SELENODESY WITH LRO: RADIO TRACKING AND ALTIMETRIC CROSSOVERS TO IMPROVE ORBIT KNOWLEDGE AND GRAVITY FIELD ESTIMATION.
E. Mazarico[1,2], D.D. Rowlands[2], G.A. Neumann[2], M.H. Torrence[2,3], D.E. Smith[1,2], M.T. Zuber[1]. [1]Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, Cambridge MA (mazarico@mit.edu); [2]NASA Goddard Space Flight, Planetary Geodynamics Laboratory, Greenbelt MD; [3]SGT Inc., Greenbelt MD.

Introduction: Since its launch in June 2009, the Lunar Reconnaissance Orbiter [1] has been tracked nearly-continuously by the LRO-dedicated White Sands S-/Ka-band station and the S-band USN network. While the orbits produced by the Navigation Team (Flight Dynamics Facility in GSFC) have generally been of sufficient quality for daily activity planning and targeting, there are tighter positioning requirements of the mission. The LOLA Precision Orbit Determination (POD) team has processed the radiometric tracking data up to the end of the nominal mission (mid-September 2010), and has put effort in utilizing the LOLA data as an additional geodetic product. Indeed, the high precision of the altimetry measurements can constrain the spacecraft trajectory at groundtrack intersection locations ('crossovers'), by forcing the planetary radii inferred at two separate times to be consistent.

Data: The data available to constrain the LRO orbit are: (1) radiometric tracking data by White Sands NASA station and USN network, with 5s-averaged Doppler (~0.1-0.3mm/s precision) and Range (~1m precision) measurements; (2) Laser Ranging data collected by a network of ground laser stations (primarily the NASA GSFC NGSLR station) and LOLA through a 1-inch HGA-mounted telescope on LRO; (3) altimetric crossover constraints based on 10cm-precision LOLA ranges [2]. The number of observations used during each phase of the nominal mission is indicated in **Table 1**.

Models: The framework used for the POD is the NASA GSFC GEODYN II package [3], which includes a number of force and measurement models that need to be applied during the integration of the spacecraft trajectory in order to properly use the measurements as constraints on the LRO orbit. The solar radiation acceleration is calculated with a 10-plate spacecraft model, which includes self-shadowing. The spacecraft center-of-mass movement is modeled, based on the fuel consumption, and the movements of the antenna and solar panel. The antenna phase offset and Laser Ranging telescope position use a 2-gimbal antenna model specific to the LRO spacecraft geometry. Altimeter pointing parameters are adjusted (roll/pitch), with separate estimation of day-side and night-side values (due to the LOLA anomaly, [2]).

Strategy: The spacecraft trajectory is integrated over short periods ('arcs'), limited in duration by the buildup of errors due to unavoidable mismodeling of certain forces or measurement corrections. We use two separate sets of arcs: (1) short arcs (~2.5 days) for initial editing/convergence and for high-quality orbits; (2) long arcs (~5 days) to construct the normal equations needed for gravity field inversion. The short arcs are defined so that they start and stop with a White Sands tracking pass. Therefore they overlap for 8-12h with the previous/next arc, which enables orbit overlap analysis for the assessment of reconstructed orbit quality. Once the arcs have been converged with the radiometric tracking data alone, they are grouped in month-long periods to allow the use of altimetric crossovers. The slow rotation of the Moon and the polar orbit of LRO mean that groundtracks normally intersect at intervals multiple of 14 days (ascending/descending) or 28 days (which also capture same-direction intersections). LOLA data around those groundtrack intersection are used to create "crossover" observations which GEODYN II can ingest in the POD process as an additional data type.

	Range	Doppler	single-beam crossover	Laser Ranges
CO_01	112279	123221	6067	-
CO_02	122281	136999	26326	-
CO_03	120179	134063	112351	-
NO_01	111603	119614	69697	16271
NO_02	129335	140200	49099	19048
NO_03	98331	106289	4266	20590
NO_04	107070	116577	16131	13668
NO_05	122226	132526	338	35690
NO_06	102316	108733	15254	15929
NO_07	120292	126705	74173	29722
NO_08	120604	131616	22185	30347
NO_09	111756	123055	43043	26981
NO_10	125635	134682	41925	N/A
NO_11	123415	131753	32010	N/A
NO_12	123673	134823	35582	N/A
NO_13	123368	134499	4223	N/A

Table 1. Number of observations used in the month-long periods processed with combined data types.
(CO=commissioning; NO=nominal)

Results: Data from commissioning to the end of the primary (exploration) mission were analyzed to

gravity field	radio-only				radio&crossover			
	A	C	R	T	A	C	R	T
LP150Q	27.35	30.10	2.39	41.27	13.78	9.64	3.48	17.47
SGM150	32.33	33.19	2.86	47.42	12.40	10.74	2.91	16.92
GLGM-3	42.94	49.10	3.64	66.15	15.38	14.24	3.71	21.51
LRO_01	12.42	12.56	1.19	17.80	11.13	10.42	1.87	15.60
LRO_02	**10.91**	**10.10**	**1.08**	**14.98**	**8.50**	**8.29**	**1.59**	**12.17**

Table 2. Average orbit overlaps over the nominal missions without (left) and with (right) the altimetric crossover observations, for various a priori gravity fields. The bottom lines are for preliminary lunar gravity fields estimated with LRO data. The various columns indicate orbit overlaps in the Along-Track (A), Cross-Track (C), Radial (R) and Total (T) directions.

