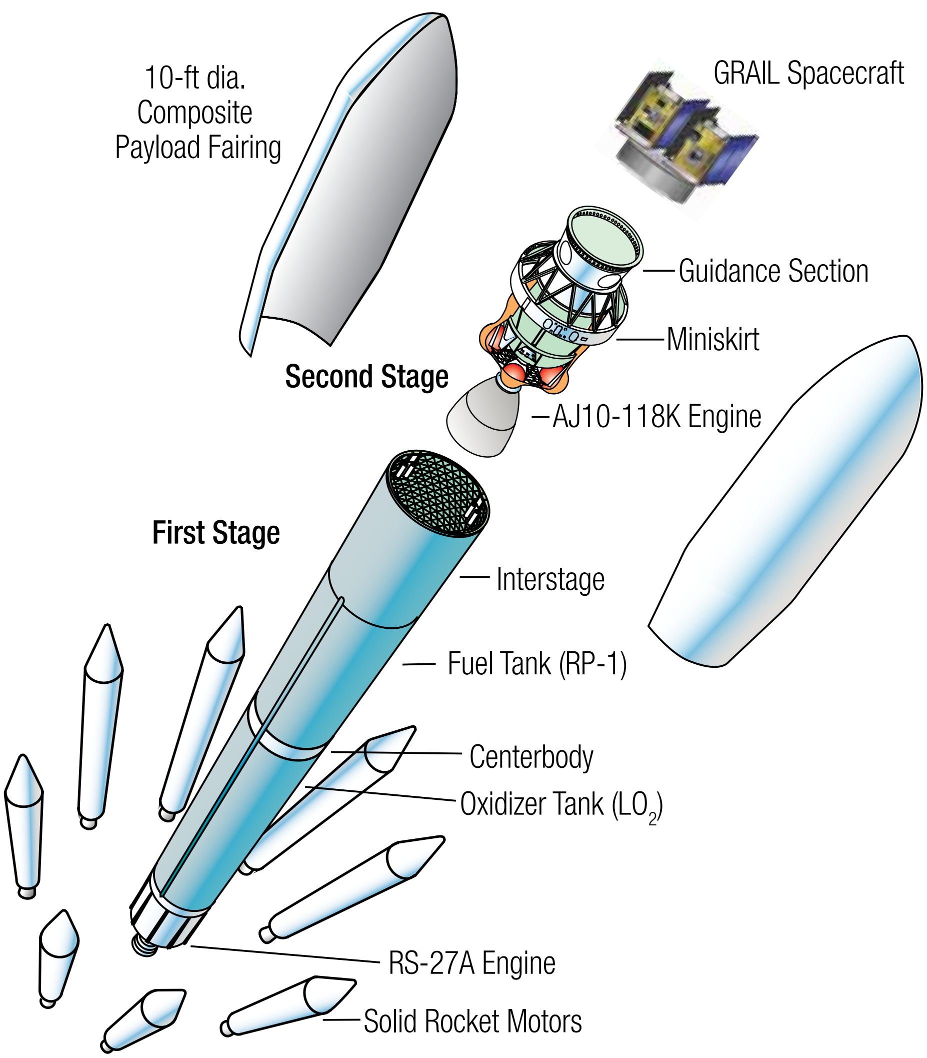
Mission Phase	Phase Start (for GRAIL-A and GRAIL-B)
Launch	08-Sep-11
Trans-Lunar Cruise (TLC)	09-Sep-11
Lunar Orbit Insertion (LOI)	28-Dec-11
Orbit Period Reduction (OPR)	02-Jan-12
Transition to Science Formation (TSF)	06-Feb-12
Science	08-Mar-12
Decommissioning	29-May-12

Launch Phase

The Launch Phase begins when the orbiters transfer to internal power at six minutes before liftoff and extends through the initial 24 hours after liftoff. During this phase, the orbiters will undergo launch, separation from the launch vehicle, initial Deep Space Network acquisition and solar array deployment.

Launch Strategy

To ensure a high probability of launching, GRAIL has developed a launch period strategy that has a 42-day launch period. On each day, there are two separate instantaneous launch opportunities separated in time by approximately 39 minutes. On Sept. 8, the first launch opportunity is at 8:37 a.m. EDT (5:37 a.m. PDT). The second launch opportunity is 9:16 a.m. EDT (6:16 a.m. PDT).



GRAIL's Ride Into Space

The launch vehicle selected for the GRAIL mission is the United Launch Alliance Delta II 7920H-10C. This is a two-stage (liquid propellant) launch vehicle with nine strap-on solid rocket motors and a 9.8-foot-diameter (three-meter) payload fairing. The "H" designation identifies the vehicle as a "Heavy" lift Delta II launch vehicle. This vehicle provides more performance than the standard Delta II vehicle by using larger strap-on solids developed for the Delta III launch vehicle. The launch vehicle is slightly more than 125 feet (38 meters) tall.

Stage I

The first stage of the Delta II uses a Rocketdyne RS-27A engine. This main engine is a single start, liquid bipropellant RS-27A engine. The Delta II propellant load consists of RP-1 fuel (thermally stable kerosene) and liquid oxygen for the oxidizer. The RP-1 fuel tank and the liquid oxygen tank on the first stage are separated by a center body section that houses control electronics, ordnance sequencing equipment, a telemetry system and a rate gyro. The main engine will burn for approximately 263 seconds, and will then be jettisoned into the Atlantic Ocean.

Graphite-Epoxy Strap-on Solid Rocket Motors

For the Delta II Heavy, nine strap-on graphite-epoxy motors are used to augment the main-engine thrust during the initial part of the ascent. The strap-ons for the Delta II Heavy launch vehicle are 46 inches (1,168 millimeters) in diameter and are fueled with approximately 37,500 pounds (17,000 kilograms) of hydroxyl-terminated polybutadiene propellant. Six of the nine solid rocket motors are ignited at the time of liftoff. The remaining three, with extended nozzles, are ignited shortly after the initial six strap-on motors burn out. Each solid rocket motor will burn for approximately 80 seconds.

Second Stage

The second stage of the Delta II is powered by an Aerojet AJ10-118K engine, burning a combination of Aerozine 50 (a 50/50 mix of hydrazine and unsymmetric dimethyl-hydrazine) and nitrogen tetroxide as the oxidizer. The second stage is a restartable stage. The first burn of the second stage occurs during the final portion of the boost phase and is used to insert the vehicle into low Earth orbit. After a coast phase, the second stage is used once again to precisely provide the velocity change needed to inject the spacecraft onto the desired low-energy flight path toward the moon.

