The Contributions of Laser Ranging to the LUNAR RECONNAISSANCE ORBITER Mission

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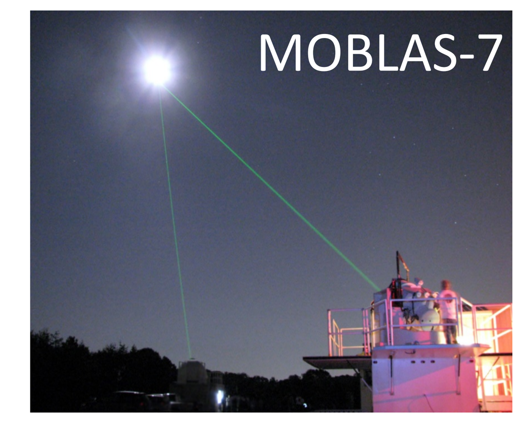
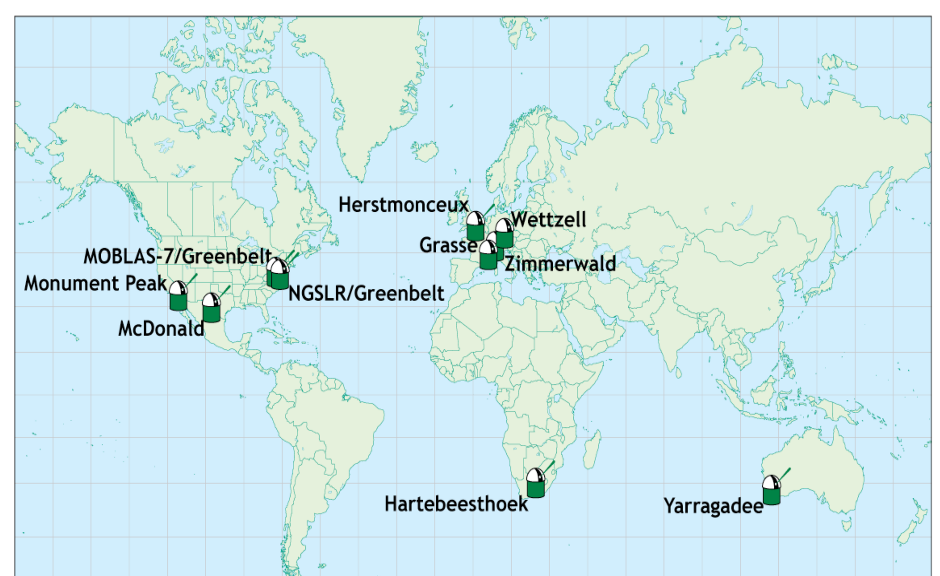
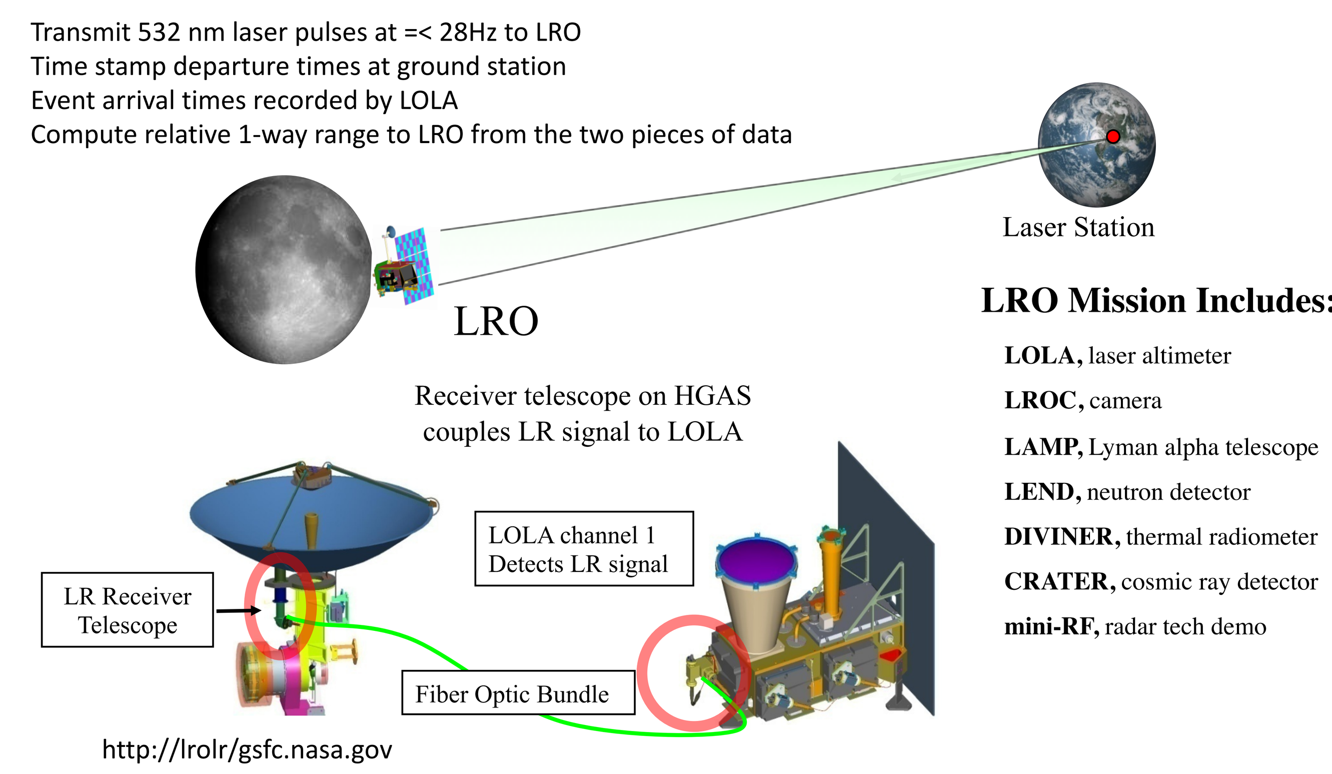


