LRO-LR:
Four Years of History Making Laser Ranging

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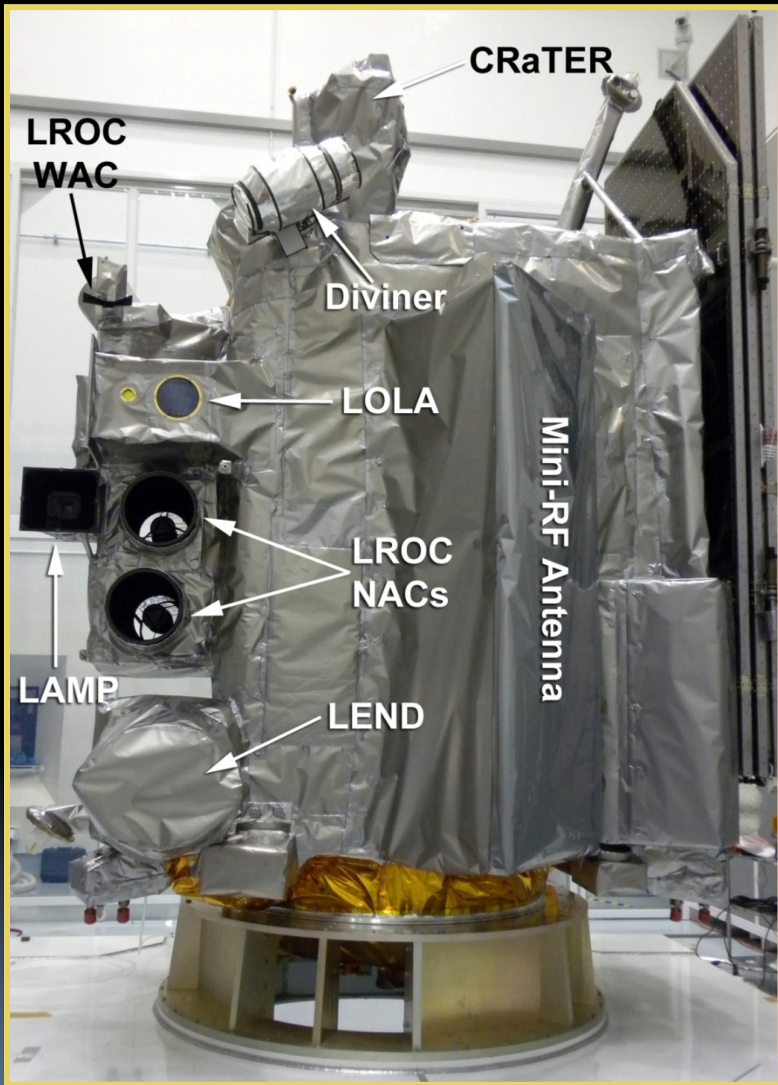
Abstract:

The Lunar Reconnaissance Orbiter launched in June 2009. The first laser ranging attempted from NASA's Next Generation Satellite Laser Ranging (NGSLR) system was on June 30th, and it was also the first successful ranging to LRO. Since that time ten ILRS systems around the world have participated in ranging to LRO and we have accumulated over 3000 hours of laser ranging data. These data have been used to very accurately determine the clock rate and drift and to produce precision orbits. By using the high-resolution GRAIL gravity models, the LRO orbits determined from LR data alone have a total position error of 10 meters in average, and show the same quality as those generated using conventional radiometric tracking data.

Many LR passes have been taken simultaneously between two, three and four stations and often global tracking achieves close to 24 hour coverage. This has opened up new opportunities for other laser timing and communication technology demonstrations. In 2013 we demonstrated the first uplink lasercom from NGSLR to LRO. We are currently conducting laser time transfer tests between SLR stations using LRO as a common receiver in space.

Lunar Reconnaissance Orbiter (LRO)



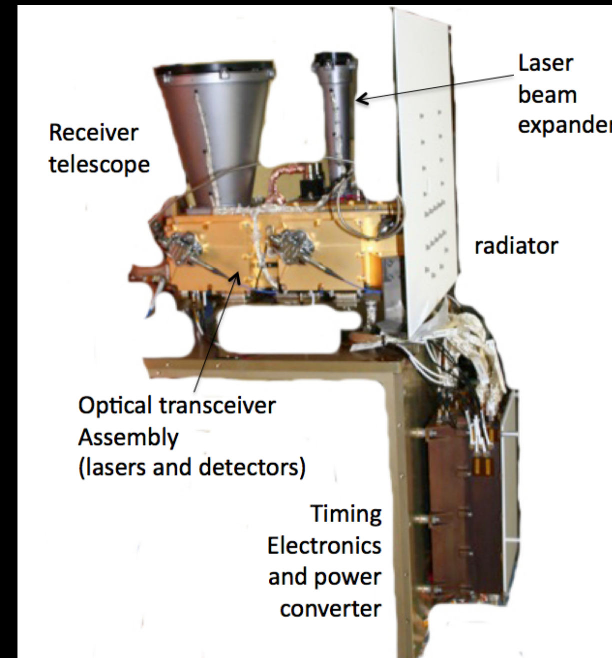
Lunar Orbiter Laser Altimeter (LOLA)

Launched:
6/18/2009

Commissioned:
Sep. 2009

Science:
Sep 2009 to Dec. 2011

Extended Science:
low maintenance (elliptical) orbits:
2012 to present



Parameter	Value
Laser Wavelength	1064.4 nm
Pulse Energy	2.7/3.2 mJ (laser1/laser2)
Pulse Width	~ 5 ns
Pulse Rate	28 ± 0.1 Hz
Beam Divergence	100 ± 10 μrad
Beam Separation	500 ± 20 μrad
Receiver Aperture Diameter	0.14 m
Receiver Field of View	400 ± 20 μrad
Receiver Bandpass Filter	0.8 nm
Detector responsivity	300 kV/W
Detector active area diameter	0.7 mm
Detector electrical bandwidth	46 ± 5 MHz
Timing Resolution	0.5 ns

Lunar Reconnaissance Orbiter Laser Ranging (LRO-LR)

