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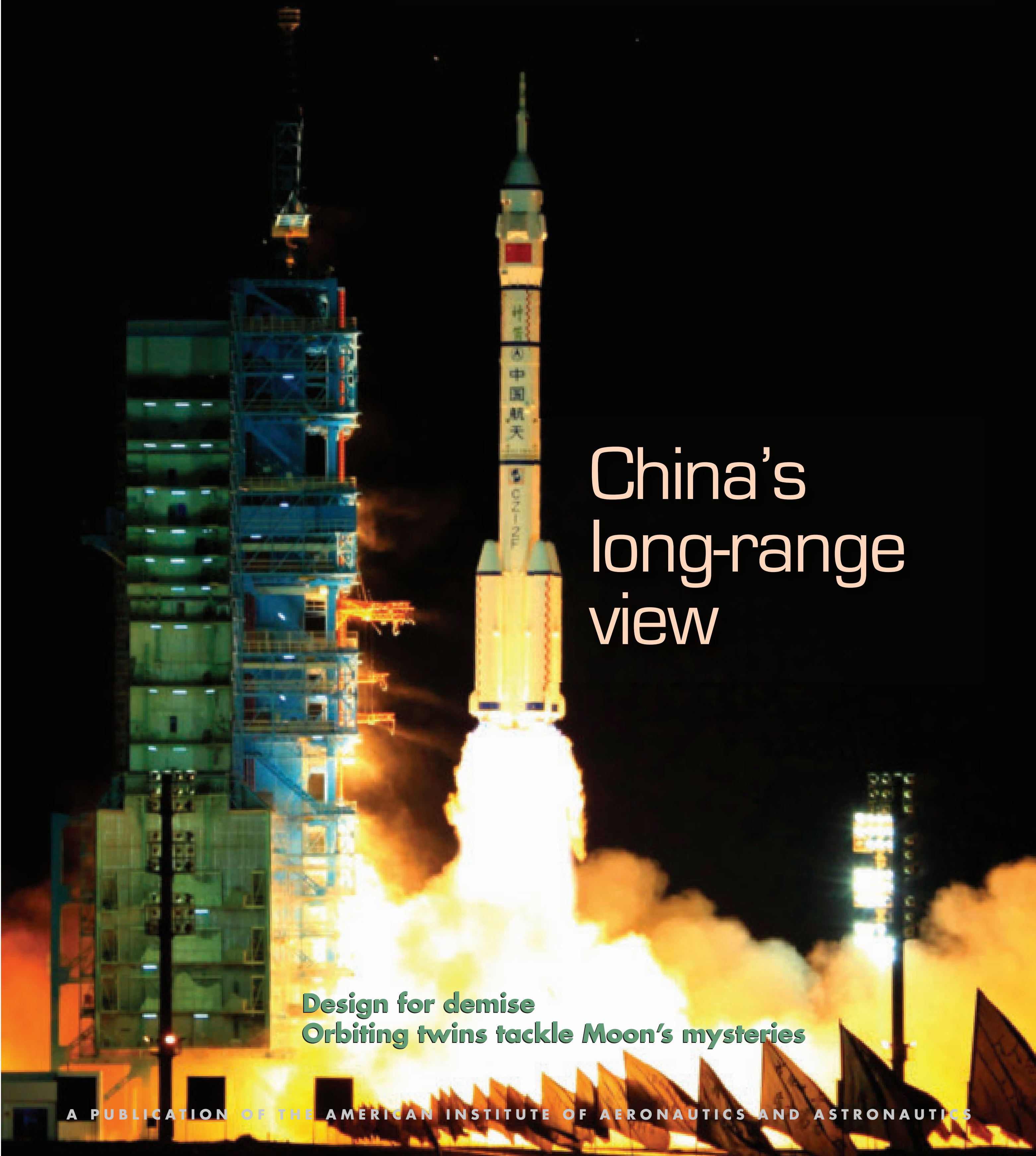

China's long-range view

Design for demise

Orbiting twins tackle Moon's mysteries

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Twin NASA spacecraft called GRAIL (gravity recovery and interior laboratory) are poised to begin mapping the Moon's gravitational field with unprecedented precision. The data they gather will open a new window into the early geology not just of the Moon but of the Earth and the other terrestrial planets as well.