Payload Interface and Fairing

The two GRAIL orbiters are housed side-by-side within a payload fairing that is 9.8 feet (3 meters) in diameter and 30 feet (8.88 meters) tall. The fairing is used to protect the orbiters during the early portion of the boost phase when the aerodynamic forces are great. The fairing will be jettisoned shortly after the ignition of Stage II, at about 281 seconds into flight and an altitude of approximately 94.4 miles (152 kilometers).

Launch Profile

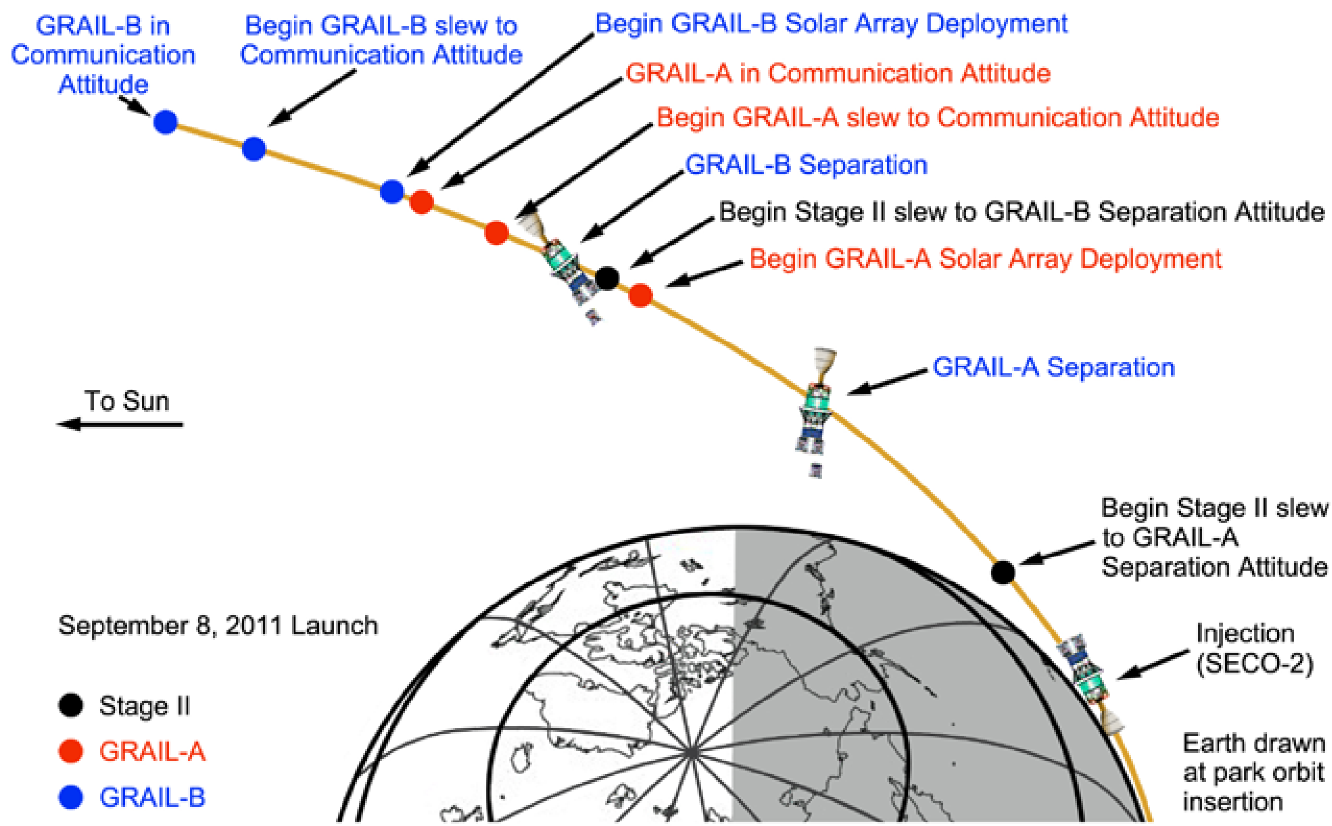
The first stage or main engine and six of the nine strap-on solid rocket motors are ignited at liftoff. The remaining three solids are ignited following the burnout of the first six solids.

Following the main engine burn, the second stage will perform the first of its two burns, placing the orbiters into a 90-nautical mile (167 kilometer) near-circular parking orbit. Following a coast period of just under an hour, the second stage will be restarted, delivering the orbiters on their trajectory to the moon.

Orbiter-Launch Vehicle Separation

Beginning approximately three minutes after the upper-stage has completed its final burn, the stage will perform an attitude maneuver that will reorient the stage to the required separation attitude. At the completion of this maneuver, nine minutes and 30 seconds after the upper stage engine cutoff, the second stage will send a signal that will cause the separation of GRAIL-A to occur. A little more than seven minutes later, the upper stage will begin the maneuver to the desired attitude for GRAIL-B separation. This maneuver will reorient the second stage 45 degrees away from the GRAIL-A separation attitude. Once the proper attitude is achieved for the GRAIL-B spacecraft, a second signal will trigger the separation of GRAIL-B at 8 minutes and 15 seconds after the GRAIL-A separation.

Separation of a GRAIL spacecraft from the launch vehicle is detected using three separation breakwires



Separation and initial acquisition graphic for a Sept. 8 launch date.

on the spacecraft. Once a majority of these breakwires indicate that separation has occurred, the spacecraft will autonomously begin to execute commands that were loaded prior to liftoff. Confirmation of the separation events will be provided by the launch vehicle telemetry. In addition, visual confirmation of each orbiter's separation is expected via video from a RocketCam mounted on the second stage of the launch vehicle.

The deployment of the solar arrays occurs in sunlight, shortly after exit from solar eclipse, and is visible from NASA's Deep Space Network tracking stations at Goldstone, Calif. This will allow the telemetry associated with the deployment to be downlinked to Earth in real time.

Both solar arrays will be commanded to deploy at nearly the same time. It will take, at most,127 seconds for the arrays to reach their fully deployed positions.

