GRAVITY RECOVERY AND INTERIOR LABORATORY (GRAIL): EXTENDED MISSION AND END-GAME STATUS. Maria T. Zuber[1], David E. Smith[1], Sami W. Asmar[2], Alexander S. Konopliv[2], Frank G. Lemoine[3], H. Jay Melosh[4], Gregory A. Neumann[3], Roger J. Phillips[5], Sean C. Solomon[6,7], Michael M. Watkins[2], Mark A. Wieczorek[8], James G. Williams[2], Jeffrey C. Andrews-Hanna[9], James W. Head[10], Walter S. Kiefer[11], Isamu Matsuyama[12], Patrick J. McGovern[11], Francis Nimmo[13], Christopher Stubbs[14], G. Jeffrey Taylor[15], Renee Weber[16], Sander J. Goossens[17], Gerhard Kruizinga[2], Erwan Mazarico[3], Ryan S. Park[2] and Dah-Ning Yuan[2]. [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02129, USA (zuber@mit.edu); [2]Jet Propulsion Laboratory, Pasadena, CA 91109-8099, USA; [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; [4]Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907; [5]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, USA; [6] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA; [7]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA. [8]Institut de Physique du Globe de Paris, 94100 Saint Maur des Fossés, France, [9]Department of Geophysics and Center for Space Resources, Colorado School of Mines, Golden, CO 80401, USA; [10]Department of Geological Sciences, Brown University, Providence, RI 02912; [11]Lunar and Planetary Institute, Houston, TX 77058, USA; [12]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721-0092 USA; [13]Department of Earth and Planetary Sciences, University of California, Santa Cruz, Santa Cruz, CA 95064, USA; [14]Department of Physics, Harvard University, Cambridge, MA 02138-2933 USA; [15]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822, USA; [16]NASA Marshall Space Flight Center, Huntsville, AL 35805-1912 USA, [17]University of Maryland, Baltimore County, Baltimore, MD 21250 USA.

Introduction: The Gravity Recovery and Interior Laboratory (GRAIL) [1], NASA's eleventh Discovery mission, successfully executed its Primary Mission (PM) in lunar orbit between March 1, 2012 and May 29, 2012. GRAIL's Extended Mission (XM) initiated on August 30, 2012 and was successfully completed on December 14, 2012. The XM provided an additional three months of gravity mapping at half the altitude (23 km) of the PM (55 km), and is providing higher-resolution gravity models that are being used to map the upper crust of the Moon in unprecedented detail.

Primary Mission: GRAIL is the lunar analog of the successful GRACE [2] twin-spacecraft terrestrial gravity recovery mission that has been mapping Earth's gravity field since its launch in 2007. GRAIL was implemented with a science payload (*i.e.,* Lunar Gravity Ranging System; LGRS) derived from GRACE and spacecraft adapted from the successful Lockheed Martin Experimental Small Satellite-11 (XSS-11) mission, launched in 2005.

GRAIL launched on September 10, 2012 and the dual spacecraft executed independent low-energy trajectories to the Moon via the EL-1 Lagrange point, inserting into lunar orbit on December 31, 2011 and January 1, 2012. After a series of maneuvers to decrease orbital periods and align the spacecraft into ranging configuration, the PM initiated on March 1, one week early. Initial analysis led to a degree and order 420 (spatial block size = 13 km) gravitational field model, named GL0420A [3] that is improved in spatial resolution by a factor of 3-4 and in quality by three to more than five orders of magnitude in comparison to previous lunar gravity models from the Lunar Prospector (LP) [4] and Kaguya [5] missions.

Extended Mission: At the completion of the PM in late May 2012, periapsis raise maneuvers circularized the spacecraft orbits at an altitude of ~84 km for the low-activity Low Beta Angle phase. For ten weeks subsequent to a lunar eclipse passage on June 4, the orientation of the orbit plane relative to the Sun did not allow for operation of the LGRS payloads while in orbiter-point configuration due to the Sun-Moon-Earth geometry. A second three-month XM science phase initiated on August 30. A heliocentric view [6] of the XM is shown in Fig. 1.

GRAIL's XM average altitude was 23-km, less than half the average altitude of the PM. Because of the low orbital altitude, XM operations were far more complex than in the PM [7]. Unlike the PM, which featured only one thrust maneuver to change the drift rate of the spacecraft over three months of mapping, the XM required three maneuvers a week to maintain the mapping altitude [6].

The objective of the GRAIL XM is to determine the structure of lunar highland crust and maria, addressing impact, magmatic, tectonic and volatile processes that have shaped the near surface. To address this objective the GRAIL XM undertakes six investigations, with measurement requirements summarized in Fig. 2:

1. Structure of impact craters.
2. Near-surface magmatism.
3. Mechanisms and timing of deformation.
4. Cause(s) of crustal magnetization.
5. Estimation of upper-crustal density.
6. Mass bounds on polar volatiles.