The second GRAIL spacecraft is hoisted above the circular Delta II launch vehicle adapter, already occupied by the first GRAIL. Credit: Lockheed Martin.

by Craig Covault
Contributing writer

Orbiting twins

tackle Moon's mysteries

The $696-million GRAIL twin spacecraft mission to lunar orbit will gather and use extremely precise gravity data as a window for looking billions of years into the past. The new gravity data are expected to reveal the earliest geological secrets of the Earth, the Moon, and other terrestrial planets and their moons.

The two identical craft are in lunar polar orbits circling the Moon at altitudes as low as 30 mi., and flying in trail as if on the same railroad track.

The mission will create 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, according to NASA.

The gravitational map, especially when combined with a comparable resolution topographical field map, will enable scientists to deduce the Moon's interior structure and composition. This will also yield insights into its thermal evolution—that is, the history of its heating and cooling, which opens the door to understanding its origin and development.

Accurate knowledge of the Moon's gravity will be an invaluable navigational aid for future lunar spacecraft as well. In addition, GRAIL will help provide a broader understanding of the evolutionary histories of the other rocky planets in the inner solar system: Mercury, Venus, Earth, and Mars, say NASA geologists.

Twin GRAIL spacecraft with covers removed are tended by two Lockheed Martin Space Systems technicians in a thermal/vacuum chamber near Denver, Colorado. Credit: Lockheed Martin.

Ultrafine tuning

The science work of GRAIL's mission will not start until March. The objective now is to carefully tweak each twin's orbit and make the spacing between them so precise that by March the differences in lunar gravity, reflected in tiny changes to spacecraft separation, can be measured to within the

A technician checks the bottom side of a solar panel, revealing the colorful internal components of the spacecraft. The horn-shaped feature at the center is the swiveling star tracker. Credit: Lockheed Martin.

diameter of human hair, says principal investigator Maria Zuber of MIT. GRAIL-A entered lunar orbit on January 31; GRAIL-B followed the next day. Each spacecraft weighs 677 lb and measures 3.5x3.1x2.5 ft on a side.

That 'human hair' level of precision for the data collected over the entire lunar surface will reveal the Moon's deep interior structure. The data should also provide insight about the great bombardment of asteroids and large meteorites that took place after the initial planetary surfaces had solidified. Many of those mountain-sized objects now lie buried, producing strong gravity signatures.

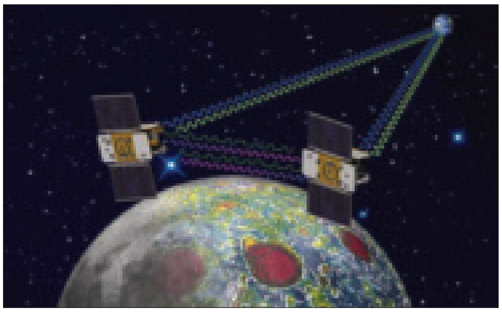
Outreach and education

The two Lockheed Martin/JPL spacecraft were launched from Cape Canaveral on September 10, 2011, by a ULA Delta II Heavy. They were originally christened GRAIL (gravity recovery and interior laboratory) A and B, but feedback to NASA's outreach program found GRAIL to be such a bland name that NASA decided to hold a national student contest to rename the craft. The winning names: Ebb and Flow.

Another educational facet of the mission involves four low-cost cameras attached to each satellite. Called MoonKAMs, they form a digital video imaging system that is used as part of the education and public outreach activities for GRAIL. Each MoonKAM system consists of a digital video controller and four camera heads—one pointed slightly forward of the spacecraft, two directly below it, and one slightly backward. The digital video controller serves as the main interface to the craft and provides storage for imagery acquired by the camera heads. Images or video of the lunar surface can be taken at the rate of up to 30 frames per second.