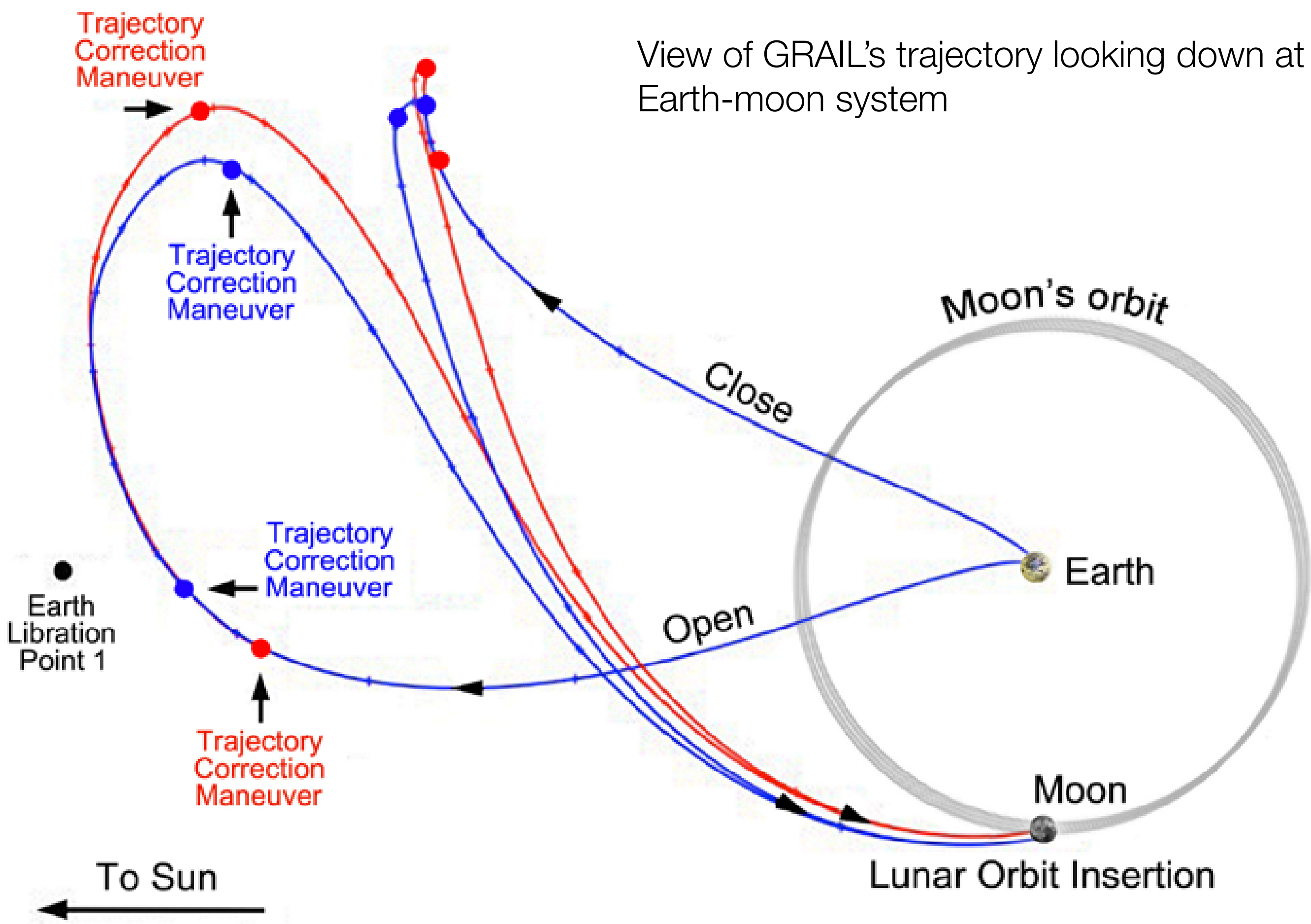
Trans-Lunar Cruise Phase

The Trans-Lunar Cruise Phase is the period of time when both orbiters will be en route to the moon via a low-energy trajectory. This phase will include a series of checkouts and calibrations to characterize the performance of the spacecraft and payload subsystems, as well as navigation activities required for determining and correcting the vehicle's flight path, and activities to prepare for lunar orbit insertion.

During the Trans-Lunar Cruise Phase, up to five trajectory correction maneuvers will be performed. The second and third maneuver will separate the GRAIL-A and GRAIL-B arrival times at the moon by approximately one day.

Lunar Orbit Insertion Phase

The primary focus for this phase is the critical lunar orbit insertion maneuver. This phase begins three days prior to GRAIL-A arrival at the moon, and ends



The figure shows GRAIL-A and GRAIL-B trajectories for a launch at the open and close of the launch period. The low-energy trajectories leave Earth following a path towards the sun, passing near the interior Sun-Earth Lagrange Point 1 (Earth Libration Point 1) before heading back towards the Earth-moon system.

one day past the Lunar Orbit Insertion burn for GRAIL-B.

Both orbiters approach the moon from the south, flying nearly directly over the lunar south pole. The lunar orbit insertion burn for each spacecraft lasts approximately 38 minutes and changes the orbiter velocity by about 427 mph (191 meters per second). Separated by about 25 hours, the lunar orbit insertion maneuvers will place each orbiter into a near-polar, elliptical orbit with a period of 11.5 hours. These maneuvers will be simultaneously visible from Deep Space Network tracking stations in Madrid, Spain and Goldstone, Calif.