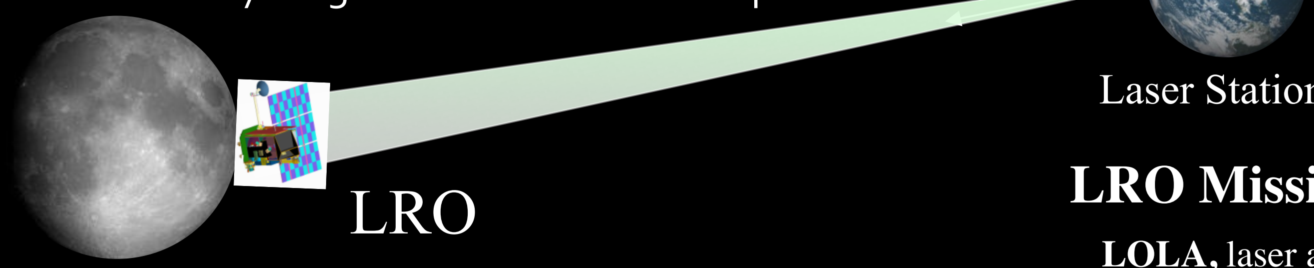
LRO-LR is the first of its kind, enabling a new measurement using existing SLR infrastructures, complementing RF tracking, with the potential to replace RF tracking in the future

Transmit 532 nm laser pulses at =< 28Hz to LRO

Time stamp departure times at ground station

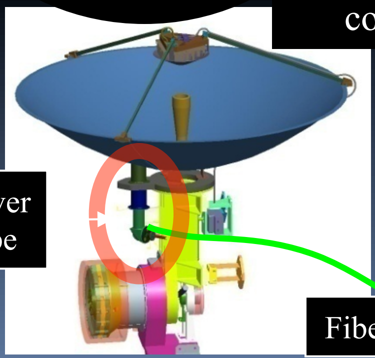
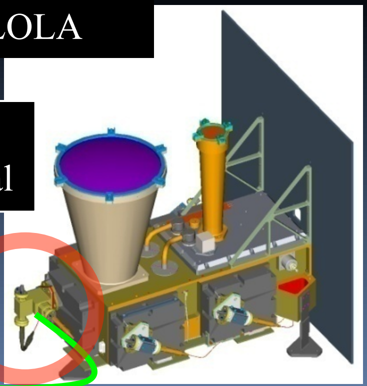
Event arrival times recorded by LOLA

Compute relative 1-way range to LRO from the two pieces of data



LRO Mission Includes:

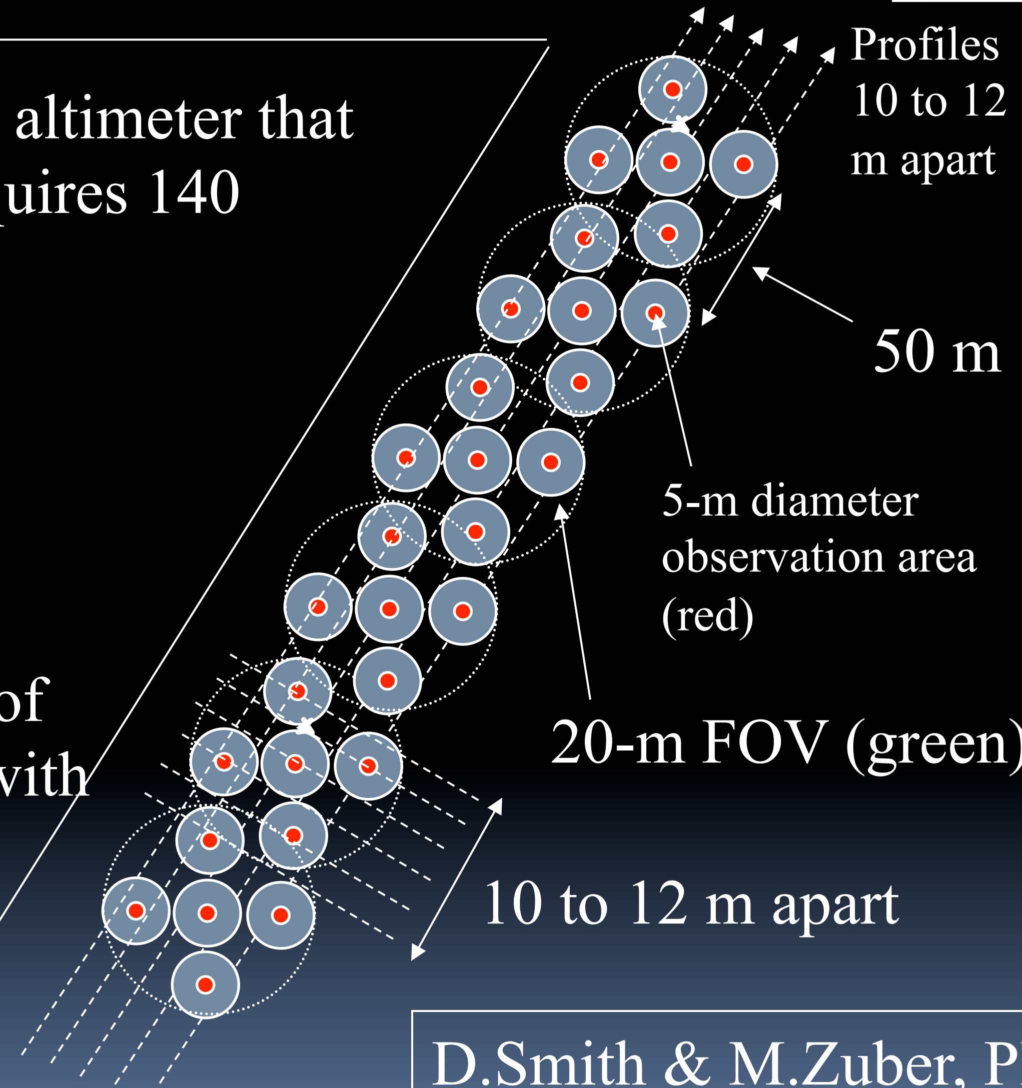
- **LOLA,** laser altimeter
- **LROC,** camera
- **LAMP,** Lyman alpha telescope
- **LEND,** neutron detector
- **DIVINER,** thermal radiometer
- **CRATER,** cosmic ray detector
- **mini-RF,** radar tech demo

Lunar Obiter Laser Altimeter (LOLA)

- LOLA is a 5-beam laser altimeter that operates at 28 Hz and acquires 140 measurements/s of
  - altimetry
  - surface roughness
  - surface reflectance

