

GRAVITY RECOVERY AND INTERIOR LABORATORY (GRAIL) MISSION: STATUS AT THE INITIATION OF THE SCIENCE MAPPING PHASE. Maria T. Zuber¹, David E. Smith¹, Sami W. Asmar², Alexander S. Konopliv², Frank G. Lemoine³, H. Jay Melosh⁴, Gregory A. Neumann³, Roger J. Phillips⁵, Sean C. Solomon⁶, Michael M. Watkins², Mark A. Wieczorek⁷ and James G. Williams², ¹Massachusetts Institute of Technology, Cambridge, MA 02129, USA (zuber@mit.edu); ²Jet Propulsion Laboratory, Pasadena, CA 91109-8099, USA; ³NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; ⁴Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907; ⁵Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, USA; ⁶Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA; ⁷Institut de Physique du Globe de Paris, 94100 Saint Maur des Fossés, France.

Introduction: The Gravity Recovery And Interior Laboratory (GRAIL) mission, a component of NASA's Discovery Program, launched successfully from Cape Canaveral Air Force Station on September 10, 2011. The dual spacecraft traversed independent, low-energy trajectories to the Moon via the EL-1 Lagrange point and inserted into elliptical, 11.5-hour polar orbits around the Moon on December 31, 2011, and January 1, 2012. The spacecraft are currently executing a series of maneuvers to circularize their orbits at 55-km mean altitude. Once the mapping orbit is achieved, the spacecraft will undergo additional maneuvers to align them into mapping configuration. The mission is on track to initiate the Science Phase on March 8, 2012.

The GRAIL Mission: GRAIL is the lunar analog of the very successful GRACE [1] twin-spacecraft terrestrial gravity recovery mission that continues to map Earth's gravity field since its launch in 2007. GRAIL was implemented with a science payload derived from GRACE and a spacecraft adapted from the Lockheed Martin Experimental Small Satellite-11 (XSS-11) mission, launched in 2005.

GRAIL has two primary objectives: to determine the structure of the lunar interior, from crust to core; and to advance understanding of the thermal evolution of the Moon. These objectives will be accomplished by implementing the following lunar science investigations:

- 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.
- Ascertain the temporal evolution of crustal brecciation and magmatism.
- Constrain deep interior structure from tides.
- Place gravitational limits on the size of the possible inner core.

In addition, as a secondary objective, GRAIL observations will be used to extend knowledge gained on the internal structure and thermal evolution of the Moon to other terrestrial planets.

GRAIL's Measurement: From the mapping orbit, GRAIL will acquire high-precision range-rate measurements of the distance change between the two

spacecraft using a Lunar Gravity Ranging System (LGRS), built by the Jet Propulsion Laboratory. The LGRS consists of dual Ka-band (32-GHz) transmitters and microwave antennae that measure the inter-satellite distance change, and S-band (2 GHz) Time Transfer Systems that are used to correlate time between the spacecraft. Ultra-Stable Oscillators (USOs), built by the Johns Hopkins University Applied Physics Laboratory, drive both the Ka-band and S-band systems. Also referenced to the same USO is an X-band (8-GHz) beacon from each spacecraft to ground stations, independent of the telecommunications system, for precision Doppler and monitoring the payload's performance.

The payload, flight system and mission design ensure that all error sources that perturb the gravity measurements are contained at levels well below those necessary to meet the mission's science requirements. Fig. 1 illustrates the performance margin between the science requirements, the allocated performance and Current Best Estimate (CBE) performance.

In the lunar mapping orbit, the spacecraft-to-spacecraft range-rate data will provide a direct measure of lunar gravity that will lead to a high-spatial-resolution (30×30 km), high-accuracy (<10 mGal) global gravity field that will address driving questions in lunar internal structure and thermal evolution.

Lunar Internal Structure and Thermal Evolution: Reconstructing the thermal evolution of the Moon [*cf.* 2, 3] requires global models of the thickness of the crust and the effective elastic thickness of the lithosphere, which are derived from a combination of global, high-resolution gravity and topography data, the latter of which are available from the Lunar Orbiter Laser Altimeter (LOLA) that is currently operating in lunar orbit [4, 5] on the Lunar Reconnaissance Orbiter (LRO) mission [6]. The volume of the crust provides the extent of melting of the magma ocean, and its distribution forms the basis for models of crustal evolution. The effective elastic thickness yields the thermal structure in the shallow Moon at the time features formed. Such analysis is particularly valuable in reconstructing the thermal state of the Moon during and subsequent to the late heavy bombardment of the lunar crust during the final stage of lunar accretion. Subtle

long-period tidal and rotational perturbations provide information on the mass distribution and mechanical state of the deep interior.

GRAIL's In-space Ranging Test: Owing to highly accurate insertion burns to the trans-lunar cruise trajectory, the first set of trajectory correction maneuvers was cancelled. This afforded the opportunity to turn the spacecraft toward each other and perform a full test of the GRAIL's LGRS.

