IMPROVED ORBIT DETERMINATION OF LUNAR ORBITERS WITH LUNAR GRAVITY FIELDS OBTAINED BY THE GRAIL MISSION. Erwan Mazarico[1,2], Sander J. Goossens[2,3], Frank G. Lemoine[2], Gregory A. Neumann[2], Mark H. Torrence[4,2] , David D. Rowlands[2], David E. Smith[1,2] and Maria T. Zuber[1]. [1] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139 (mazarico@mit.edu); [2] Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771; [3] Center for Research and Exploration in Space Science and Technology, University of Maryland, Baltimore County, Baltimore, MD 21250; [4] SGT Inc., Greenbelt, MD 20770.

Introduction: The twin GRAIL spacecraft Ebb and Flow [1], launched in September 2011, successfully mapped the gravity field of the Moon during their primary and extended science phases. Three months (March-May 2012) of mapping at an average altitude of 55km enabled the recovery of the lunar gravity field to unprecedented accuracy and spatial resolution by the two analysis centers at the Jet Propulsion Laboratory and the NASA Goddard Space Flight Center [2,3], with very good agreement. In addition to implications for the history and geophysical evolution of the Moon, the GRAIL data can prove useful in the analysis of other spacecraft datasets, in particular considering the trajectory reconstruction aspect of spacecraft carrying high-resolution instruments. This work focuses on the Lunar Reconnaissance Orbiter (LRO), but of course also serves to illustrate improvements to be expected for future missions to the Moon.

Data and Methods: The Lunar Reconnaissance Orbiter was launched in June 2009 and has been tracked by the Universal Space Network (USN) since. We analyzed more than three years of S-band Doppler and Range tracking data (July 2009 to August 2012), using the NASA GSFC orbit determination (OD) program GEODYN [4]. Following [5], the data are processed in 2.5-day batches ('arcs'). The trajectory of the spacecraft is numerically integrated with models for the various accelerations affecting the spacecraft. Parameters for those force models are iteratively adjusted to minimize the measurement residuals. While needed, a good fit to the tracking data does not necessarily result in an accurate (i.e., close to truth) orbit. To assess the orbit quality, we evaluate the orbit consistency between successive arcs, which were designed to overlap over the tracking pass of the primary LRO ground station at White Sands (New Mexico), e.g. generally a 8-12 hour period.

We compare the statistics of the orbit overlaps obtained after convergence with various gravity field models. The LLGM-1 [5] and LLGM-2 are degree and order 150 pre-GRAIL models based on historical tracking data (Lunar Orbiters, Apollo sub-satellites, Clementine, Lunar Prospector) and respectively one year and 2.5 years of LRO data. The other three fields are derived exclusively from GRAIL data from the primary science phase. While the harmonic solutions produced by the GRAIL GSFC team now typically extend beyond degree and order 420, we produced two special solutions for this work, up to degree and order 150 and 270 respectively. Another solution to degree and order 420 truncated to degree 270 is also used in the comparison.

Results: The 537 LRO arcs were converged with the five *a priori* gravity fields. The Root Mean Square (RMS) of the orbit differences is computed during each overlap period in the Along-track, Cross-track and Radial directions as well as in Total position. For easier interpretation, these values are then combined over each LRO mission phase (about a month). Figure 1 displays the results graphically. The black and gray curves correspond to LLGM-1 and LLGM-2, and show that with the inclusion of LRO data, those pre-GRAIL fields perform reasonably well for a posteriori reconstruction; beyond their data coverage period, they degrade as the inclination of the LRO spacecraft slowly changes due to the 18.6-year lunar nutation cycle. The degree and order 150 field obtained from GRAIL data alone shows relatively poor performance, indicating its corresponding spatial resolution is too low for properly converging the LRO orbits. The LLGM-1 and LLGM-2 fields perform reasonably well at the same expansion coefficient, presumably due to lumped coefficients beneficial to LRO OD specifically. However, when using a degree and order 270 field (either fully or truncated from a larger solution), the performance is significantly improved. The radial accuracy is now on the order of 50cm, and the position knowledge is better than 10m over most of the mission. Tables 1 and 2 show the RMS values in the nominal ~50km altitude orbit, during the exploration mission (September 2009 to September 2010) and the primary science mission (September 2010 to December 2011).