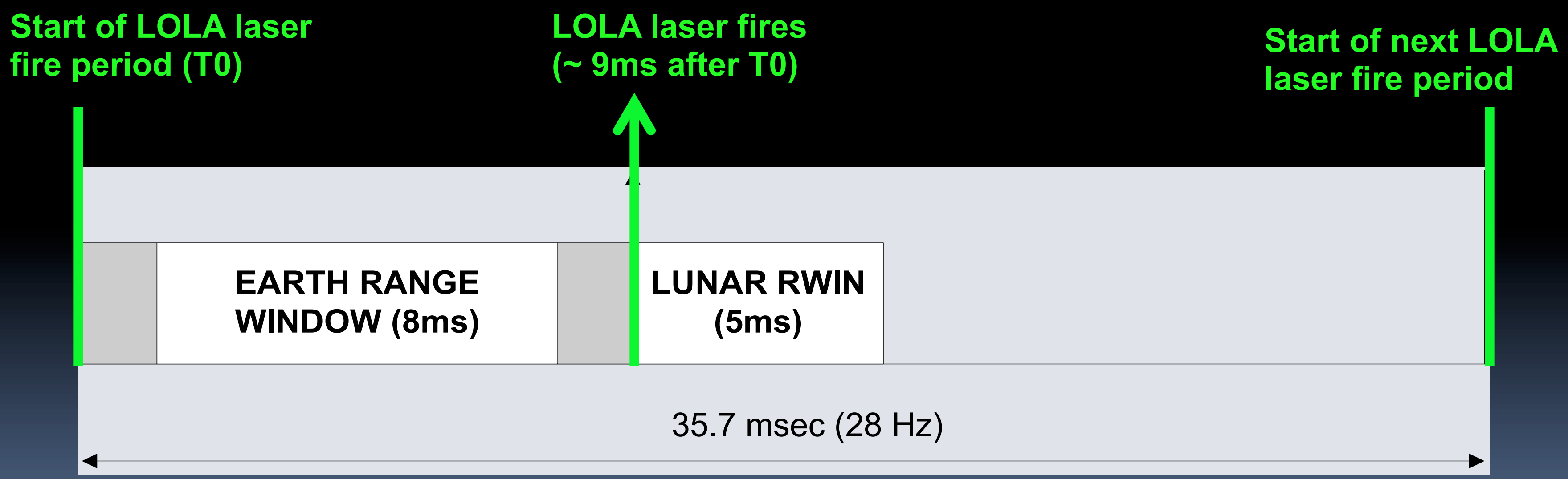
and 180 measurements/s of derivable surface slopes with baselines of 25 to 50 m.



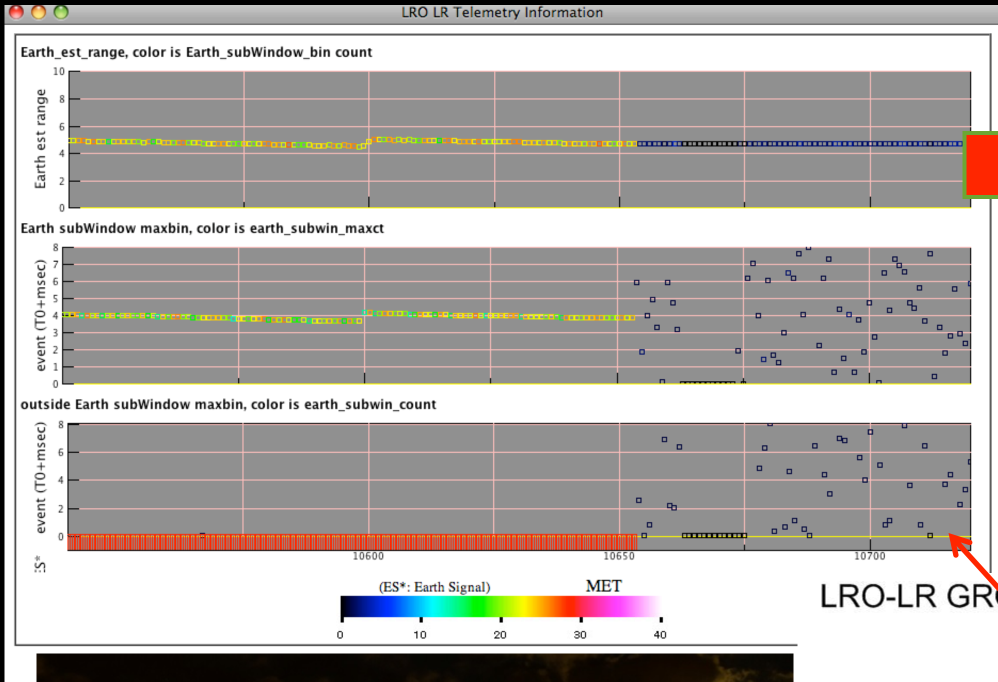
D.Smith & M.Zuber, PIs

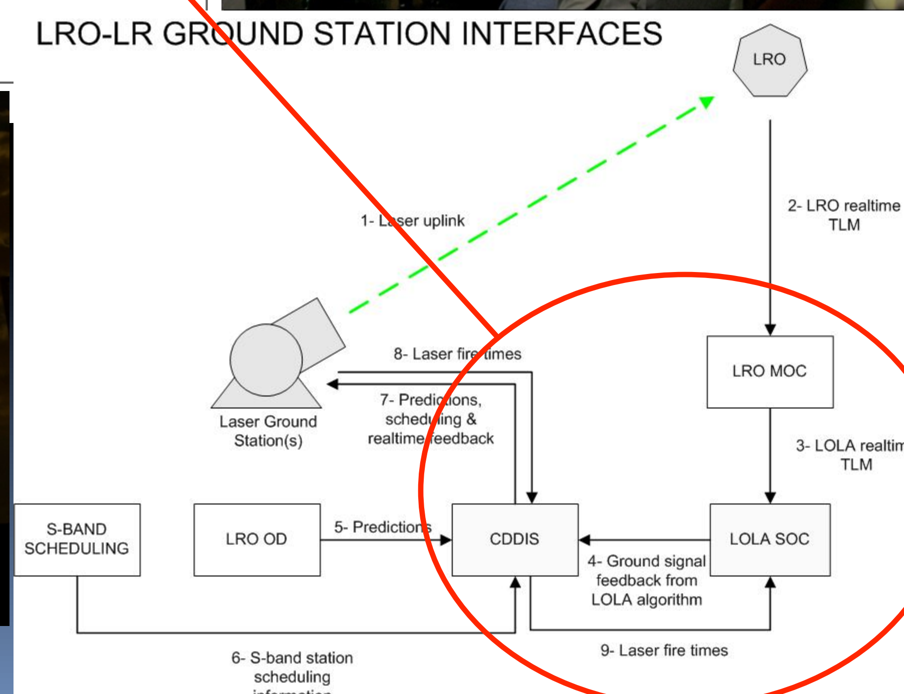
One LOLA Detector does both Earth and Lunar

- Two range windows in one detector: fixed 8 msec earth and up to 5 msec lunar.
- Range to LRO changes ~ 5-10 ms over an hour's visibility.
- Need to either synchronize the ground laser fires to LOLA to ensure pulses land in every Earth Window, or fire asynchronously to LOLA (eg 10Hz).