The MoonKAM system, from Ecliptic Enterprises in Pasadena, California, is operated by undergraduate students at the University of California at San Diego under the supervision of members of the faculty and in coordination with Sally Ride Science, a company founded to provide classroom materials and programs for K-12 educators. Middle school students from around the country will have an opportunity to become involved with MoonKAM imaging by selecting which lunar features to image and determining which camera can view the feature and when.

A graphic depicting the GRAIL spacecraft also shows the lumpy lunar surface gravity map and the twin spacecraft exchanging data with each other and with Earth. Credit: JPL.



Science goals

According to Zuber, the main science objectives of the flight are "determining the structure of the lunar interior, from crust to core, while also advancing understanding of the thermal evolution of the Moon; then applying the data gained from the Moon to other terrestrial planets."

"GRAIL's gravity observations will be used to support six scientific investigations," she says. These are to map the structure of the crust and lithosphere; understand the Moon's asymmetric thermal evolution; determine the subsurface structure of impact basins and the origin of mascons (subsurface regions of high density); ascertain the evolution of crustal molten lavas; assess the effects of tidal forces on deep interior structure; and place limits on the size of a possible solid inner core.

The GRAIL mission will obtain the lunar gravity field by measuring the precise instantaneous relative range-rate between the two spacecraft while they are separated by about 107-140 mi., at a mean altitude of 30 mi. in lunar polar orbit.

Moving into position

GRAIL's transit to the Moon was 3.5 months. This was unusually long because mission planners wanted extra time set up for an extremely precise lunar orbit insertion using very little propellant to keep the spacecraft small.

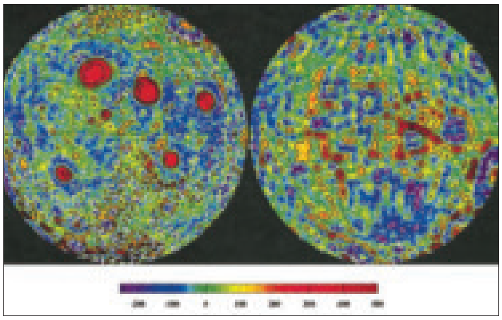
The GRAIL spacecraft's 2.5-million-mi. trajectory to the Moon was by way of the L1 Earth/Sun Lagrangian point. There the two spacecraft could essentially linger, taking time to move into position after cruising on separate paths to their location a million miles beyond the Moon. This resulted in the pair flying several weeks beyond the Moon and then curving back slowly toward it again, approaching by way of a flight path under the lunar south pole, where they executed a 38-min lunar orbit insertion maneuver. That put them on an elliptical path with an orbital period of just over 11.5 hr. Each spacecraft made those maneuvers using cold gas helium thrusters. There are 234 lb of highly pressurized helium on each satellite.

Another series of maneuvers then reduced the orbits to become nearly circular, with a 34-mi. altitude. The 82-day science phase is divided into three 27.3-day mapping cycles.

During the science phase, beginning in March, the Moon will rotate three times underneath the GRAIL orbit. The collection of gravity data over one complete rotation (27.3 days) is called 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.

The slow approach was timed to ensure that the spacecraft arrived in lunar orbit on December 31 and January 1 with low relative velocity. This requires a smaller engine firing to reduce their speed enough for them to enter an orbit around the Moon.

Another process that required extra transit time was the outgassing of the GRAIL spacecraft. When a craft enters the vacuum and zero-*g* of space, small amounts of gas are vented from its materials and structures. Those gases would have enough force to interfere with precise gravity measurements in lunar orbit. The hope was that during the longer cruise time, all the gases would be vented. To aid this process, the vehicles were rotated so the Sun could speed the venting of these gases.



A lunar gravity map compiled from earlier spacecraft missions shows bright red strong gravity features on the lunar nearside (left) located at major basins formed by the impacts of mountain-sized asteroids. The far side has a complex gravity signature but fewer giant impacts. Credit: JPL.

