13-Po26

Lunar Reconnaissance Orbiter Orbit Determination with Laser Ranging Data

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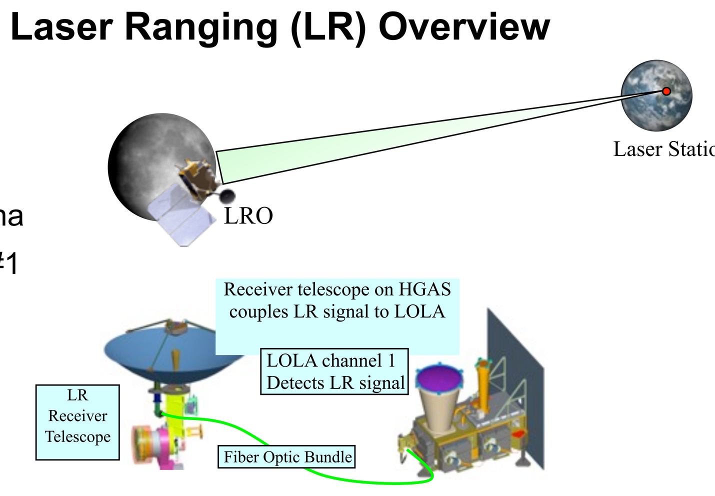
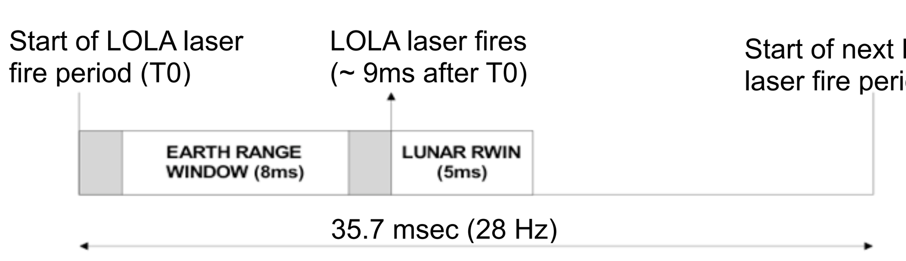
Lunar Reconnaissance Orbiter (LRO) – Laser Ranging (LR) Overview



- Flight Segment:
  - 3.81 cm diameter aperture mounted on High Gain Antenna
  - Fiber optic bundle carries the light to the LOLA detector #1
- Ground Segment:
  - Transmit 532 nm laser pulses at <= 28 Hz
  - Departure time stamped at ground station

One LOLA Detector does both Earth and Lunar Measurements



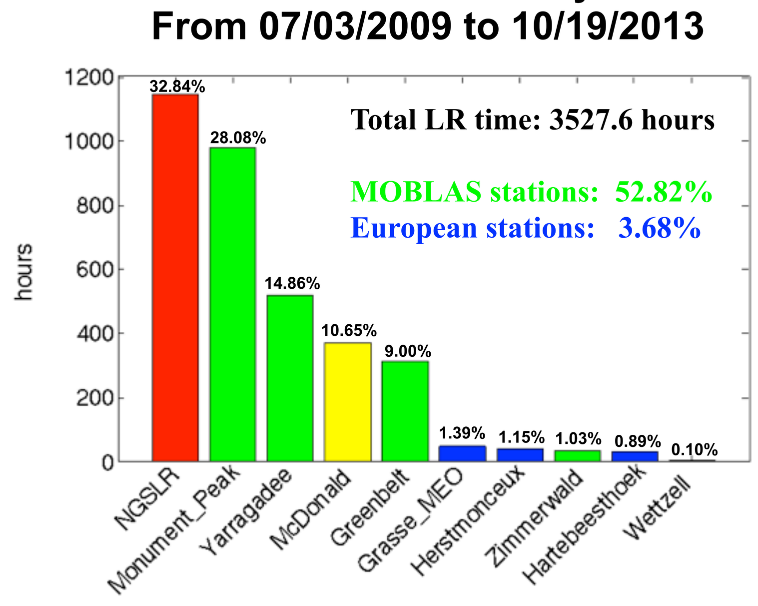
- Two range windows in one detector: 8 msec earth and up to 5 msec lunar
- Range to LRO changes ~ 5-10 ms over an hour's visibility