Real-Time Telemetry Website





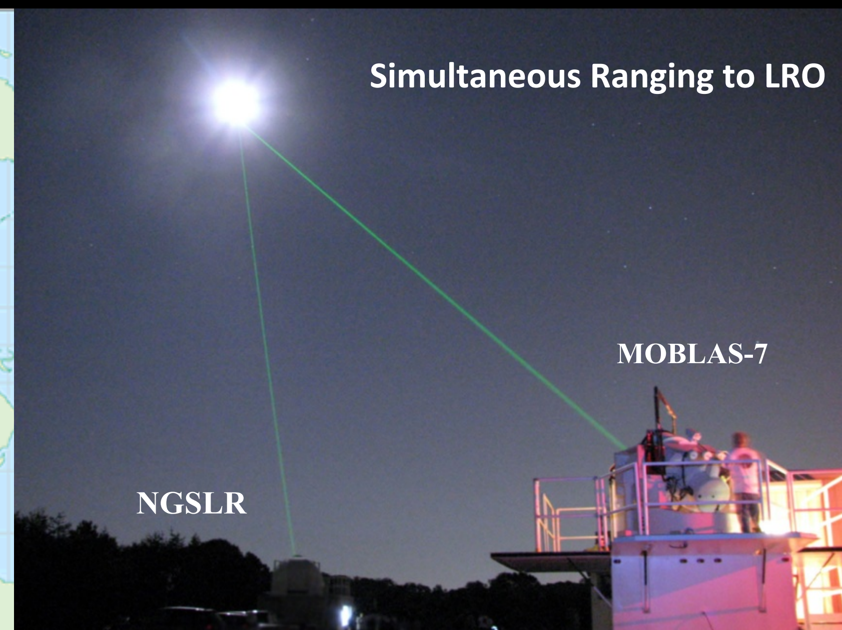
http://lrolr/gsfc.nasa.gov

LR Network First Successes

FIRSTS

- Ranging to LRO: 30 Jun 2009 – GO1L on first attempt
- 2-way simultaneous: 28 Jul 2009 (GO1L,GODL)
- 3-way simultaneous: 1 Nov 2010 (GO1L,MDOL,MONL)
- 4-way simultaneous: 11 Mar 2011 (GO1L,GODL,MDOL,MONL)
- Lasercom over LR: 10 May 2011 (GO1L) & 26 Mar 2012 (GO1L)

10 participating stations



LR Statistics over Four Years

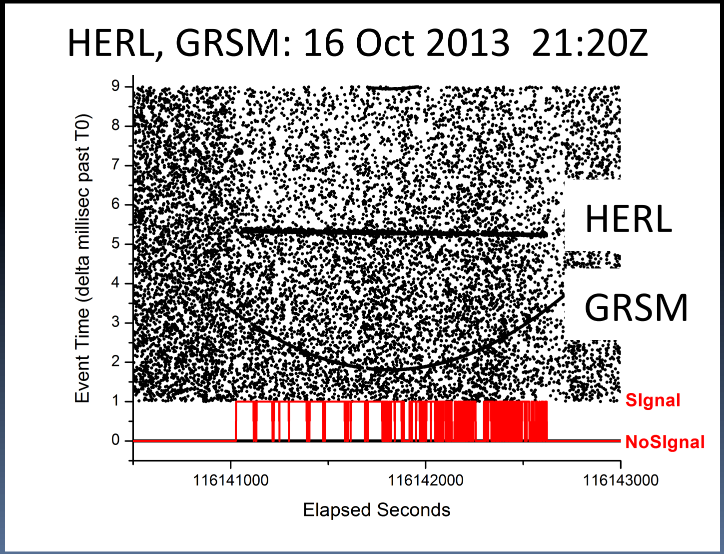
June 2009 through September 2013

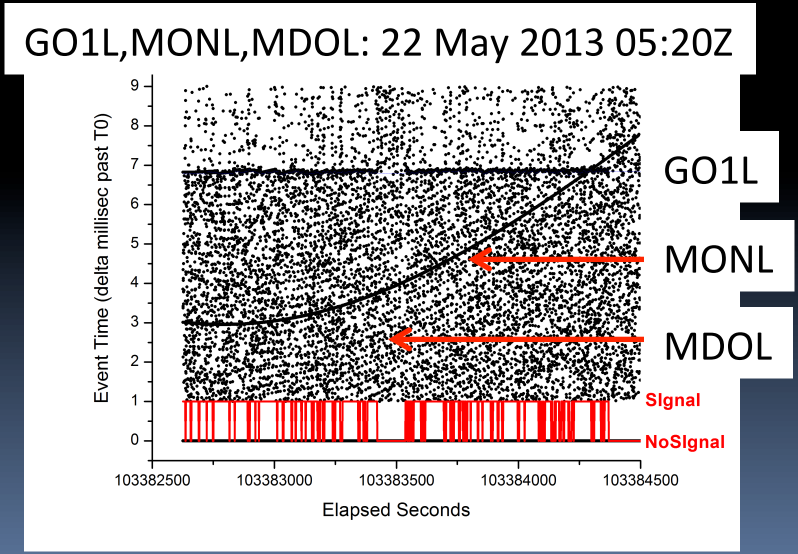
- **Total of LRO-LR data: 3489 hours.**

- **Number of minutes & percentage of total data for each station:**

	GO1L	GODL	MDOL	HERL	ZIML	WETL	HARL	YARL	MONL	GRSM
Minutes	68605	18771	21926	2290	2249	216	1849	30513	57646	2820
Percentage	33%	9%	11%	1%	1%	< 1%	1%	15%	28%	1%

- **Ground station events as seen at LRO by the LOLA instrument:**





Simultaneous LR Passes

June 2009 through September 2013

2-way

Stations	# 2-way
GO1L&GODL	48
GO1L&MDOL	111
GO1L&MONL	241
GODL&MDOL	58
GODL&MONL	92
MDOL&MONL	105
HARL&HERL	1
HARL&ZIML	4
GRSM&ZIML	26
GRSM&HERL	1
ZIML&HERL	1
HERL&WETL	2