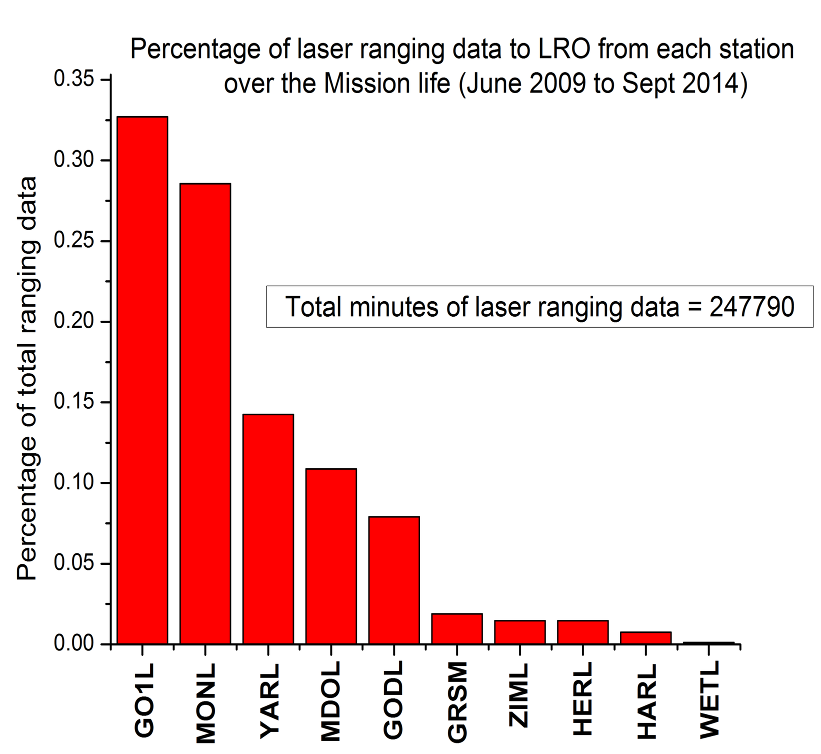
Laser Ranging (LR) to the Lunar Reconnaissance Orbit (LRO) was active from June 2009 to September 2014 using a one-way (uplink only) technique where the ground stations fired their lasers at LRO and recorded the fire times and the spacecraft altimeter, the Lunar Orbiter Laser Altimeter (LOLA), measured the receive events, telemetering them down in the S-band data stream. Ten ILRS stations (with NGSLR at Goddard's Geophysical and Astronomical Observatory being the primary) participated in this ranging, generating over 4000 hours of successful LR data. LR data was used to calibrate the spacecraft clock and to improve the orbital accuracy in the radial direction over just S-Band data alone. In addition the data was used to demonstrate that LR data alone can provide good orbital solutions when used with high-resolution gravity models.