Ten Participating Stations from the International Laser Ranging Service (ILRS)

- Fire times recorded at each station:
  - Accuracy to UTC < 100 ns
  - Relative fire time error RMS < 200 ps (over 10 sec).
- NASA's Next Generation Satellite Laser Ranging System (NGSLR):
  - 50 mJ Northrop Grumman laser (532.2 nm wavelength, 6 ns pulsewidth)

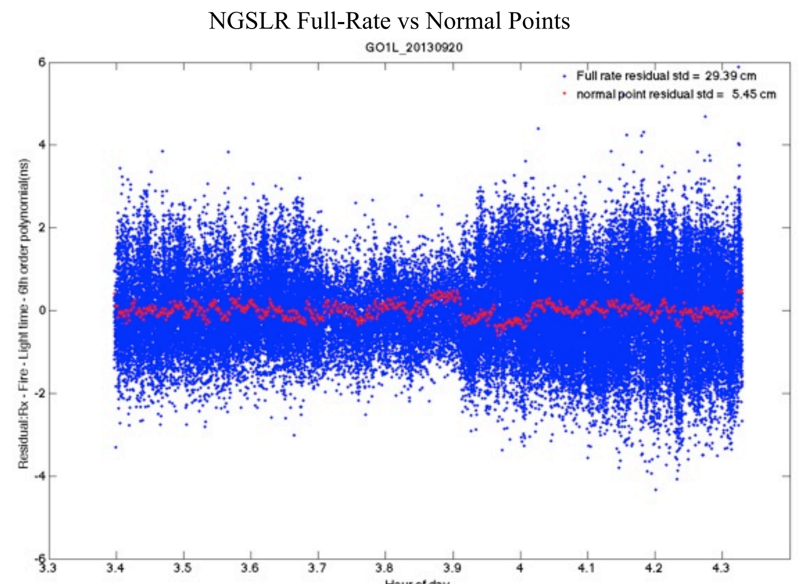
Tracking station	Synchronous	FireRate	Events/second in Earth Window	Energy per pulse at LRO (fJ/cm²)
NGSLR (Greenbelt,MD,USA)	YES	28 Hz	28	2 to 5
McDonald (TX,USA)	NO	10 Hz	2 to 4	4 to 10
Monument Peak (CA,USA)	NO	10 Hz	2 to 4	1 to 2
Yarragadee (Australia)	NO	10 Hz	2 to 4	1 to 2
Hartebeesthoek (South Africa)	NO	10 Hz	2 to 4	1 to 2
Greenbelt (MD, USA)	NO	10 Hz	2 to 4	1 to 2
Herstmonceux (Great Britain)	YES	14 Hz	14	1 to 3
Zimmerwald (Switzerland)	YES	14 Hz	14	2 to 10
Wettzell (Germany)	EFFECTIVELY	7 Hz	7	1 to 2
Grasse (France)	NO	10 Hz	2 to 4	1 to 2