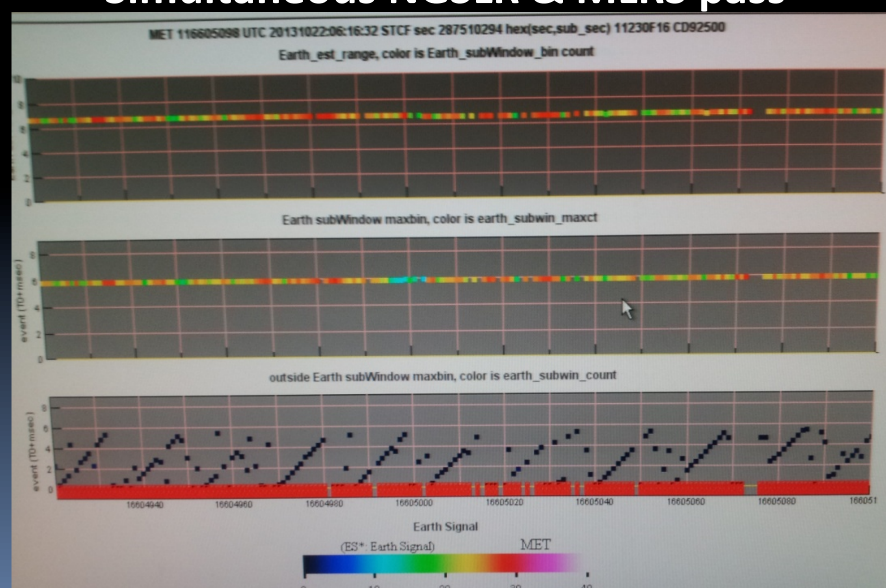
3-way

Stations	# 3-way
GO1L,GODL & MDOL	3
GO1L,GODL & MONL	5
GO1L,MDOL & MONL	52
GODL,MDOL & MONL	40

4-way

Stations	# 4-way
GO1L, GODL, MDOL & MONL	6

Simultaneous NGSLR & MLRS pass

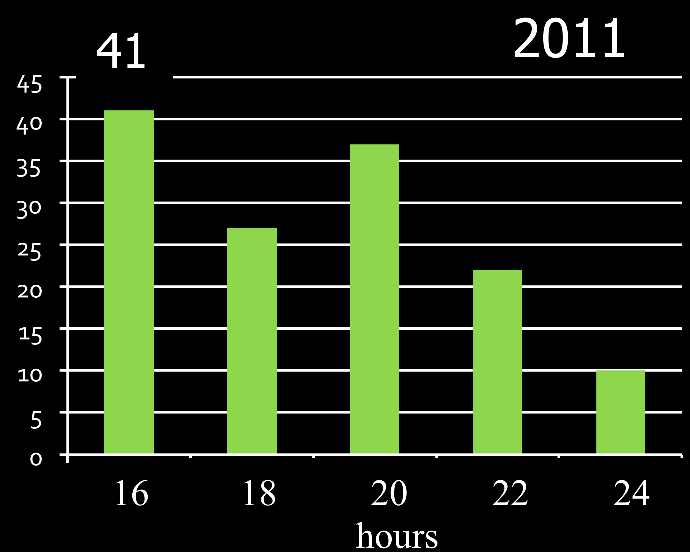


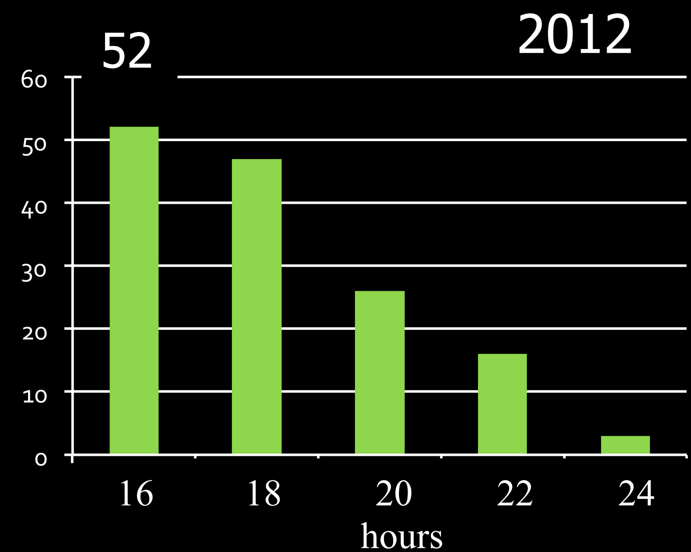
NGSLR

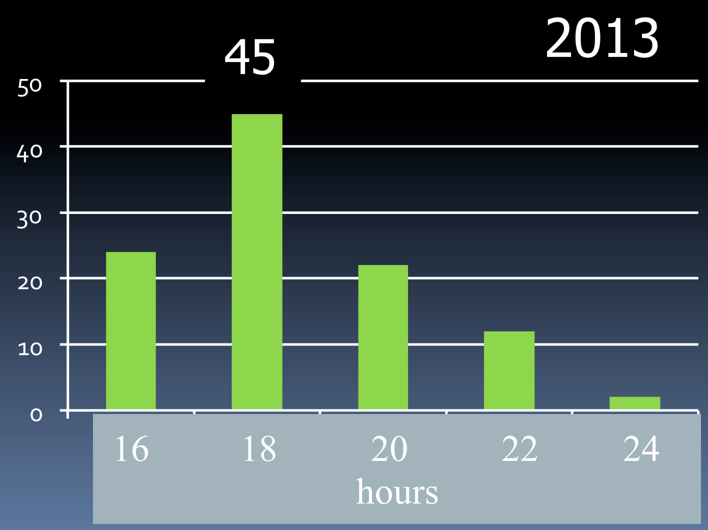
MLRS

Global Coverage over 24 Hours

January 2011 through September 2013







Number of days in year we achieved >= 16 hours of LR coverage (50% duty cycle):