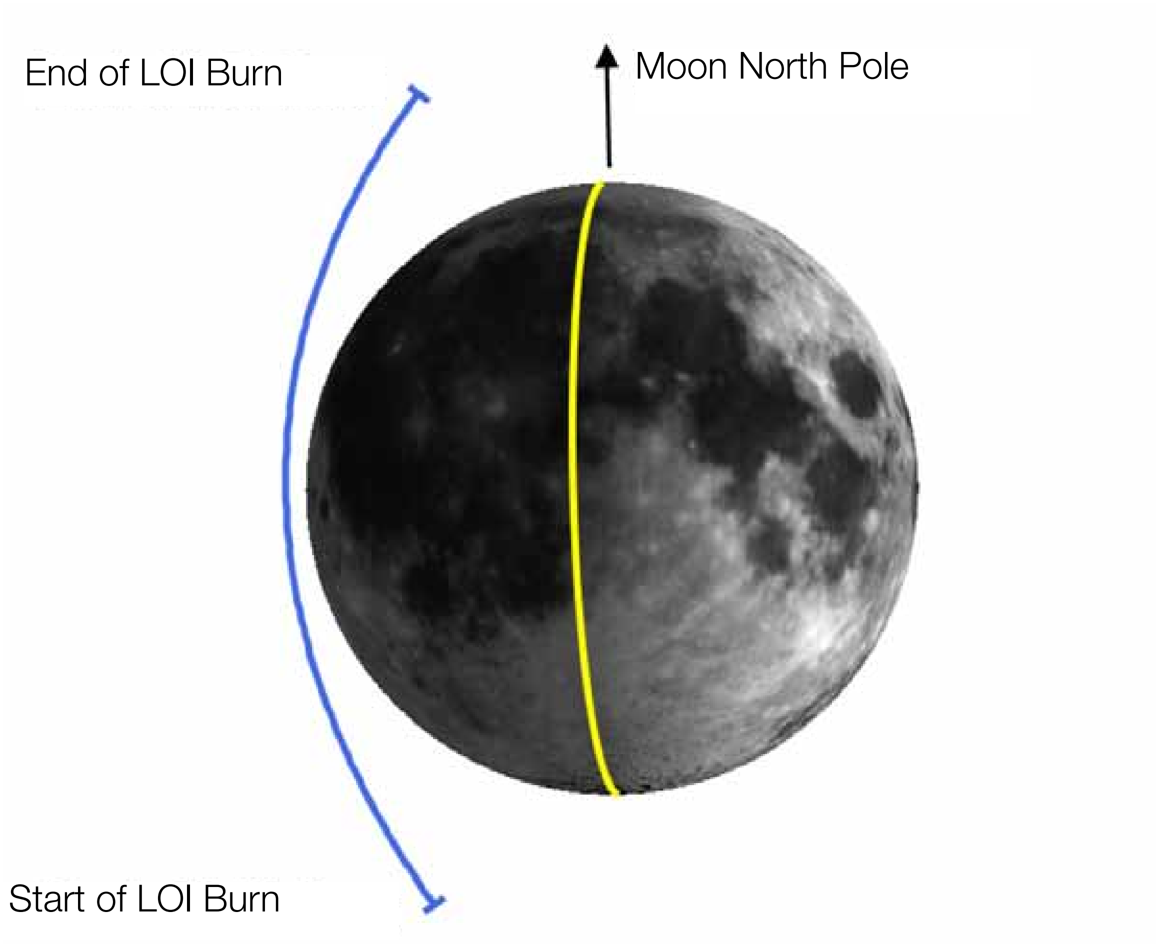
Orbit Period Reduction Phase

The Orbit Period Reduction Phase starts one day after the lunar orbit insertion maneuver for GRAIL-B and continues for five weeks. It includes a series of maneuvers, grouped into two different clusters for each orbiter, performed to reduce the orbit period from 11.5 hours down to just under two hours.

Transition to Science Formation Phase

From launch through the end of the previous phase, the two orbiters will be operated essentially independently. Activities on GRAIL-A and GRAIL-B are separated in time to reduce operations conflicts and competition for ground resources. No attempt is made to fly the two orbiters in a coordinated manner. That all changes in the Transition to Science Formation Phase, when for the first time, the position of one orbiter relative to the other becomes relevant.

The configuration of the two GRAIL orbiters is slightly different, making the order in which they orbit the moon extremely important. At the beginning of the Transition to Science Formation Phase, the orbit



The incoming trajectory and Lunar Orbit Insertion (LOI) burn of GRAIL-A.Blue line depicts the "burn arch" for the spacecraft. Yellow line marks the moon's terminator at time of insertion.

period for GRAIL-B is targeted to be approximately three minutes larger than the period of GRAIL-A. This difference in period means that the GRAIL-A orbiter, flying below the GRAIL-B orbiter, will lap the GRAIL-B orbiter once every three days. This creates a situation where subsequent maneuvers can be timed so that the distance between the two orbiters can be managed and reduced in a controlled manner.

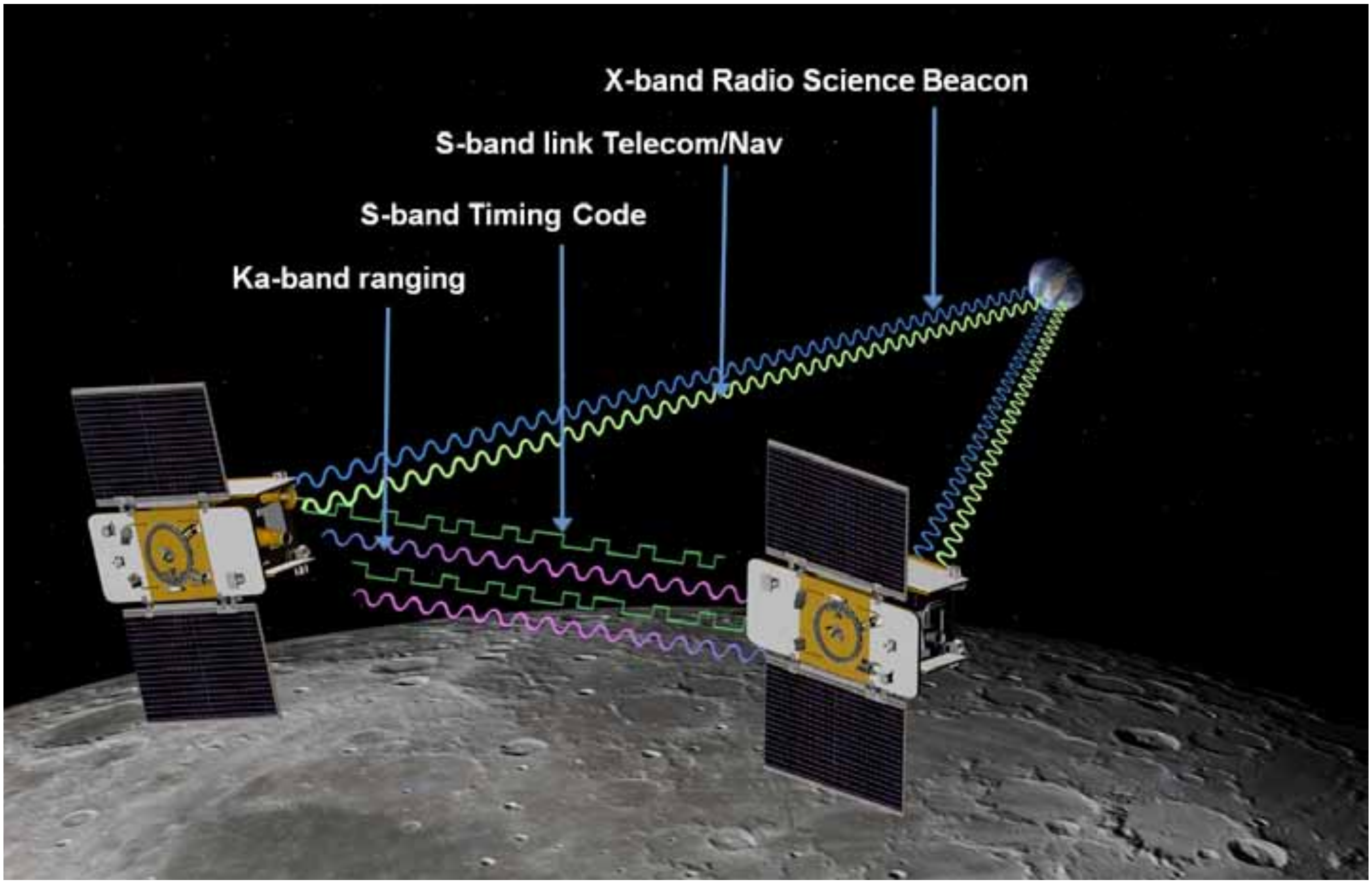
A series of rendezvous-like maneuvers will be performed in this phase to achieve the desired initial separation distance and ensure that GRAIL-B is ahead of the GRAIL-A in the formation.