LR Data Summary From 07/03/2009 to 10/19/2013



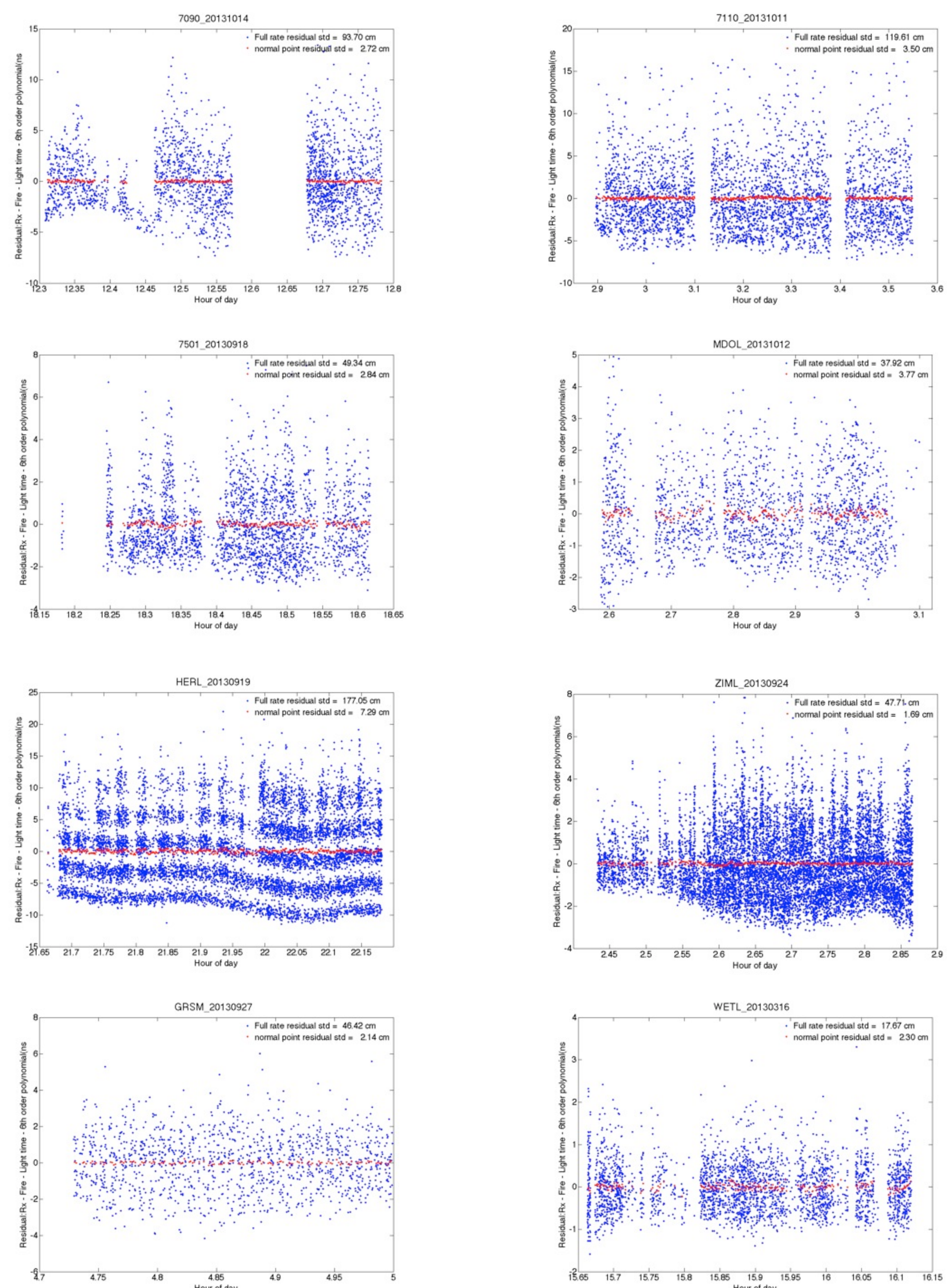
LR Data Structure and Precision

NGSLR Full-Rate vs Normal Points



LR Data Precision at Participating Ground Stations in frozen orbit

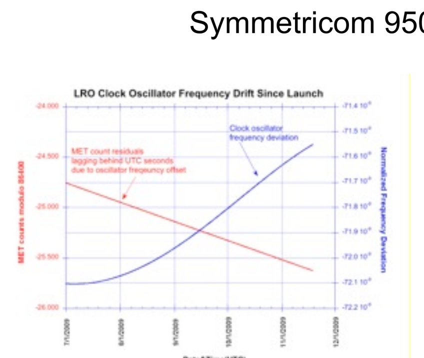
note the different scale on the y-axis



- Use predictions (CPFs) generated by GSFC Flight Dynamics Facility (FDF) with accuracy < 1 km (3D, 3 sigma), and event arrival times recorded by LOLA
- Earth tracking stations fire time files are combined with LRO "Earth window" receive times calculating time of flight considering relativistic effects to match the fire and receive times every morning to form 1-way laser range observations
- The resulting "full-rate" observations are aggregated to form normal points every 5 seconds
- One way LR precision: 10 ~ 50 cm for full rate, and 2 ~ 5 cm for normal points

