GLOBAL GRAVITY FIELD MODELS OF THE MOON USING GRAIL PRIMARY AND EXTENDED MISSION DATA. Sander Goossens1,2, Frank G. Lemoine2, Terence J. Sabaka2, Joseph B. Nicholas2,3, Erwan Mazarico2,4, David D. Rowlands2, Bryant D. Loomis2,5, Douglas S. Chinn2,5, Gregory A. Neumann2, David E. Smith2,4, Maria T. Zuber5. 1CRESST, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore MD 21250 U.S.A. (email: sander.j.goossens@nasa.gov), 2NASA GSFC, Code 698, 8800 Greenbelt Road, Greenbelt MD 20771 U.S.A.; 3Emergent Space Technologies, 6411 Ivy Lane, Greenbelt, MD 20770, U.S.A.; 4Massachusetts Institute of Technology, MIT 54-518, 77 Massachusetts Avenue, Cambridge MA 02139 USA; 5Stinger Ghaffarian Technologies, 7701 Greenbelt Road, Greenbelt, MD 20770 U.S.A.

Introduction: The twin Gravity Recovery and Interior Laboratory (GRAIL) spacecraft were launched in September 2011 on a Discovery-class NASA mission to study the gravitational field of the Moon [1]. Extremely accurate range-rate observations between the two spacecraft at the Ka-band radio wavelength (KBRR) enable the determination of the gravity field of the Moon to very high degree since the data are acquired continuously, even when the spacecraft are not tracked from the Earth.

The primary mapping mission for GRAIL commenced on March 1, 2012 and continued until May 29, 2012. During the primary mission, the altitude of the spacecraft was on average 55 km above lunar surface. Initial analysis resulted in a global model of the lunar gravity field expressed in spherical harmonics of degree and order 420 (equivalent to a spatial block-size resolution of 13 by 13 km at the equator) [2]. Subsequent analysis of primary mission data allowed the determination of models up to degree and order 660 (a block-size of 8.2 by 8.2 km) [3,4]. GRAIL’s extended mission initiated on August 30, 2012, and was successfully completed on December 14, 2012. The average altitude during the extended mission was 23 km above lunar surface, but the lowest altitudes achieved during the extended mission are much lower, with altitudes above topography as low as 2 km (cf. Fig. 1). This allows the estimation of gravity field models at finer and finer resolutions, currently up to and beyond degree and order 900 (a block-size of 6 by 6 km) [5,6]. Here, we present the current status of GRAIL gravity modeling at NASA/GSFC.

Methods: Our processing relies on a dynamical approach called precision orbit determination, in which the satellite orbits are integrated over a certain time-span (called an arc), using high-precision force models. In addition, measurements are modeled at high precision as well, and compared to actual observations, resulting in data residuals from which model parameters are estimated iteratively. Precision orbit determination for the GRAIL satellites is done with the GEODYN II software [7].

The data used in our processing are 2-way tracking data at the S-band frequency using the Deep Space Network (DSN), and precise Ka-band range-rate data, consisting of the change in time of the distance between the two spacecraft (KBRR). We weight the DSN data at 0.12 mm/s (close to its expected noise level of 0.1 mm/s). KBRR data for the primary mission are weighted at 0.05 micron/s, and those for the extended mission at 0.1 micron/s. DSN data has a sample time of 10 s, that of primary mission KBRR data is 5 s, and that of extended mission KBRR data is 2 s. Arc lengths for the primary mission are on average 2.5 days, whereas those for the extended mission are currently 1 day.

The force models used for integrating the satellite orbits include a lunar gravity field model, degree-2 potential Love numbers, third-body perturbations, and solar and indirect (planetary) radiation pressure. The measurement modeling uses high-precision corrections for relativity, station motion, and troposphere and ionosphere-induced media delays.

Per arc we first estimate arc-dependent parameters, which include the initial position and velocity vectors of both satellites, a solar radiation pressure coefficient per satellite, a measurement and time-bias on the KBRR data, and empirical accelerations. When the orbits are converged after iterative adjustment of the arc-dependent parameters, we create partial derivative files, which contain the partials of the data with respect to both the arc-dependent parameters, as well as the

Figure 1: Lowest altitude above LOLA topography [11] achieved during the entire GRAIL mission.
partials with respect to the common parameters such as those related to the selenopential, tidal potential Love numbers and the product of the lunar mass and gravitational constant, $GM$.

The high degree and order models we develop from the GRAIL data require the estimation of a large number of parameters. We have therefore turned to using the supercomputers of the NASA Center for Climate Simulation (NCCS) at NASA/GSFC for the inversions.

**Results:** We have processed all primary mission and extended mission data, resulting currently in a model of degree and order 900, called GRGM900C [6]. For this model, we used a Kaula rule of $36\times 10^{-5} l^2$ for degrees $l$ larger than 600. Fig. 2 shows the power and error spectra of this solution, along with those of the model GRGM660PRIM [4], which used only primary mission data. Compared to GRGM660PRIM, the new model GRGM900C shows increased power from around degree 350. Correlations between gravity and gravity predicted from LOLA topography have been extended likewise when compared to the primary mission models. For both models shown in Fig. 2, the error curves intersect the power curves. We stress that both models are calibrated in such a way that the formal residual statistics from the covariance matrix match the observed statistics. For GRGM660PRIM this was done using variance component estimation [4,8], while for GRGM900C this was done using a scaling factor derived from the square-root information filter [4,9].

![Figure 2: Power and error spectra of the GSFC GRAIL gravity solutions (and calibrated associated errors) GRGM660PRIM (primary mission only, [4]) and GRGM900c (extended mission data included, [6]).](image)

Fig. 3 shows the post-fit root-mean-square (RMS) of the KBRR residuals with respect to GRGM900C for the entire extended mission period. Up to November 18, the fit is at around 0.12 micron/s. After this date, the perisphere altitude was lowered, and it was further lowered on December 6, where GRAIL achieved the lowest altitudes of its entire mission, cf. Fig. 1, over the Orientale basin [10]. For these parts, the KBRR fits increase, indicating that the data in the latter part of the extended mission still support models of higher resolution.

![Figure 3: Post-fit residual statistics for the KBRR data over the entire extended mission with respect to GRGM900C.](image)

**References:**