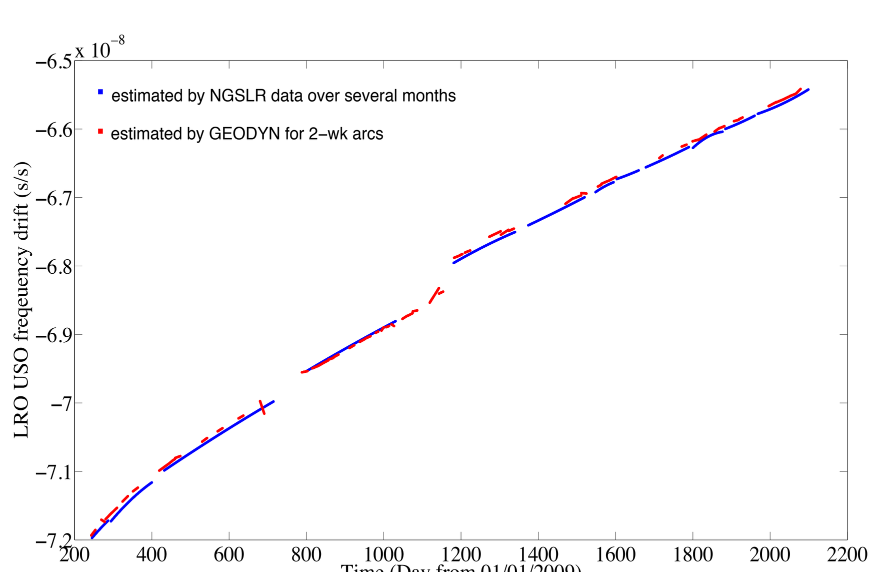
Station	Location	Synch to LOLA?	Firerate (Hz)	Max # / sec in LOLA window	Expected energy at LRO (fJ / sqcm)	Station Frequency Source	Date of first successful ranging to LRO	LR Status
NGSLR	Maryland, US	Yes	28	28	1 to 5	Maser (18-Oct-2010)	30-Jun-2009	Operational
MLRS, McDonald	Texas, US	No	10	2 to 4	1 to 10	Cesium	02-Jul-2009	Operational
MOBLAS-7, Greenbelt	Maryland, US	No	10	2 to 4	1 to 3	Maser	02-Jul-2009	Operational
Herstmonceux	Great Britain	Yes	14	14	1 to 3	Maser (13-May-2010)	13-Jul-2009	Operational
Zimmerwald	Switzerland	Yes	14	14	1 to 3	Ovenized crystal oscillator	20-Jul-2009	Operational
Wettzell	Germany	Yes	7	7	1 to 10	Cesium	30-Oct-2009	Operational
MOBLAS-6, Hartebeesthoek	South Africa	No	10	2 to 4	1 to 3	Maser	05-Dec-2009	Operational
MOBLAS-5, Yarragadee	Australia	No	10	2 to 4	1 to 3	Maser (14-May-2010)	25-Jan-2010	Operational
MOBLAS-4, Monument Peak	California, US	No	10	2 to 4	1 to 3	GPS steered Rubidum	03-Feb-2010	Operational
Grasse/MEO	France	No	10	2 to 4	1 to 10	Cesium	18-May-2010	Operational