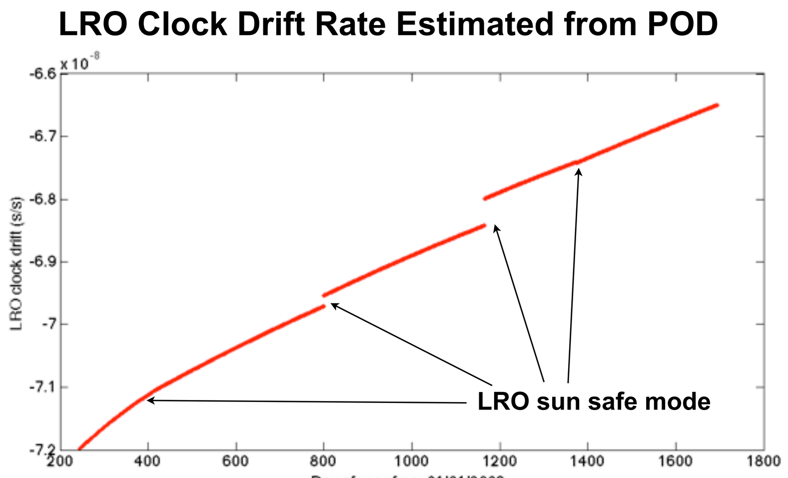
LOLA/LR Clock Oscillator Long-Term Stability

Symmetricom 9500 series Oven Controlled Crystal Oscillator

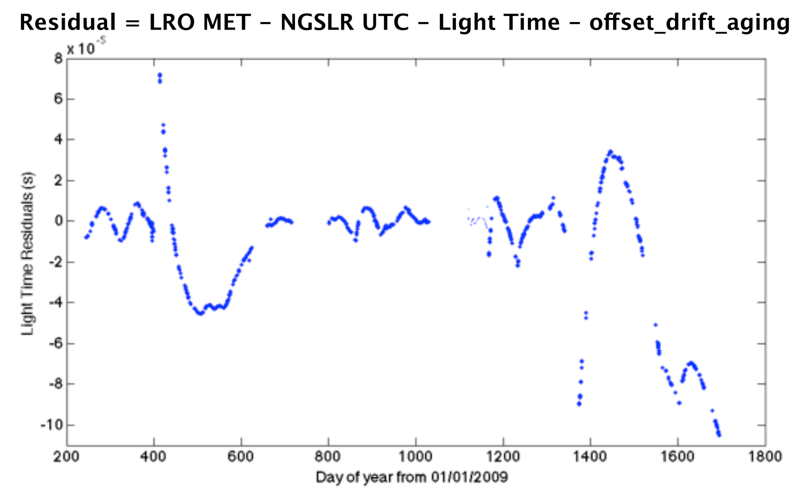


- Oscillator long term frequency stability is about +/-1.5e-12 per day before removing the temperature effect
- The drift rate of the LRO project-supplied spacecraft clock is approximately 1.00000006754 seconds per 1 s clock tick at present, and the clock has been slowing down gradually and steadily
- After removing a constant time offset, a linear time drift, a quadratic frequency aging, a cubic frequency aging rate, and a calculated light time, the residuals are less than 0.01 ms for the entire mission, which is ~30 times better than the 3 ms mission requirement
- LRO sun-safe incidents showed impacts on LRO clock's drift and aging rates due to the change of clock temperature