2011: 137

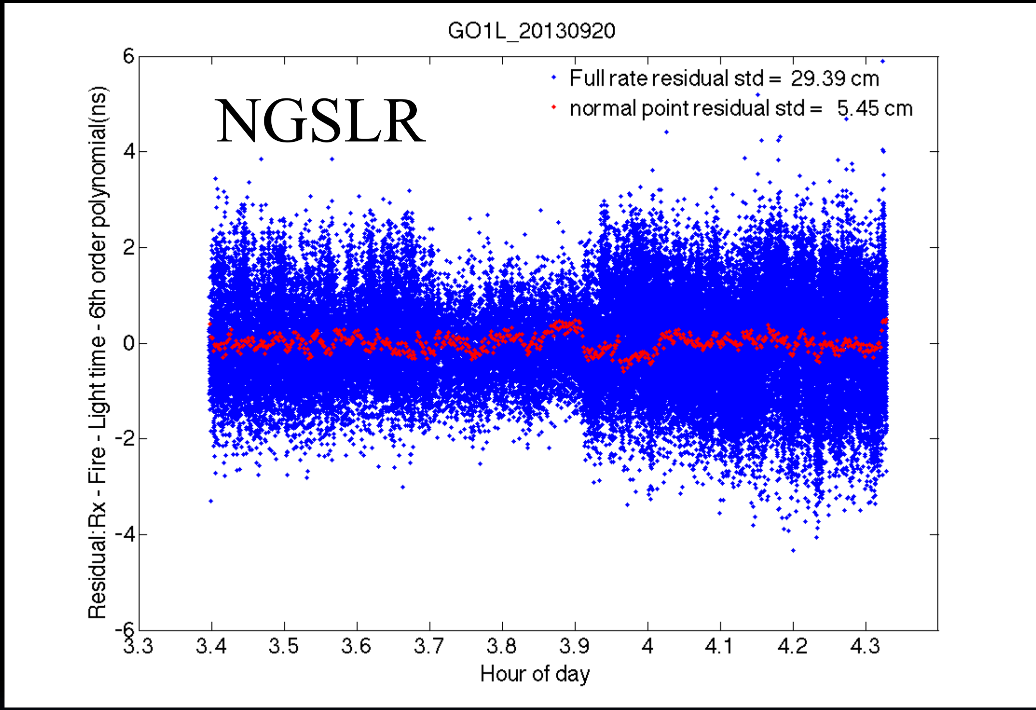
2012: 144

2013: 105

Ground Station Precision

-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 times are combined with LRO "Earth window" receive times calculating the time of flight considering orbital relativistic effects to match the fire and receive times every morning to form 1-way laser range observations

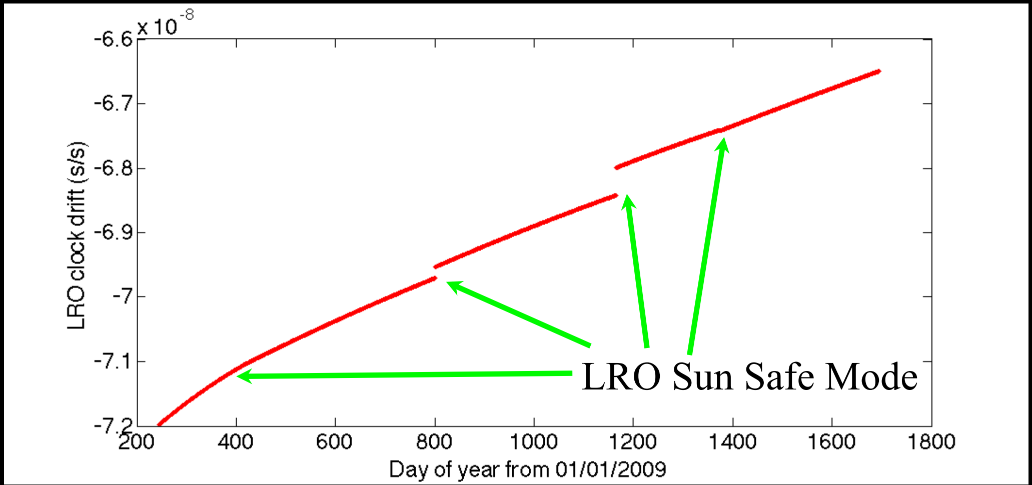


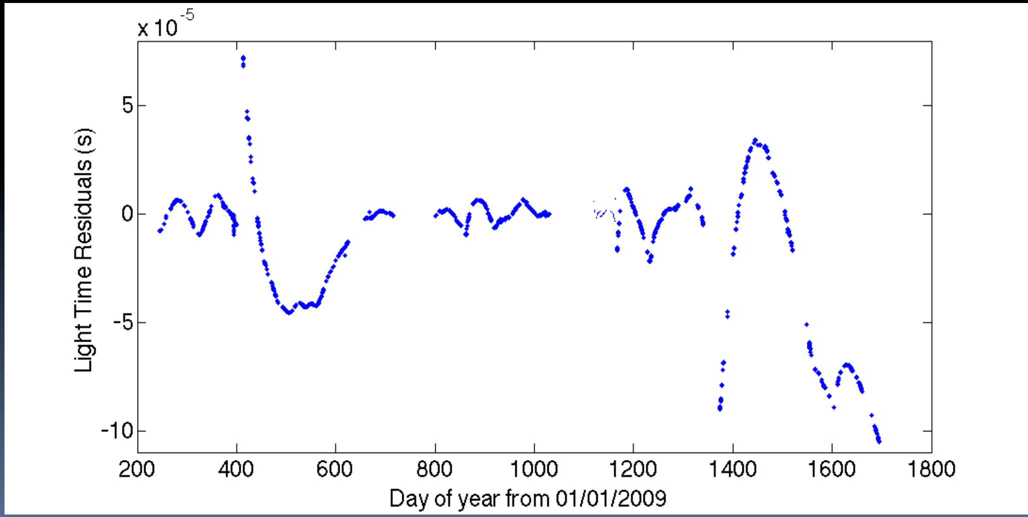
- The resulting "full-rate" observations are aggregated to form normal points every 5 sec

- **One way LR precision: 10 ~ 50 cm for full rate, and 1 ~ 5 cm for normal points**