NGSLR = GO1L, MLRS=MDOL, Greenbelt(MOB7)=GODL, MonPeak(MOB6)=MONL, Yarragadee(MOB5)=YARL Herstmonceux=HERL, Zimmerwald=ZIML, Wettzell=WETL, Grasse(MEO)=GRSM



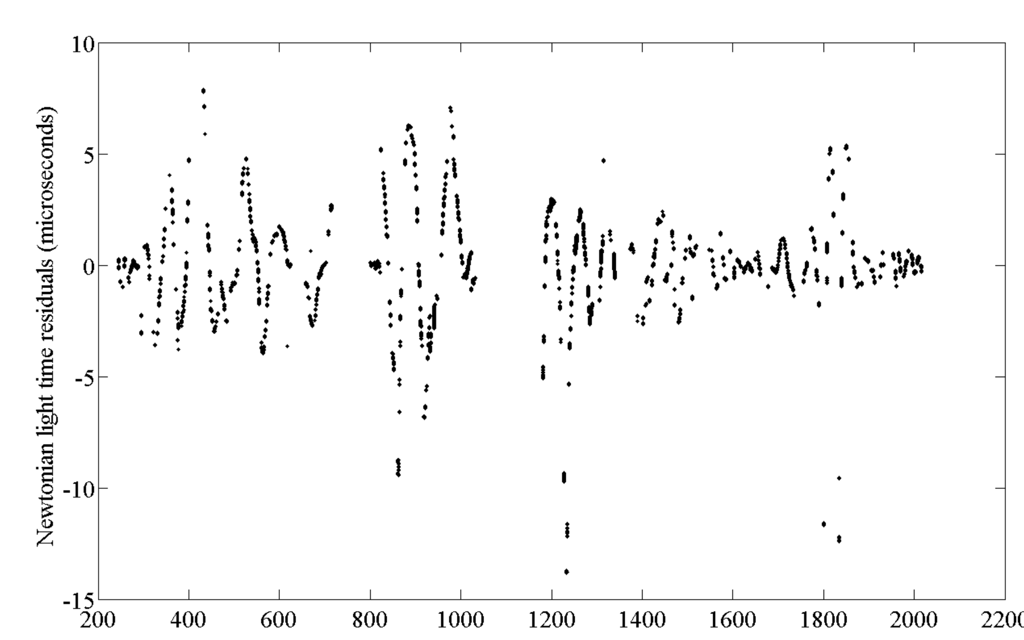




LRO USO characterization:
Method 1: direct estimation from NGSLR data (blue)
Method 2: GEODYN estimation for each 2-week arc with LR data from all available stations (red). This plot shows that when NGSLR data is not available, data from other participating SLR stations provides a good supplement for LRO clock estimation.

SUMMARY OF LRO-LR ACHIEVEMENTS

- Enabled a new range measurement capability using existing SLR infrastructures, complementing and potentially replacing RF tracking in the future.
- Demonstrated operational laser ranging to a target orbiting a body other than Earth over a 5 year period.
- Showed that the ILRS Network can be coordinated to provide close to 24 hour coverage for laser ranging to targets beyond the Earth's orbit.
- Developed & demonstrated a successful method for providing tracking feedback to ground stations for 1-way uplink ranging (real-time website from instrument housekeeping data).
- Exceeded the Mission requirements for characterization of the LRO onboard oscillator.
- Demonstrated that LR data alone can be used to provide good orbit reconstruction. In addition, showed that combining LR and S-band data yield great improvement from S-band only results in the radial direction.
- Provided the opportunity to test new space technologies and mission concepts (laser com & time transfer) using established SLR infrastructures.