LRO Clock Drift Rate Estimated from POD



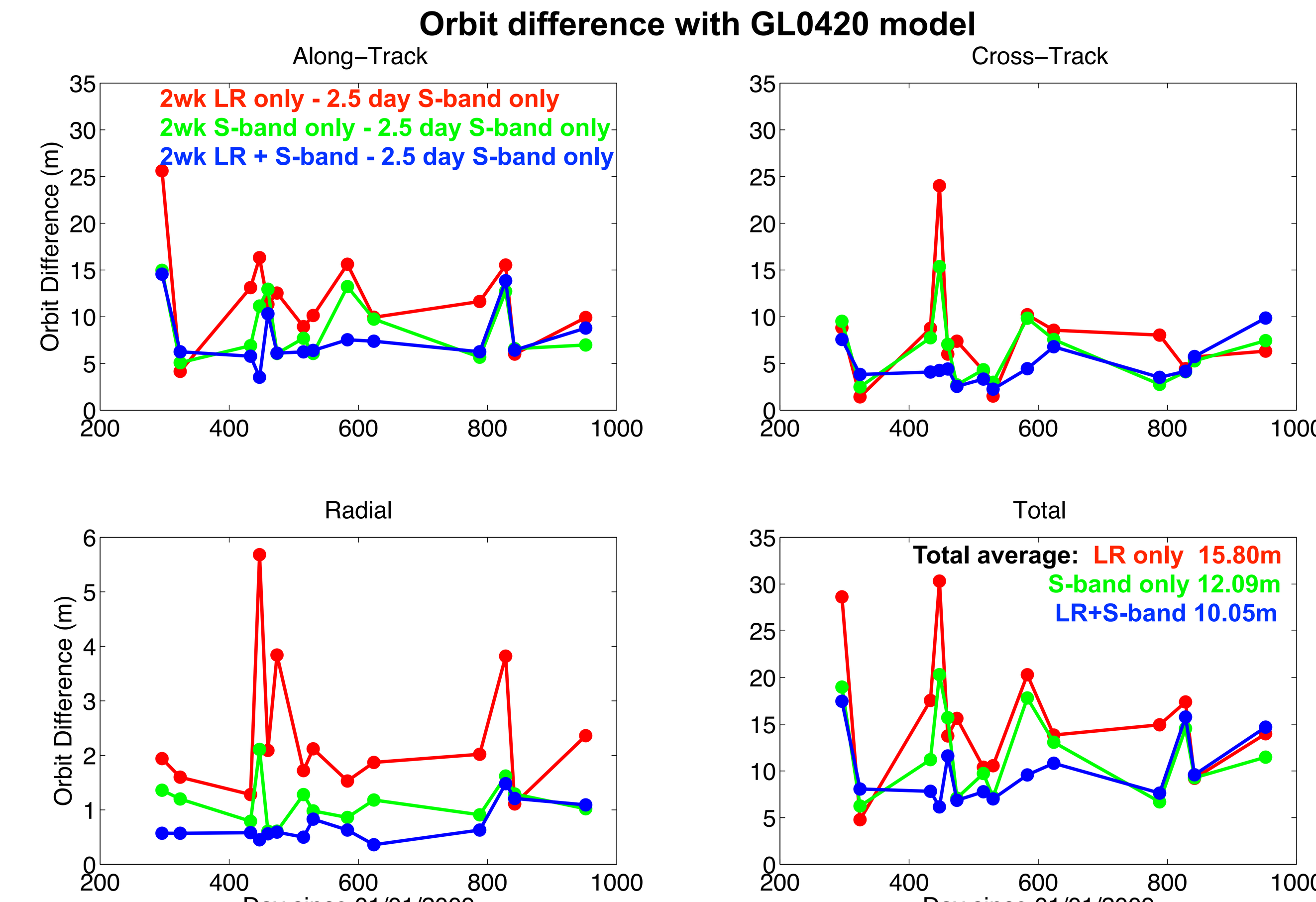
Residual = LRO MET – NGSLR UTC – Light Time – offset_drift_aging



LRO Orbit Determination Results with LR and GRAIL GL0420 Gravity Field Model*

* Zuber, *et. al.*, Science, Vol. 339 no. 6120 pp. 668-671 (8 February 2013)