Science Phase

The Science Phase activities consist of the collection of gravity science data and the execution of Education and Public Outreach activities using the MoonKAM system.

At the start of the Science Phase, the GRAIL spacecraft will be in a near-polar, near-circular orbit with an altitude of about 34 miles (55 kilometers). The initial conditions have been designed so that the natural perturbations of the lunar gravity field allow the orbit to evolve without requiring any orbit maintenance maneuvers.

The science orbit is designed to satisfy the basic science requirements of the GRAIL mission, which are for a low-altitude, near-circular, near-polar orbit that does not require any maneuvers to maintain the orbit. The primary design parameter from a science perspective is the orbit altitude, since sensitivity to the lunar gravity field is driven by orbit altitude (i.e. the lower the altitude, the more sensitive the science measurements). Limits on the minimum orbit altitude are driven primarily by orbit lifetime considerations.



The two GRAIL spacecraft.

During the 82-day Science Phase, the moon will rotate three times underneath the GRAIL orbit. The collection of gravity data over one complete rotation (27.3 days) is referred to as a Mapping Cycle.

During Mapping Cycle 1, the mean separation distance between the two spacecraft is designed to increase from approximately 62 to 140 miles (100 kilometers to 225 kilometers). A very small Orbit Trim Maneuver executed near the end of Mapping Cycle 1 will then be used to change the separation drift rate. Following this orbital trim maneuver, the mean separation distance will decrease from 140 miles (225 kilometers) to approximately 40 miles (65 kilometers) at the end of Mapping Cycle 3 (the end of the Science Phase). The change in separation distance is required to meet the GRAIL science objectives. The data collected when the orbiters are closer together helps to determine the local gravity field, while data collected when the separation distances are larger will be more useful in satisfying the science objectives related to detection and characterization of the lunar core.

Decommissioning Phase

The final phase of the GRAIL mission is the Decommissioning Phase. During this seven-day phase, the orbiters will perform a final Ka-band calibration and will continue to acquire science data, as power and thermal resources allow. The mission phase ends at the time of a partial lunar eclipse on June 4, 2012.

The design of the GRAIL science orbit is such that, at the end of the Science Phase, the orbits of the two spacecraft carry them to within approximately 9.3 to 12.4 miles (15 to 20 kilometers) above the lunar surface at their lowest point. If no maneuvers are executed after this point, both orbiters will impact the lunar surface during, or shortly after, this mission phase. The GRAIL mission is expected to end within a few days of the partial lunar eclipse in June 2012. There are no plans to target the impact points on the lunar surface.

Spacecraft

Two orbiters are part of the GRAIL mission; one is designated GRAIL-A and the other GRAIL-B.

Technicians prepare to hoist one of the two GRAIL spacecraft upon completion of a thermal vacuum test at the Lockheed Martin Space Systems facility in Denver. Image Credit: NASA/JPL-Caltech/LMSS

The two Lockheed-Martin built spacecraft are nearly identical, but there are a few important differences between them due to the need to point the spacecraft at one another during the Science Phase of the mission. These include the angles at which their star trackers are pointing, the Lunar Gravity Ranging System antenna cant angle, and the MoonKAM mounting. In addition, during the Science Phase, the orientation of the orbiters is different. They will fly facing each other — one forward and the other backward — so they can point their Ka-band antennas at each other.

Structure

GRAIL comprises twin spacecraft built on the Lockheed Martin Experimental Small Satellite (XSS-11) bus, with a science payload derived from the GRACE terrestrial gravity mission. The GRAIL bus is a rectangular composite structure with a dry mass of about 443 pounds (201 kilograms), and fully fueled mass of about 677 pounds (307 kilograms).

Attitude Control Subsystem

The Attitude Control subsystem is used to provide three-axis stabilized control throughout the mission.

This subsystem consists of a sun sensor, a star tracker, reaction wheels, and an inertial measurement unit.

Propulsion System

The propulsion subsystem provides propulsive impulse for all large maneuvers including trajectory correction maneuvers, lunar orbit insertion and circularization maneuvers. The propulsion system consists of a propellant storage tank, a high-pressure helium recharge tank, a feed system for propellant loading and distribution, a hydrazine catalytic thruster for change-in-velocity impulse delivery, a warm gas attitude control system, and eight warm gas attitude control system thruster valves.

The main engine is an MR-106L 22 Newton liquid hydrazine thruster. The main engine provides the majority of the thrust for spacecraft trajectory correction maneuvers. The warm gas attitude control system thrusters will be used for the small maneuvers planned for the Science Phase of the mission.

The warm gas attitude control system utilizes eight 0.9 Newton thrusters. The attitude control thrusters are canted to provide coupled thrust during main engine maneuvers. The warm gas thruster locations have been designed to minimize plume impingement on the main body and solar arrays.

Command & Data Handling

The Command and Data Handling subsystem is used for telemetry and command processing for the orbiter. The single-string command and data handling subsystem also features an enhanced RAD-750 spacecraft computer with 128 megabytes of Static Dynamic random access memory. In addition, there are 512 megabytes of storage within the Memory and Payload Interface Card for recorded data.

Power

The electrical power subsystem is responsible for generating and storing energy for each orbiter and its systems. This power subsystem includes two solar arrays and a lithium-ion battery.

There are two solar arrays, which generate the energy to operate the orbiter systems. Each solar array has an area of 6.2 square feet (1.88 square meters) and is capable of producing 700 watts of power at the end of the mission. There are 20 cells per string and 26 strings per panel. The solar arrays are deployed shortly after separation from the launch vehicle and remain fixed throughout the mission.

The lithium-ion battery has a capacity of 30 amp-hours, and is used to provide energy to the orbiter during periods when the solar arrays are not able to generate enough power for the orbiter systems.

Telecommunications

The telecom subsystem is responsible for sending telemetry and radiometric data from the orbiter and receiving commands from the ground during the mission. The telecom subsystem for GRAIL consists of an S-band transponder, two low gain antennas, and a single-pole, double-throw coaxial switch used to alternate between the two antennas. The low gain antennas are the mission controllers' primary means of communicating with the spacecraft and enable each spacecraft to communicate with each other.

Science Instruments

The payload on each orbiter consists of a Lunar Gravity Ranging System and an education and public outreach MoonKAM System.

