HIGH DEGREE AND ORDER GRAVITY FIELD MODELS OF THE MOON DERIVED FROM GRAIL PRIMARY AND EXTENDED MISSION DATA. Sander Goossens[1,2], Frank G. Lemoine[2], Terence J. Sabaka[2], Joseph B. Nicholas[2,3], Erwan Mazarico[2,4], David D. Rowlands[2], Bryant D. Loomis[2,5], Douglas Caprette[2,5], Douglas S. Chinn[2,5], Gregory A. Neumann[2], David E. Smith[2,4], Maria T. Zuber[4]. [1]CRESST, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore MD 21250 U.S.A. (email: sander.j.goossens@nasa.gov), [2]NASA GSFC, Code 698, 8800 Greenbelt Road, Greenbelt MD 20771 U.S.A.); [3]Emergent Space Technologies, 6411 Ivy Lane, Greenbelt, MD 20770, U.S.A; [4]Massachusetts Institute of Technology, MIT 54-518, 77 Massachusetts Avenue, Cambridge MA 02139 USA; [5]Stinger 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 mission builds on the success of the GRACE (Gravity Recovery and Climate Experiment) mission, which has been mapping the gravity field of the Earth since its launch in 2002 [2].

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. This allowed the determination of a lunar gravity field model of degree and order 420 in spherical harmonics (equivalent to a spatial block-size resolution of 13 km) [3]. 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, half of the altitude during the primary mission, allowing gravity field models at even finer resolution.

Methods: In addition to the precise Ka-band ranging between the two spacecraft, the twin spacecraft were tracked separately in 2-way mode at S-band using the Deep Space Network (DSN). We use these data, from both the primary and extended mission, to determine precise orbits for the GRAIL spacecraft. X-band data were collected in 1-way mode using the Ultra-stable Oscillators (USOs) on both of the GRAIL spacecraft, but these data were not used here.

Precision orbit determination for the GRAIL satellites is done with the GEODYN II software [4]. We take a dynamical approach, which means that the data are divided into arcs, which are continuous spans over which the orbits of the satellites are integrated. The force model used for integrating the satellite orbits includes 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, we create partial derivative files, which contain the partials of the data with respect to both the arc-dependent parameters, as well as for the common parameters such as those related to the selenopotential, tidal potential Love numbers and the lunar 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 Goddard for the inversions. Initially, for most of the primary mission processing, we relied on direct accumulation of the normal equations, which where then inverted using a Cholesky decomposition. For the extended mission processing however, we have turned to a strategy based on the use of the square root information filter (SRIF) [5], and we have tested the inversion of GRAIL data using both strategies and identical background modeling to degree 540x540.

Results: We have processed all primary mission data, and included extended mission data up to December 5, 2012 in our current solution, a model of degree and order 660 in spherical harmonics denoted GRGM660A. We also estimated the degree-2 potential Love numbers, which help constrain models for the deep interior structure of the Moon [cf. 6]. We weighted primary mission DSN data at 0.12 mm/s (10 s averaged data), extended mission DSN data at 0.05 mm/s (10 s averaged data), primary mission KBRR data at either 0.05 or 0.1 micron/s (5 s intervals), and extended mission KBRR data at 1 micron/s (2 s intervals). Since GRGM660A is the result of our first pass over the extended mission data, we included a Kaula rule of 25x10^{-5}/l^2 for degrees *l* larger than 450. Figure 1 shows the power and error spectra of this solution, together with GRGM420A, which is a 420 degree and order model from primary mission data only [7]. Figure 1 shows that the power spectrum for the new model does not cross the power in the coefficient standard deviations.

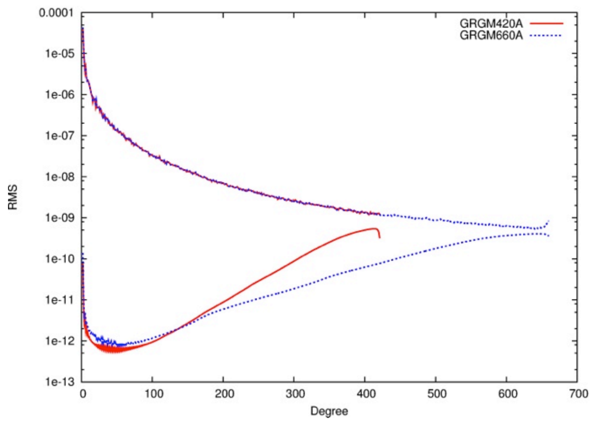

Fig. 1: Power and error spectra of the GSFC GRAIL gravity solutions (and associated errors) GRGM420A (primary mission only) and GRGM660A (extended mission data included).

We calibrate our solutions using variance component estimation (VCE) [8] utilizing different statistical sets: for GRGM660A, these were the primary mission data set versus the extended mission data set, whereas for GRGM420A the statistical sets consisted of subsets of the two different data types. VCE determines scale factors on the data covariance matrices to assure that the observed weighted residual variances equal the expected weighted residual variances. Due to the different number of sets, there are some differences in the sigmas for the lower degrees between GRGM420A and GRGM660A, but we expect future solutions with extended mission data to have sigmas below those for GRGM420A, through iteration over and upweighting of the data.

Figure 2 shows the post-fit root-mean-square (RMS) of the KBRR residuals with respect to GRGM660A for the extended mission period. For a large part of the extended mission the fit is already below 1 micron/s for this model, but the fits are higher especially for parts where the periapsis altitude was further lowered. It should also be noted that our processing currently includes data up to December 5, whereas the altitude of the GRAIL satellites was lowered to an average of 11 km on December 6. Together with the fact that the power spectrum does not cross the error spectrum (Figure 1), this indicates that the extended mission data will support model resolutions beyond degree and order 660.

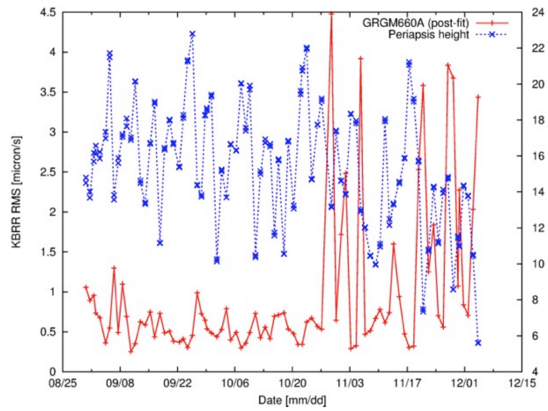

Fig. 2: Post-fit residuals (red) for the KBRR data with respect to GRGM660A. The periapsis altitude per arc is also shown (blue).

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