Fig. 3 shows a power spectrum of a 660x660 field that includes PM and some XM observations in comparison to fields from the GRAIL PM [3] and LP [4]. The RMS power of the GRAIL field is considerably greater than the error spectrum, indicating higher resolution fields are possible from these data.

GRAIL Endgame. On December 6, 2012, the average the altitude of the GRAIL orbiters was lowered by another factor of two, to 11 km. This maneuver enabled a very high-resolution mapping campaign over the Orientale Basin. Residuals with respect to GL0420A obtained during this period are shown in Fig. 4. Residuals are large in magnitude in comparison to the PM field and indicate that substantial new gravity information has been obtained. GRAIL's science mapping ended on December 14, 2012, after which a series of engineering experiments was performed prior to a controlled deorbit on December 17, 2012.

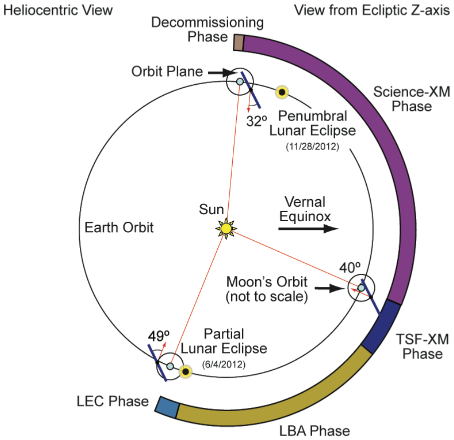

Figure 1. Heliocentric view of GRAIL Extended Mission (XM) showing various mission phases.

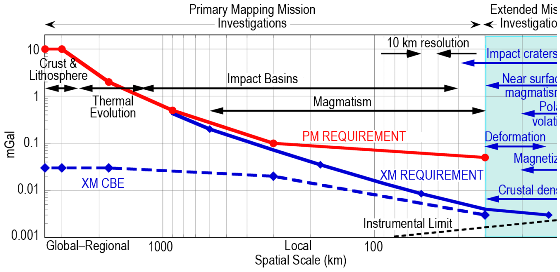

Figure 2. Measurement requirements for GRAIL's XM (in blue) in comparison to the PM (in red and black). The dashed blue line corresponds to the Current Best Estimate (CBE) of expected XM performance prior to initiating the XM. The black dotted line represents the instrumental limit.

References: [1] Zuber M. T. et al. (2012) *Space Sci. Rev.,* doi: 10.1007/s11214-012-9952-7. [2] Tapley B. D. et al. (2004) *Science, 305,* 503-505. [3] Zuber M. T. et al. (2012) *Science* doi: 10.1126/science.1231507. [4] Konopliv A. S. et al. (2001) *Icarus, 150,* doi:10.1006/icar.2000.6573, pp. 1-18. [5] Matsumoto K. et al. (2010) *J. Geophys. Res., 115,* doi:10.1029/2009JE003499. [6] Sweetser T. H. et al. (2012) *AIAA Astrodyn. Specialist Conf.,* AIAA-2012-4429, Minneapolis, MN. [7] Wallace M. S. et al. (2012) *AIAA Astrodyn. Specialist Conf.,* AIAA-2012-4748, Minneapolis, MN.

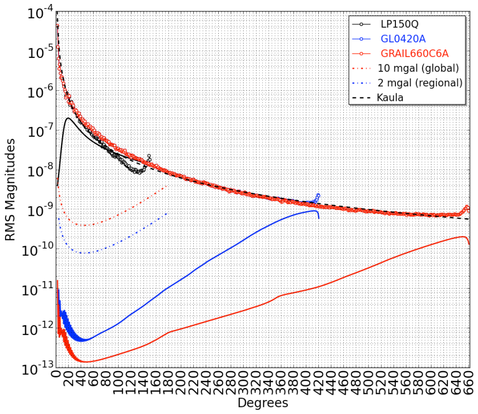

Figure 3. Power and error spectra for a GRAIL 660x660 degree and order gravity field model that includes observations from March 1-November 13, 2012 in comparison to fields LP150Q [4] and GL0420A [3]. The red and blue dotted lines correspond to GRAIL's global and regional requirements, respectively. Errors are orders of magnitude less than the requirements.

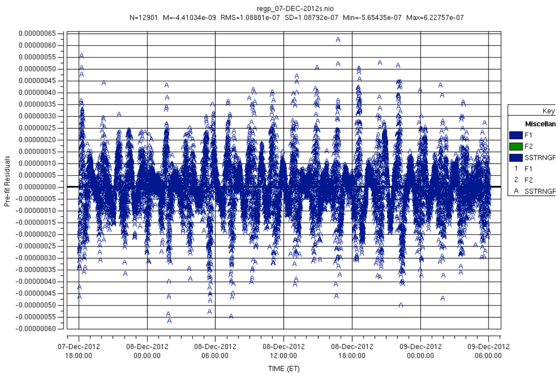

Figure 4. Residuals with respect to GL0420A obtained during the GRAIL endgame.