Lunar Gravity Ranging System

The primary payload of the GRAIL spacecraft is the Lunar Gravity Ranging System. The system is responsible for sending and receiving the signals needed to accurately and precisely measure the changes in range between the two orbiters as they fly over lunar terrain of varying density. To accomplish this, the Lunar Gravity Ranging System consists of an ultra-stable oscillator, microwave assembly, a time transfer assembly, and the gravity recovery processor assembly.

The ultra-stable oscillator provides a steady reference signal that is used by all the instrument subsystems. The microwave assembly converts the oscillator's reference signal to the Ka-band frequency, which is transmitted to the other orbiter. The function of the time transfer assembly is to provide a two-way time transfer link between the spacecraft to both synchronize and measure the clock offset between the clocks aboard the two spacecraft.

The time transfer assembly generates an S-band signal from the ultra-stable oscillator reference frequency and sends a GPS-like ranging code to the other spacecraft. The gravity recovery processor assembly combines all the inputs received to produce the radiometric data that is downlinked to the ground.

Outreach Instrument — MoonKAM

MoonKAM is a digital video imaging system that is used as part of the education and public outreach activities for GRAIL. Each MoonKAM system (one per spacecraft) consists of a digital video controller and four camera heads — one pointed slightly forward of the spacecraft, two pointed directly below it, and one pointed slightly backward. The digital video controller serves as the main interface to the spacecraft and provides storage for images acquired by the camera heads. This system can be used to take images or video of the lunar surface with a frame rate up to 30 frames per second.

The MoonKAM system is provided by Ecliptic Enterprises Corporation, Pasadena, Calif., and is operated by undergraduate students at the University of California at San Diego under supervision of faculty and in coordination with Sally Ride Science. Middle school students from around the country will have an opportunity to become involved with MoonKAM imaging. During the Science Phase, operations will be conducted in a non-time-critical, ground-interactive mode.

GRAIL Bloodline

GRAIL will build on the heritage of a predecessor mission called the Challenging Minisatellite Payload, or "Champ." Built by Germany's Earth Research Center (GeoForschungsZentrum) and launched in July 2000, Champ's instruments and its orbit have allowed it to generate simultaneous, highly precise measurements of Earth's gravity and magnetic field.

While Champ has significantly advanced the field of geodesy, scientists desired an even more advanced mission based upon dual satellites flying in formation. The unique design of NASA's GRACE Earth-observing mission led to a hundred-fold improvement in existing gravity maps and allow much improved resolution of the broad- to finer-scale features of Earth's gravitational field over both land and sea, while also showing how much Earth's gravitational field varies with time.

The design of the GRAIL spacecraft is based on the Experimental Small Satellite-11 (XSS-11) technology demonstration mission for the United States Air Force, the Mars Reconnaissance Orbiter (MRO) and the Gravity Recovery and Climate Experiment (GRACE) missions for NASA.

Why Study Gravity?

Gravity is Newton's apple and the stuff of Einstein's theory of relativity, but it is also the law that we all learn to obey from our first breath of life. Gravity is the mutual attraction that pulls two masses together and keeps us firmly planted on Earth.

Sir Isaac Newton first revealed the law of gravity more than 300 years ago. During the 20th century, geophysicists developed techniques to locate mineral deposits and underground formations using spatial changes in Earth's gravity field. Their work laid the modern foundation for the science of geodesy. Today, scientists use measurements from several dozen satellites to develop models of Earth's "geoid" — an imaginary surface upon which the pull of gravity is equal everywhere.

Planetary scientists have taken the study of gravity fields to new heights — and other worlds. The GRAIL mission will forward this scientific endeavor, creating the most accurate gravitational map of the moon to date.

If the moon were a smooth sphere of uniform density, there would be no need for a mission like GRAIL — it would measure no changes in the gravity field. However, the moon isn't smooth and homogeneous — its surface includes mountains that are many miles high, lava flows several hundred miles long and enormous lava tubes and craters of every size. Below the surface, things are even more complex and variable. In fact, the moon has the lumpiest gravitational field known in our solar system. Studying its gravity allows us to better understand the forces that have shaped our natural satellite.

For example, the material that makes up the moon's highlands has a different density than that making up its "seas," or "maria." Since the highland material is less dense than maria material, the gravity in the maria region is usually subtly stronger. Such uneven distribution of mass on the moon's surface and in its interior manifests itself as "lumps" in the planet's gravity field.

Previous space missions have mapped the gravity fields of asteroids, Venus, Mars, Jupiter, Saturn and Earth. Even Earth's moon, the object of GRAIL's attention, has had its gravity field measured on numerous occasions with varying degrees of success. But the accuracy of the GRAIL data will surpass by orders of magnitude that previously obtained, which will allow a new level of understanding about Earth's nearest neighbor.

Science Overview

GRAIL Science Overview

The primary science objectives are to determine the structure of the lunar interior, from crust to core, and to advance understanding of the thermal evolution of the moon. The secondary science objective is to extend knowledge gained from the moon to other terrestrial planets. These objectives will be achieved by obtaining a global, high-accuracy, high-resolution lunar map during a 90-day Science Phase.

The GRAIL mission will create the most accurate gravitational map of the moon to date, improving our knowledge of gravity on the side facing Earth by 100 times and of gravity on the side not facing Earth by 1,000 times. The high-resolution gravitational field, especially when combined with a comparable-resolution topographical field, will enable scientists to deduce the moon's interior structure and composition, and to gain insights into its thermal evolution — that is, the history of the moon's heating and cooling, which opens the door to understanding its origin and development. Accurate knowledge of the moon's gravity will also be an invaluable navigational aid for future lunar spacecraft. Ultimately, the information contributed by the GRAIL mission will increase our knowledge of how Earth and its rocky neighbors in the inner solar system developed into the diverse worlds we see today.

Science Objectives

The moon is the most accessible and best studied of the rocky (aka "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. In fact, orbital observations combined with samples of surface rocks returned to Earth indicate that no other body preserves the record of geological history as clearly as the moon.

The need to understand the lunar internal structure in order to reconstruct planetary evolution motivates GRAIL's primary science objectives, which are to determine the structure of the lunar interior from crust to core and to further the understanding of the thermal evolution of the moon.

Why thermal evolution? A planetary body such as the moon, Earth, and the other terrestrial planets,forms by accretion of primordial dust and rock. Eventually, this protoplanet is heated to the melting point by meteoroids smashing into it and by breakdown of radioactive elements within it. Then, over the eons, it cools off by radiating its heat into space. While it's still molten, heavy materials sink down toward the core and lighter materials float on top, ultimately forming a crust. The story of how a particular planetary body processes its heat and how, when and where heat is replenished by meteorite impacts and radioactive elements break down is the story of how its structure came to be. So understanding the moon's thermal evolution is essential to understanding its origin and development.