See D. Mao poster for more details

LRO Clock Long Term Characteristics

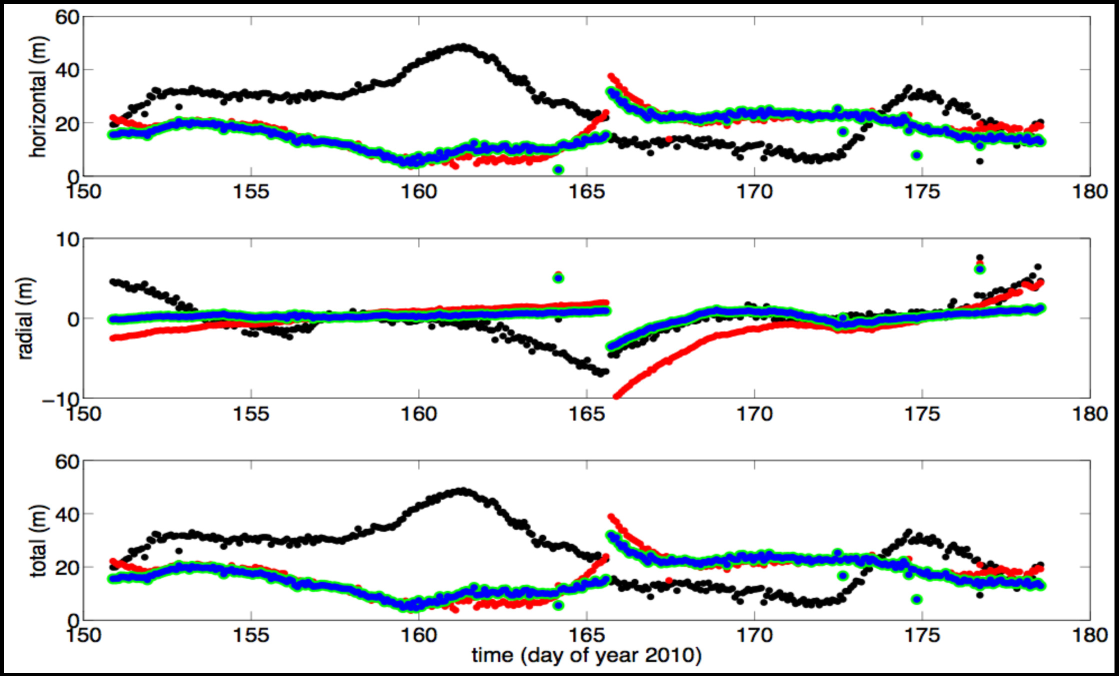




- Oscillator long term frequency stability is about +/-1.95e-12 per day before removing the temperature effect at present
- The drift rate of the LRO project-supplied spacecraft clock is approximately 1.00000006754 seconds per 1 s clock tick at present, and the clock has been slowing down gradually and 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 0.1 ms for the entire mission, which is ~30 times better than the 3 ms mission requirement.**
- LRO sun-safe incidents show impacts on LRO clock's drift and aging rates due to the change of clock temperature

Comparison of LR with S-band Orbits

Two week arc fits and using the latest LOLA map



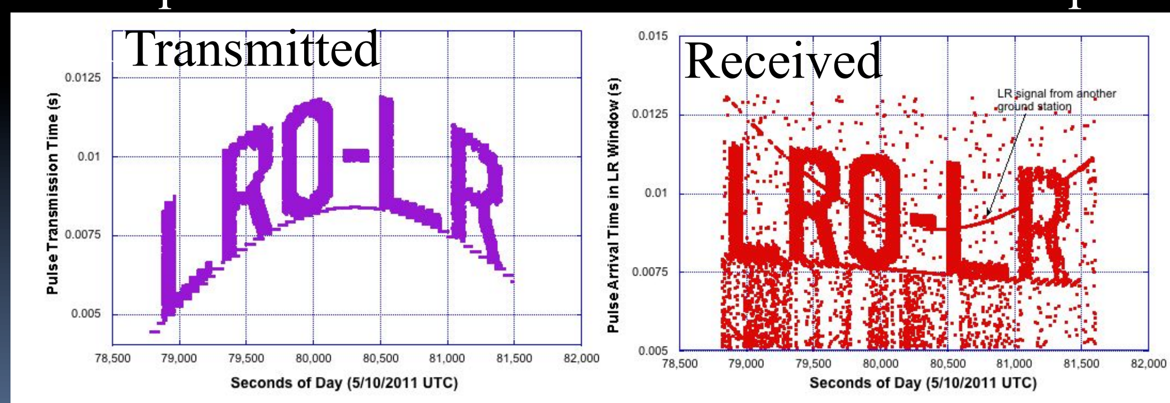
- To determine the quality of the orbital solutions, a LOLA adjusted grid is used as the "truth"
- Various POD orbits are used to locate LOLA altimetry returns, which are compared to the "true" LOLA grid
- GL0420 gravity model shows obvious improvement over the LLGM-1 model
- LR data can independently generate orbital solutions with comparable quality with respect to those from S-band data due 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

Laser Communications Prelim Test

May 10, 2011 (X. Sun, PI)

Pulse positions vs. laser shot count over 1 LRO pass



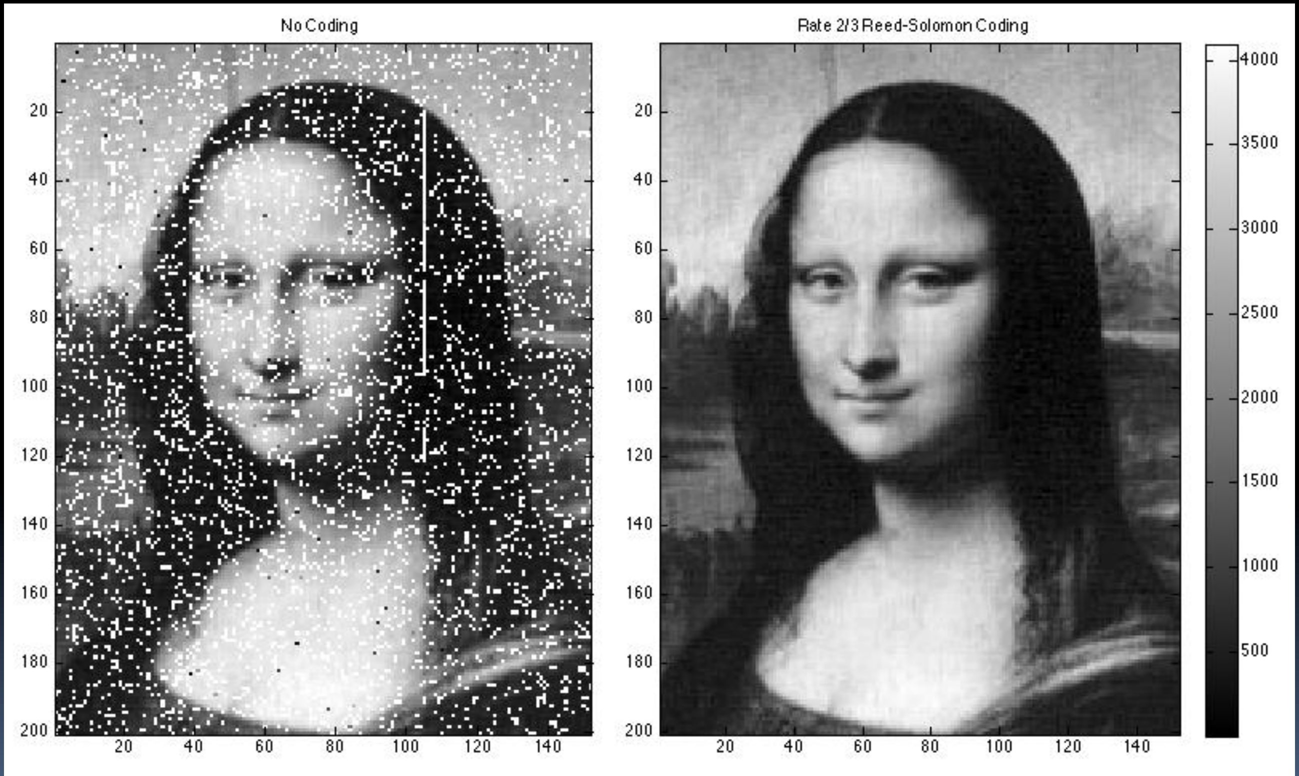
Laser Communications Image Transmission

“Mona Lisa to the Moon”