On September 22, 2011, from a distance of ~500 km, the spacecraft successfully established radio links and acquired signals from each other's Ka-band and S-band transmitters for ~30 minutes. Results of the test are shown in Fig. 2. For the Ka-band system the signal-to-noise (SNR) of the spectrum was better than the

requirement at high frequencies and is expected to significantly improve throughout the spectrum in the mapping phase. The figure highlights a part of the low-frequency range that includes signal associated with the gravitational attraction of Earth. The SNR of the S-band system exceeded the lunar mapping requirement over the full spectrum. Data from the test were successfully run through the GRAIL processing software.

Mapping the Moon: The mission is on track to initiate its 82-day gravity mapping Science Phase on March 8. An initial gravity model will be developed after the first full lunar rotation (~30 days). All data products will be delivered to NASA's Planetary Data System (PDS) no later than 6 months after the end of data acquisition.

References: [1] Tapley B. D. et al. (2004) *Science*, 305, 503-505. [2] Solomon S. C. et al. (1981) in *Basaltic Volcanism on the Terrestrial Planets*, ed. T. R. McGetchin, R. O. Pepin and R. J. Phillips, Pergamon Press, NY, pp. 1129-1233. [3] Zuber M. T. et al. (1994) *Science*, 266, 1839-1843. [4] Smith D. E. et al. (2010) *GRL*, 37, doi:10.1029/2010GL043751. [5] Smith D. E. et al. (2011) *LPSC*, 42, 2350. [6] Chin G. et al. (2007) *SSR*, 129, doi:10.1007/s11214-007-9153-y. [7] Kaula W. M. (1966) *Theory of Satellite Geodesy*, Blaisdell, Waltham, MA, 124 pp.

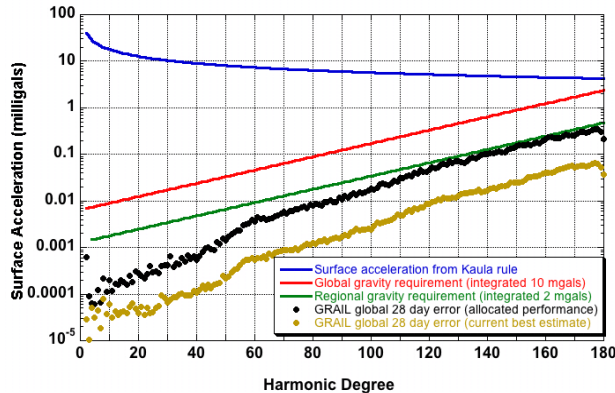


Figure 1. Error spectra from simulations illustrating margin between global (red) and regional (green) science requirements and the allocated (black) and current best estimate (gold) of GRAIL's performance. The blue line is the expected surface acceleration spectrum based on an empirical estimation of the power (Kaula's rule) [7] in the Moon's gravitational field.

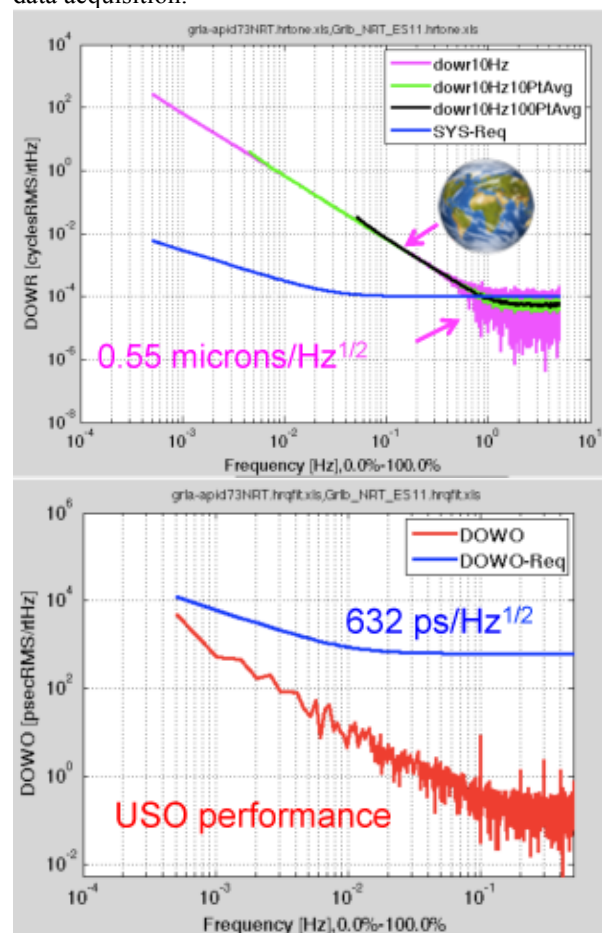


Figure 2. Results of GRAIL in-space ranging test, which verified the performance of the mission payload. (Top) Ka-band ranging system performance, plotted as dual one-way range vs. frequency, showing observations (magenta, green black) and requirements (blue). (Bottom) S-band system performance plotted as dual one-way offset vs. frequency. Observed noise (in red) is less than the requirement (in blue) over the full frequency range.