The mission's secondary objective is to extend the knowledge it will gain about the moon to inform our understanding of the development of the other planetary bodies in the inner solar system: Mercury, Venus, Earth and Mars. As the most accessible planetary body besides Earth, and as one that is thought to have changed little since its initial development (unlike Earth, Mars, and Venus), the moon offers a unique look into the distant past of planetary evolution.

The GRAIL mission's six science investigations:

1. Map the structure of the lithosphere.

The lithosphere is the portion of the crust and upper mantle with significant strength over a geological time scale. Since the strength of rock is highly dependent on temperature, the thickness of the lithosphere is directly related to thermal evolution. GRAIL will provide evidence of how rigid the lithosphere was — and therefore what the thermal conditions were — at various locations when features were formed.

2. Understand the moon's asymmetric thermal evolution.

The thickness of the crust suggests the extent to which the surface was melted in its early history. The moon's crust has a variable structure, thinner on the near side than on the far side, except for the south pole Aitken basin region, and thinned beneath the major impact basins. Scientists would like to know why.

3. Determine the subsurface structure of impact basins and the origin of mascons.

A surprising discovery was made in the 1960s, when it was found that the moon's gravity was unexpectedly strong over certain impact basins, and that this is what had been pulling lunar spacecraft off course. It was deduced that these impact basins have large mass concentrations (or "mascons" for short) underneath them. GRAIL will provide more information about the nature of these mascons.

4. Ascertain the temporal evolution of crustal brecciation and magmatism.

Analyses of a set of lunar craters indicate that those that formed less than 3.2 billion years ago show less gravity than the surrounding plain, while those formed earlier show about the same gravity as the surrounding plain. GRAIL will help to explain the reasons, including the roles played by brecciation (the formation of new rocks by cementing together fragments of older rocks, often found beneath impact craters on Earth), magmatism (the movement of molten rock inside the moon), and isostatic compensation (a process by which a planetary body evens out the distribution of its mass — for example, by distorting the boundary between the crust and mantle beneath a large impact basin).

5. Constrain deep interior structure from tides.

Earth's gravity creates tides in the solid moon, just as the moon creates tides in Earth's ocean. Of course, the moon's rocky surface doesn't bulge as much as water would — it only deforms about 3.5 inches (9 centimeters) in response to Earth's gravity from one part of the lunar orbit to another. But what's significant to GRAIL is that the moon responds to Earth's gravity all the way down to the core, and different internal structures would produce differences in the way the moon's gravitational field deforms. By analyzing how the field deforms at various parts of the moon's orbit around Earth, scientists will be able to deduce information about the core and other deep features.

6. Place limits on the size of a possible solid inner core.

GRAIL scientists will search for evidence of a solid core within the liquid core the moon is believed to have, and the data they receive will place limits on how big that solid core could be.

Science Team

GRAIL Science Team

Maria Zuber,
principal investigator,
Massachusetts Institute of Technology,
Cambridge

David E. Smith,
deputy principal investigator,
Goddard Space Flight Center,
Greenbelt, Md.

Michael Watkins,
project scientist,
Jet Propulsion Laboratory,
Pasadena

Sami Asmar,
deputy project scientist,
Jet Propulsion Laboratory, Pasadena

Co-Investigators

Alexander S. Konopliv,
NASA's Jet Propulsion Laboratory,
Pasadena, Calif

Frank G. Lemoine,
Goddard Space Flight Center,
Greenbelt, Md.

Jay Melosh,
University of Arizona, Tucson

Gregory A. Neumann,
Goddard Space Flight Center,
Greenbelt, Md.

Roger J. Phillips,
Southwest Research Institute,
San Antonio

Sean C. Solomon,
Carnegie Institution for Science,
Washington, DC

Mark Wieczorek,
University of Paris

James G. Williams,
Jet Propulsion Laboratory,
Pasadena, Calif.

Missions to the Moon

Historical Exploration of the Moon

1609
Hans Lippershey invented the telescope.

1610
Italian astronomer Galileo Galilei made the first telescopic observation of the moon.

1610
Thomas Harriot and Galileo Galilei drew the first telescopic representation of the moon.

1645
Michael Florent van Langren made the first map of the moon.

1647
Johannes Hevelius published the first treatise devoted to the moon.

1651
Giovanni Battista Riccioli named craters after philosophers and astronomers.

1753
Roger Joseph Boscovich proved the moon has no atmosphere.

1824
Franz von Gruithuisen thought craters were formed by meteor strikes.

1920
Robert Goddard suggested sending rockets to the moon.

1959
Soviet spacecraft Luna 2 reached the moon, impacting near the crater Autolycus.

1961
President John F. Kennedy proposed a manned lunar program.

1964
NASA's Ranger 7 produced the first close-up TV pictures of the lunar surface.

1966
Soviet spacecraft Luna 9 made the first soft landing on the moon.

1967
NASA's Lunar Orbiter missions completed photographic mapping of the moon.

1968
NASA's Apollo 8 made the first manned flight to the moon, circling it 10 times before returning to Earth.

1969
Apollo 11 mission made the first landing on the moon and returned samples.

1969
(Nov.) Apollo 12 made first precision landing on the the moon.

1972
Apollo 17 made the last manned landing of the Apollo Program.

1976
Soviet Luna 24 returned the last sample to be returned from the moon (to date).

1990
NASA's Galileo spacecraft obtained multispectral images of the western limb and part of the far side of the moon.

1994
NASA's Clementine mission conducted multispectral mapping of the moon.

1998
NASA's Lunar Prospector launched.

2007
Japanese SELENE (Kaguya) launched.

2007
Chinese Chang'e 1 launched.

2008
Indian Chandrayaan 1 launched.

2009
NASA's Lunar Reconnaissance Orbiter launched

Future NASA Lunar Missions

2012 LADEE (orbiter) — Lunar Atmosphere and Dust Environment Explorer is a NASA mission that will orbit the moon. Its main objective is to characterize the atmosphere and lunar dust environment. In addition to the science objectives, the mission will be testing a new spacecraft architecture called the "Modular Common Bus," which is being developed by NASA as a flexible, low-cost, rapid-turnaround spacecraft for both orbiting and landing on the moon and other deep space targets.

NASA's Discovery Program

GRAIL will be the eleventh Discovery Program mission to enter space.

As a complement to NASA's larger "flagship" planetary science explorations, the Discovery Program goal is to achieve outstanding results by launching many smaller missions using fewer resources and shorter development times. The main objective is to enhance our understanding of the solar system by exploring the planets, their moons, and small bodies such as comets and asteroids. The program also seeks to improve performance through the use of new technology and broaden university and industry participation in NASA missions.

Further information on NASA's Discovery program can be found at: http://discovery.nasa.gov/.