March 26, 2012 (X. Sun, PI)

Raw data, ~14% error, mostly erasures

With Rate 2/3 Reed-Solomon coding



“Free Space Laser Communication Experiments from Earth to the Lunar Reconnaissance Orbiter in Lunar Orbit,” Xiaoli Sun [http://www.opticsinfobase.org/oe/home.cfm]

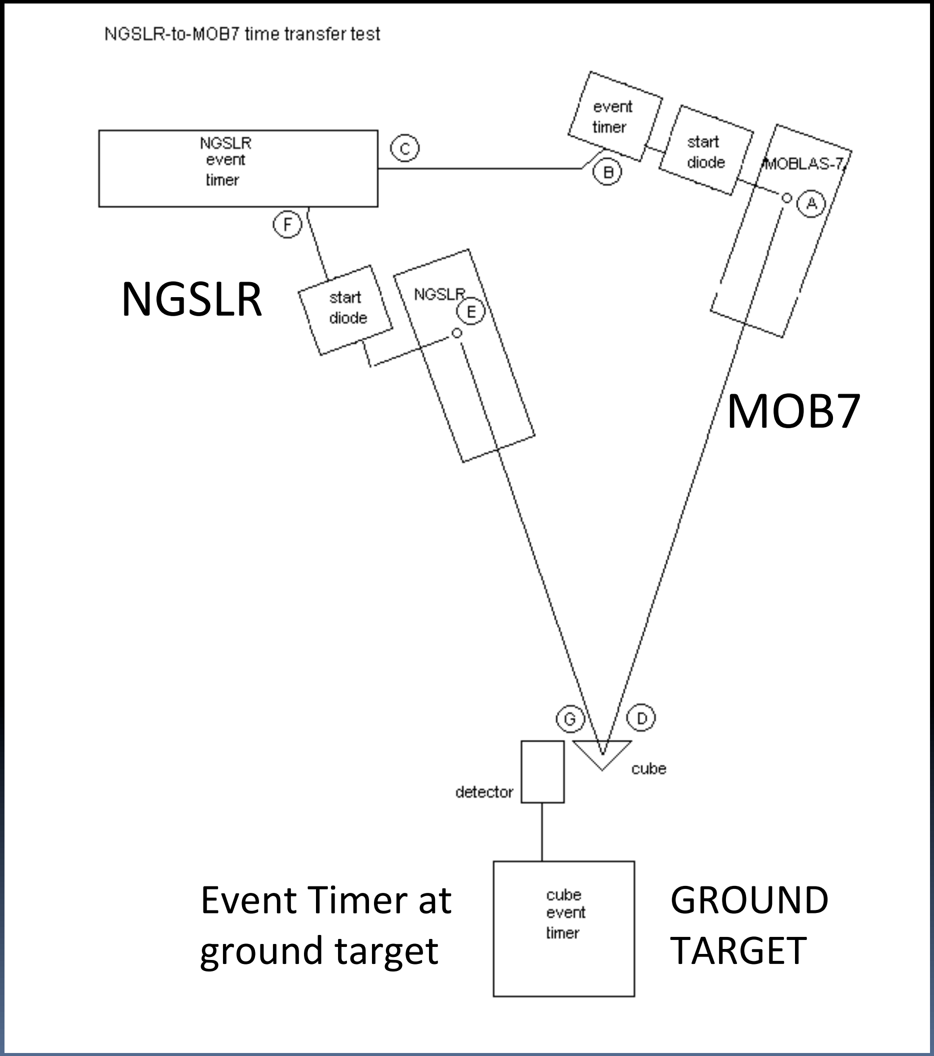
Time Transfer using LRO
Establishing 1 ns timing accuracy

- Symmetricom MHM-2010 Hydrogen Maser (VLBI2010)
  < 1 ns drift or jitter in 1pps over one day
- All-View GPS Receiver at NGSLR
  - Developed by Czech Republic and distributed by DiCom in US
  - Measures external 1 pps input wrt GPS with ~ 1 ns accuracy
- Started with simultaneous ranging to ground target
- Performed simultaneous ranging to LRO from side by side systems (NGSLR and LRO) and recorded all measurements at NGSLR.
- Time transfer planned in 2014 with MLRS and Grasse.

See Sun poster for more details

Time Transfer Preparation

Measure fire delays and verify via ground target ranging



NGSLR

- Fire time delay measured to be -13.6 ns.
- Independent measurement by Tom Varghese was ~ -15 ns.

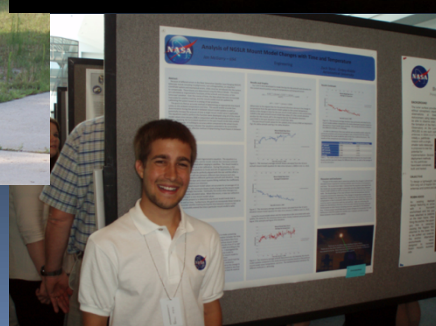
MOB-7

- Fire delay verified by simultaneous ranging using setup at left to be -53.7 ns.

See Sun poster for more details

Internships & Tours

Tours for colleagues, students, teachers, and public



Summary of LRO-LR Achievements

- Enabled a new measurement using existing SLR infrastructures, complementing and potentially replacing RF tracking in the future.
- Demonstrated operational laser ranging over a four year period to a target orbiting a body other than Earth.
- Showed that the ILRS Network can provide close to 24 hour coverage for laser ranging to targets beyond Earth.
- Developed and demonstrated a successful method for providing feedback to ground stations for 1-way uplink ranging (real-time website from instrument housekeeping data).
- Successfully sent the Mona Lisa image to LRO using laser communication over laser ranging.
- Demonstrated 1 ns time accuracy at NGSLR. Working toward successful demonstration of time transfer using LRO.
- Inspired many students and teachers through tours and internships.

THANK YOU!