Conclusion: The lunar gravity field solutions obtained with the GRAIL data alone, except when truncated too aggressively, provide significant improvements to the orbit determination of LRO. This can help the calibration and combination of the various high-resolution datasets being acquired, and should help future missions with stringent position knowledge requirements.

References: [1] Zuber M.T. et al. (2012), *Space Sci. Rev.* doi: 10.1007/s11214-012-9952-7. [2] Zuber et al. (2012), *Science*, doi: 10.1126/science.1231507. [3] Lemoine et al., Abstract G32A-03, presented at 2012 Fall Meeting, AGU, San Francisco, California, 3-7 Dec 2012. [4] Pavlis, D.E. et al. (2009), *GEODYN Operations Manual.* [5] Mazarico, E. et a. (2012) *J. Geod.*, doi:10.1007/s00190-011-0509-4.

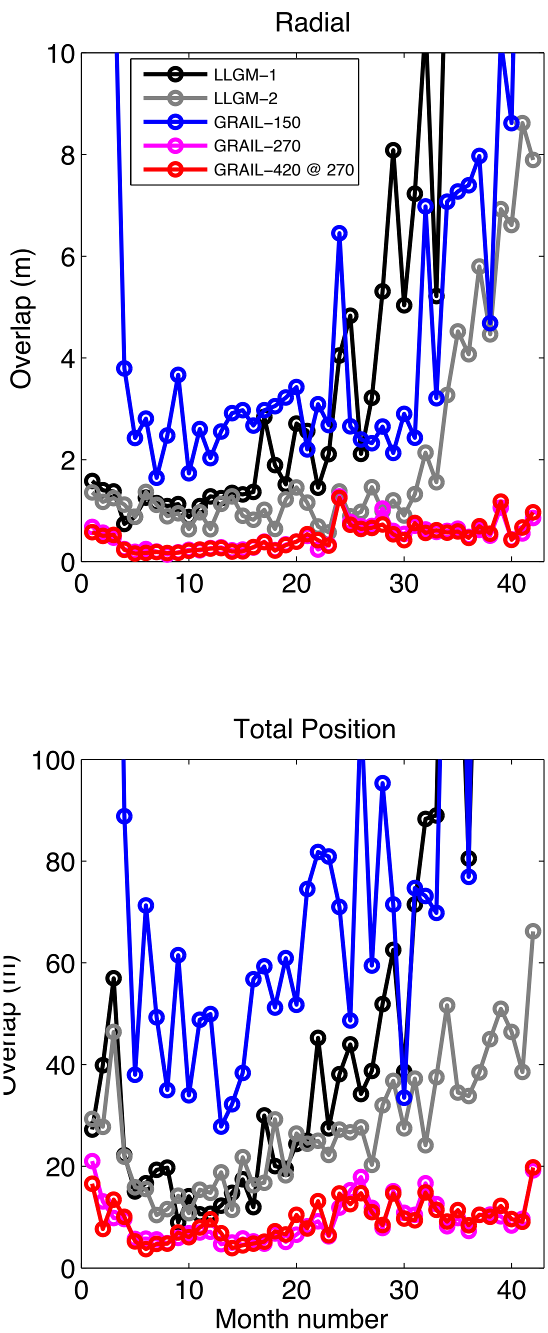

Figure 1. RMs values of the orbit overlaps (in meters) over the whole LRO mission (July 2009-August 2012).

	Along	Cross	Radial	Total
LLGM-1	10.82	10.85	1.15	15.38
LLGM-2	12.17	9.88	1.00	15.71
GRAIL-150	35.55	37.04	2.71	51.43
GRAIL-270	5.13	3.51	0.23	6.22
GRAIL-420@270	5.15	3.80	0.21	6.40

Table 1. RMS values of the orbit overlaps (in meters) over the Exploration mission of LRO (Sept. 2009-Sept. 2010).

	Along	Cross	Radial	Total
LLGM-1	41.30	25.71	4.84	48.92
LLGM-2	22.59	15.92	1.21	27.68
GRAIL-150	53.16	46.79	3.49	70.89
GRAIL-270	8.47	7.22	0.64	11.16
GRAIL-420@270	8.34	7.05	0.60	10.94

Table 2. RMS values of the orbit overlaps (in meters) over the Science mission of LRO in the nominal 55-km altitude orbit (Sept. 2010-Dec. 2011).