Previous NASA Discovery program missions:

- Near Earth Asteroid Rendezvous was launched Feb. 17, 1996. It became the first spacecraft to orbit an asteroid when it reached Eros in February 2000. After a year in orbit, it achieved the first landing on an asteroid in February 2001, after returning more than 160,000 detailed images. "Shoemaker" was later added to the spacecraft's name in honor of the late planetary scientist Eugene Shoemaker.

- Mars Pathfinder was launched Dec. 4, 1996, and landed on Mars on July 4, 1997. It was the first free-ranging rover to explore the Martian surface, conducting science and technology experiments. Pathfinder's lander operated nearly three times longer than its design lifetime of 30 days, and the Sojourner rover operated 12 times its design lifetime of seven days. After sending back thousands of images and measurements, the mission ended Sept. 27, 1997.

- Lunar Prospector was launched Jan. 6, 1998. It orbited Earth's moon for 18 months, looking for water and other natural resources and returning extensive mapping data to provide insights into lunar origin and evolution. At the mission's end on July 31, 1999, the spacecraft was intentionally crashed into a crater near the moon's south pole in an attempt to detect the presence of water.

- Launched Feb. 7, 1999, Stardust captured and returned to Earth interstellar dust particles and comet dust using an unusual substance called aerogel. On Jan. 2, 2004, it flew within 149 miles (240 kilometers) of the nucleus of Comet Wild 2, collecting samples of comet dust and snapping detailed pictures of the comet's surface. On Jan. 15, 2006, Stardust's sample return capsule returned to Earth, providing scientists worldwide with the opportunity to analyze the earliest materials that created the solar system. NASA extended Stardust's mission to fly by comet Tempel 1, which occurred on Feb. 14, 2011. That mission was referred to as Stardust-NExT. The spacecraft obtained images of the scar on Tempel 1's surface produced by NASA's Deep Impact in 2005 and revealed changes to the comet's surface since a recent close approach to the sun. It also imaged new terrain not seen during the Deep Impact mission and took new dust measurements.

- Launched Aug. 8, 2001, Genesis collected atoms of solar wind beyond the orbit of Earth's moon to accurately measure the composition of our sun and improve our understanding of solar system formation. Its sample return capsule made a hard landing at the time of Earth return on Sept. 8,2004. The mission's samples of solar wind were recovered and are currently being analyzed by scientists at laboratories around the world.

- The Comet Nucleus Tour launched from Cape Canaveral on July 3, 2002. Six weeks later, contact with the spacecraft was lost after a planned maneuver that was intended to propel it out of Earth orbit and into a comet-chasing solar orbit. The probable proximate cause was structural failure of the spacecraft due to plume heating during the embedded solid-rocket motor burn.

- The Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft was launched Aug. 3, 2004. It entered orbit around the planet closest to the sun in March 2011. The spacecraft is mapping nearly the entire planet in color and measuring the composition of the surface, atmosphere and magnetosphere.

- Launched Jan. 12, 2005, Deep Impact was the first experiment to send a large projectile into the path of a comet to reveal the hidden interior for extensive study. On July 4, 2005, traveling at 23,000 mph (39,000 kilometers per hour) a larger flyby spacecraft released a smaller impactor spacecraft into the path of comet Tempel 1 as both recorded observations. The Spitzer, Hubble and Chandra space telescopes also observed from space, while an unprecedented global network of professional and amateur astronomers captured views of the impact, which took place 83 million miles (138 million kilometers) from Earth. NASA extended the Deep Impact mission as EPOXI, a combination of the names for the mission's two components: the Extrasolar Planet Observations and Characterization (EPOCh),and the flyby of comet Hartley 2, called the Deep Impact Extended Investigation (DIXI). The EPOXI mission successfully flew by comet Hartley 2 on Nov. 4, 2011, obtaining the first images clear enough for scientists to link jets of dust and gas with specific surface features.

- Launched on Sept. 27, 2007, NASA's Dawn spacecraft will be the first to orbit two bodies in the main asteroid belt, Vesta and Ceres. Dawn arrived at Vesta on Friday, July 15. The spacecraft will spend a year orbiting the giant asteroid, before traveling to its second destination, arriving at Ceres in February 2015. Studying Vesta and Ceres, the two most massive objects in the asteroid belt, allows scientists to do historical research in space, opening a window into the earliest chapter in the history of our solar system. At each target, Dawn will acquire color photographs, compile topographic maps, map the elemental composition, map the mineralogical composition, measure the gravity field and search for moons. The data gathered by Dawn will enable scientists to understand the conditions under which these objects formed, determine the nature of the building blocks from which the terrestrial planets formed and contrast the formation and evolution of Vesta and Ceres.

- Launched on March 6, 2009, Kepler is in the middle of its prime mission to monitor more than 100,000 stars similar to our sun. The mission was designed to find Earth-sized planets in orbit around stars outside our solar system. With its vast field of view, Kepler detects transits of thousands of planets. So far, it has identified more than 1,200 planet candidates, some of which lie in the "habitable" zones of their stars, where temperatures permit water to be in a liquid state. Kepler has also discovered the smallest known rocky planet, called Kepler-10b, measuring at 1.4 times the size of Earth.

Program/Policy Management

GRAIL's principal investigator is **Maria Zuber** of the Massachusetts Institute of technology, Cambridge.

Michael Watkins and **Sami Asmar**, of NASA's Jet Propulsion Laboratory, Pasadena, Calif., are GRAIL's project scientist and deputy-project scientist, respectively.

The GRAIL project is managed by the Jet Propulsion Laboratory, Pasadena, Calif., for NASA's Science Mission Directorate, Washington. The GRAIL mission is part of the Discovery Program managed at NASA's Marshall Space Flight Center in Huntsville, Ala. Launch management for the mission is the responsibility of NASA's Launch Services Program at the Kennedy Space Center in Florida.

At NASA Headquarters, **Ed Weiler** is associate administrator for the Science Mission Directorate.

James Green is director of the Planetary Division.

William Knopf is GRAIL program executive, and **Robert Fogel** is GRAIL program scientist.

Dennon Clardy of NASA's Marshall Space Flight Center is the Discovery program manager.

At JPL, **David Lehman** is GRAIL project manager. Tom Hoffman is deputy project manager. JPL is a division of the California Institute of Technology, Pasadena, Calif.

Lockheed Martin Space Systems Company, Denver built the GRAIL spacecraft and will handle its day-to-day operations. **John Henkis** is the company's GRAIL program manager and leads the flight team.

The United Launch Alliance is responsible for the Delta II rocket which will carry GRAIL into space.

More information about NASA's GRAIL mission can be found online at http://www.nasa.gov/grail and http://grail.nasa.gov.