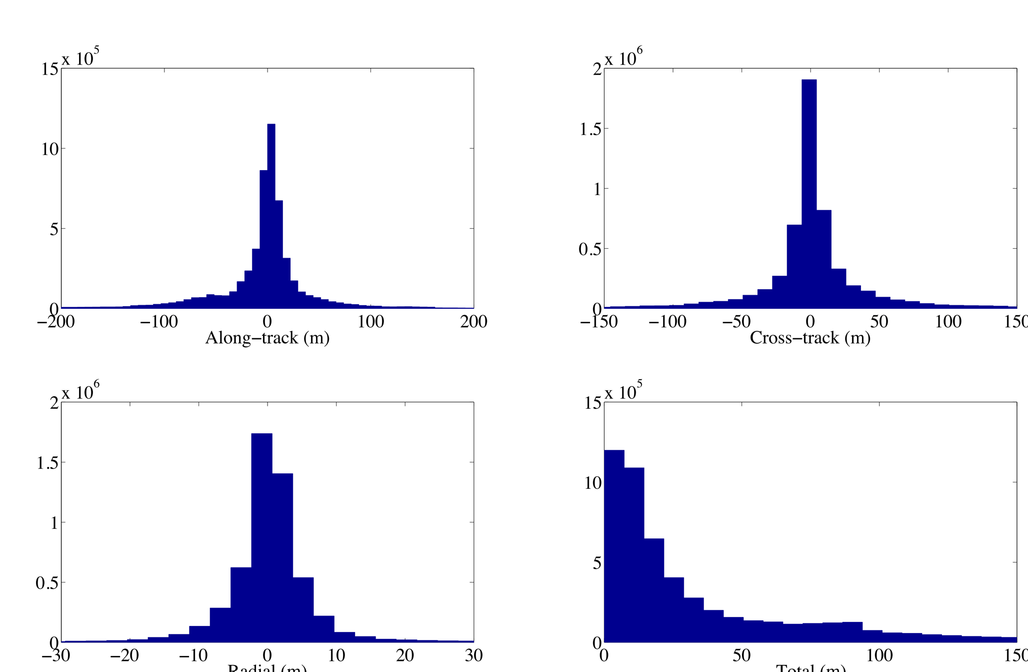


Newtonian light time residuals of the LRO USO (clock drift and aging removed) are less than 15 microseconds over the entire 5-year of LR operation. This plot shows that LR data provides much more accurate USO knowledge than the LRO mission requirement of 3 ms.

LR + S-band provides improved radial orbit results

Mean values and RMS of the orbit difference between solutions for 2-week arcs (high resolution GRAIL gravity model) and definitive LRO orbits from the LOLA team

Orbital Difference	Average Along-track (m)	Average Cross-track (m)	Average Radial (m)	Average total (m)	RMS Along-track (m)	RMS Cross-track (m)	RMS Radial (m)	RMS Total (m)
S-band data only	3.876	-0.437	0.653	26.609	34.372	30.705	10.251	46.213
LR data only	-6.731	1.826	0.200	53.065	78.325	64.256	21.669	100.989
S-band & LR data	-3.070	0.534	-0.143	33.589	39.954	34.522	6.322	52.534



Histogram of orbital difference: LR-only orbits vs. LRO definitive orbits (58 2-wk arcs over the entire 5-year operation). This histogram shows that LR data alone can provide good orbit determination results with a high-resolution gravity model (e.g. GRAIL gravity models).

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Ref: D. Mao et al., The laser ranging experiment of the Lunar Reconnaissance Orbiter: Five years of operations and data analysis, Icarus (2016), http://dx.doi.org/10.1016/j.icarus.2016.07.003

Similar results can be found in Bauer et al., Planetary and Space Science 129 (2016), http://dx.doi.org/10.1016/j.pss.2016.06.005