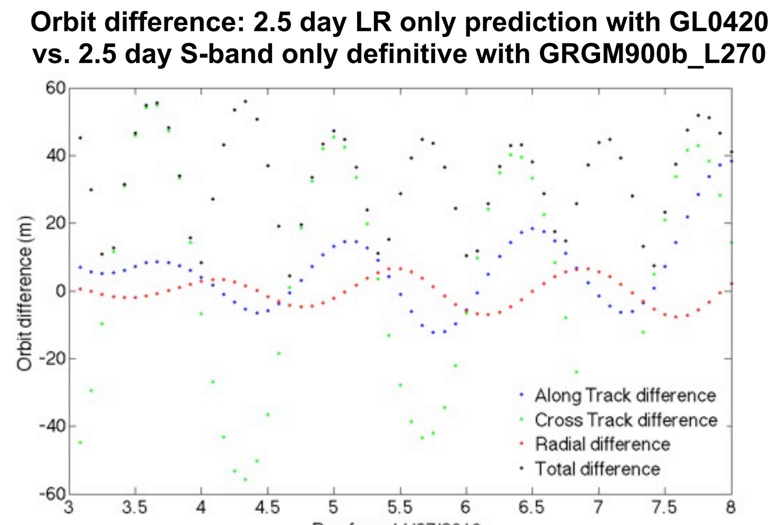
Orbit difference with GL0420 model



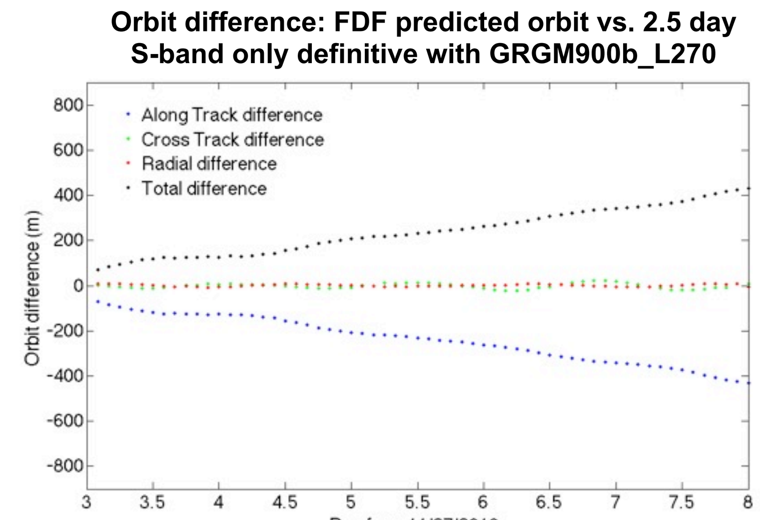
- Two-week arcs with LR only, S-band only, and LR + S-band data are constructed and used with the GRAIL 420 model in the POD process, respectively.
- The orbit results from September, 2009 to December, 2012 are compared with a 2.5 day S-band only orbit solution, which is considered as the best orbit results at present.
- Average number of LR normal point data per 2 week arc: 15339
- Average number of S-band range data points per 2 week arc: 65055
- Plot on the left shows that less than 6 m in radial, and 35 m in total orbit differences have been achieved using LR data only. Total average orbit difference are comparable between LR only orbit solutions and S-band only solutions.

LRO Orbit Prediction Results with LR and GRAIL GL0420 Gravity Field Model

Orbit difference: 2.5 day LR only prediction with GL0420 vs. 2.5 day S-band only definitive with GRGM900b_L270



Orbit difference: FDF predicted orbit vs. 2.5 day S-band only definitive with GRGM900b_L270



- Up to 6 day orbit prediction from 2.5 day LR data with GL0420 model are compared to a definitive LRO orbit solution from 2.5 day S-band only arc with GRGM900b model truncated at degree 270, and FDF prediction orbit, respectively. Results are shown in plots above.
- Compared with the FDF predicted orbit, LR predicted orbit has smaller error with respect to the definitive orbit, especially in the along track direction.
- Less than 80 m of total difference, and less than 10 m of radial difference with respect to the definitive orbit well satisfy the FDF orbit prediction requirement of 800 m along track difference over 84 hours, hence suggesting that LR data can be used independently for LRO orbit prediction

- To determine the quality of the orbital solutions, the latest LOLA adjusted grid* is used as the "truth"
- Various POD orbits are implemented with LOLA altimetry returns to generate topography data, which are compared to the LOLA grid
- The plot on the left and the table below showed results from two 2-week arc's as an example
- GL0420 gravity model shows obvious improvement over the LLGM-1 model
- LR data can independently generate orbital solutions with comparable quality with respect to those from S-band data thanks to GL0420 model

	rms_horizontal (m)	rms_radial (m)	rms_total (m)
LR only - grid GL0420	18.17	2.57	18.35
S-band only - grid GL0420	17.43	0.85	17.45
LR + S-band - grid GL0420	17.42	0.85	17.44
LR + S-band - grid LLGM-1	27.37	2.31	27.47

Orbit quality with respect to the latest LOLA grid*

* Zuber, *et. al.*, Nature, **486**, 378–381 (21 June 2012)