Benefiting from GRACE

The GRAIL spacecraft have direct heritage from the XSS-11 Earth orbit technology satellite flown about 10 years ago. GRAIL's purpose is also very similar to the Earth orbit gravitational mission of GRACE (gravity recovery and climate experiment), which is still in progress. "What we're trying to do is measure the gravity," says David Lehman, GRAIL project manager at JPL, "but there are nongravitational accelerations that look like gravity to the instruments.

"On GRACE they developed models to decipher out the nongravity accelerations, so we were able to use those models, tweaked a little bit. Basically we had to model the attitude control thrusters firing, and the effect of the Sun pushing on the spacecraft, the effect of the reflected moonlight pushing on it. All these had to be modeled, and we were able to derive a lot of the models from the GRACE program," Lehman says.

Helping that work along were several engineers from the GRAIL development team who had participated in producing the models used on GRACE.

The lunar mission, however, is far different from the Earth gravity mission, because Earth's gravity concentrations change almost daily as storms deposit heavy rains in some places and not others. The Moon's gravity has stayed fixed for most of the last 3 billion years, says NASA.

Mapping cycles

During mapping cycle 1, the mean separation distance between the two GRAIL space-

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had one support flange that was initially designed with flat legs, which presented high drag during reentry. By redesigning these supports to use square tubular legs, the component retained its strength, but was more likely to burn up while falling through the atmosphere," Hull says.

In another case, spacecraft designers looked at balance weights that might survive and potentially injure people. "By redesigning to a cluster of very small pieces," they made the weights "small enough that they would not cause a serious injury, even in the unlikely event that one would hit a person," says Hull.

Cost and schedule challenges

Yet another plus in reducing the reentry risk for most new missions is the growing use of lithium-ion battery technology in spacecraft. Hull says stainless steel and Invar pressure vessels used in nickel-hydrogen batteries have often been replaced by a thin stainless steel or aluminum case, with highly demisable materials inside. While the choice of battery technology is generally a result of other factors such as power usage rates, he adds that there have been cases where the demisability of the battery was a factor in this decision.

In summing up D4D techniques, Hull stresses that there are challenges, including cost and schedule impacts. There is also the qualification of a new design.

"By employing these techniques early in the process, the cost and schedule impacts can be minimized," Hull says. "Unfortunately, though, high survivability objects are often not noticed or added into the spacecraft design until late in the design process, when D4D is more difficult and costly to implement."

Hull adds that that there is always reluctance to move away from a heritage design approach, even when other benefits are shown. The proven success of a design that has 'always been done this way' is difficult to argue with in the face of an elevated—but still very small—risk of something that might happen decades from now. "The increased reentry risk must be dealt with at design, though, since there are no existing options for retrieving a spacecraft before it reenters," he concludes. ▲

GRAIL

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craft is designed to increase from approximately 62 mi. to 140 mi., says NASA.

A very small orbit trim maneuver executed near the end of mapping cycle 1 will then be used to change the separation drift rate. After this, the mean separation distance will decrease from 140 mi. (225 km) to approximately 40 mi., at the end of mapping cycle 3 (the end of the science phase).

The change in separation distance is needed to meet the GRAIL science objectives. The data collected when the orbiters are closer together will help to determine the local gravity field. When they are farther apart, the data they gather will be more useful for detection and characterization of the lunar core, according to Zuber and other GRAIL geologists.

Instrumentation

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 two antennas. The low-gain antennas enable the two spacecraft to communicate with each other and are also the mission team's principal means of contacting them.

The primary science payload on each spacecraft is the lunar gravity ranging system (LGRS), which sends and receives the signals needed for precisely measuring the changes in range between the two orbiters as they fly over lunar terrain of varying density. The LGRS consists of an ultrastable oscillator, a microwave assembly, a time transfer assembly, and the gravity recovery processor assembly.

The ultrastable 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 time transfer assembly provides a two-way time transfer link between the spacecraft, to both synchronize and measure the clock offset between the two LGRS clocks.

The time transfer assembly generates an S-band signal from the ultrastable oscillator's 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 will then be downlinked to the ground. ▲