produce high-quality orbits. The crossover data were systematically used (**Table 1**), and are a major contributor to the position knowledge improvements compared to navigation orbits. As shown in **Table 2**, the addition of crossovers generally reduce the orbit overlaps (a measure of the repeatability and quality of the reconstructed orbits) by 50-60%, down to the level of 15-20m total position error (compared to 50-60m with the radio tracking only). Normal equations for the gravity field spherical harmonics expansion coefficients to degree and order 150 were produced for each month with the long arcs. Combined with existing normal equations of historical lunar orbiter (Lunar Orbiters, Apollo sub-satellites, Clementine and Lunar Prospector), we obtained new solutions of the lunar gravity field. Those fields, not surprisingly, perform better with the LRO arcs than pre-LRO fields (**Table 2**). More interestingly, with these fields, arcs processed with the radiometric data alone perform nearly as well as those that use the altimetric crossovers.

Conclusion: The Precision Orbit Determination performed on LRO enables excellent orbital accuracy to be achieved, with the LOLA-derived altimetric crossovers critical to these improvements. Current position knowledge are ~1m radial and 10-15m total. This is supported by the significant decrease of orbit overlaps (**Table 2**), and visually by the better clarity of topographic maps produced by those orbits (**Figure 1**).

Availability: The current LOLA PDS release [4] makes use of those accurate orbits when available, in order to geolocate the laser bouncepoints and calculate the lunar topography. A separate and upcoming Radio Science PDS release will contain SPICE kernels [5] containing the spacecraft trajectory.

References: [1] Chin G. et al. (2007) Space Sci. Rev. *129*; [2] Smith et al. (2010), *Geophys. Res. Lett.*, 37, L18204; [3] Pavlis et al. (2006), GEODYN Operations Manual; [4] NASA Planetary Data System, http://geo.pds.nasa.gov/missions/lro/; [5] Acton (1996), *Planet. Sp. Sci.*, 44 (1), 65-70.

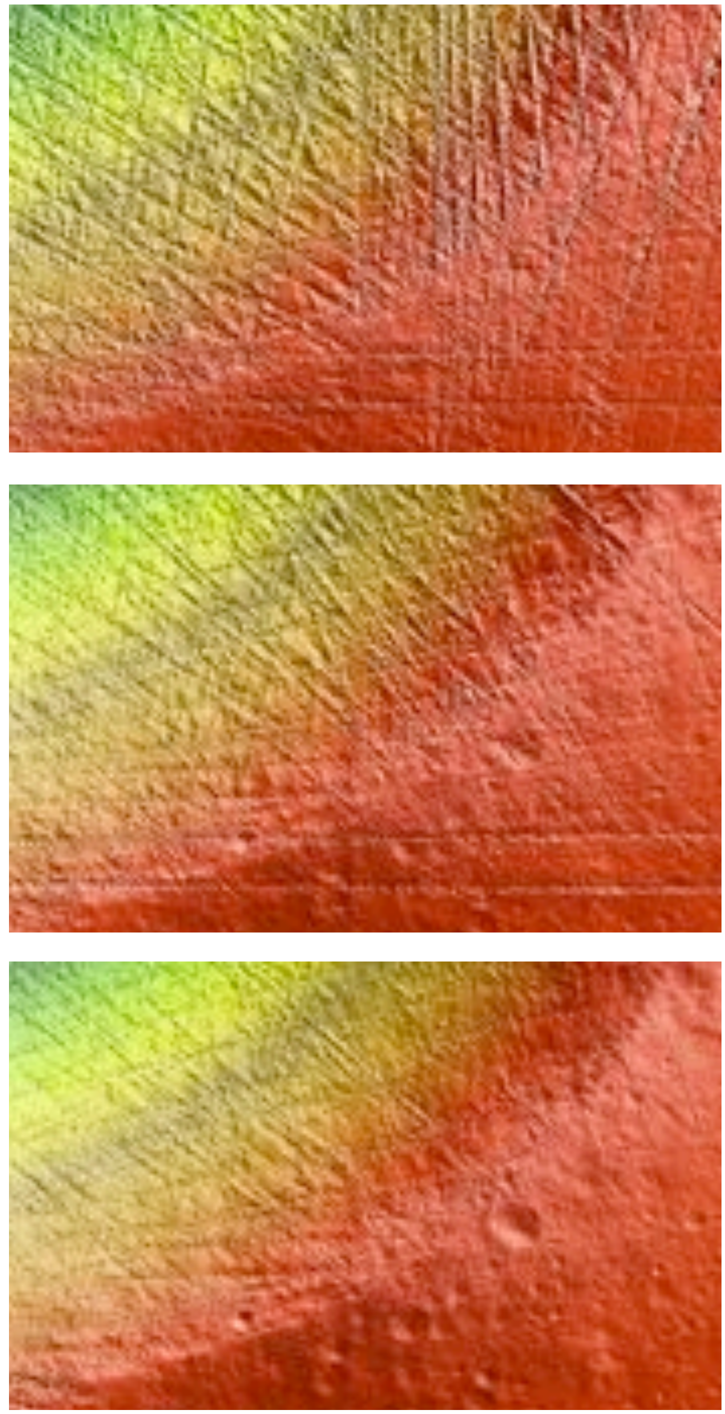

Fig.1 LOLA topographic maps near the lunar South Pole constructed based on various LRO orbit reconstructions: navigation (top), LOLA POD with only radiometric data (middle) and LOLA POD with radiometric data and altimetric crossovers (bottom).