

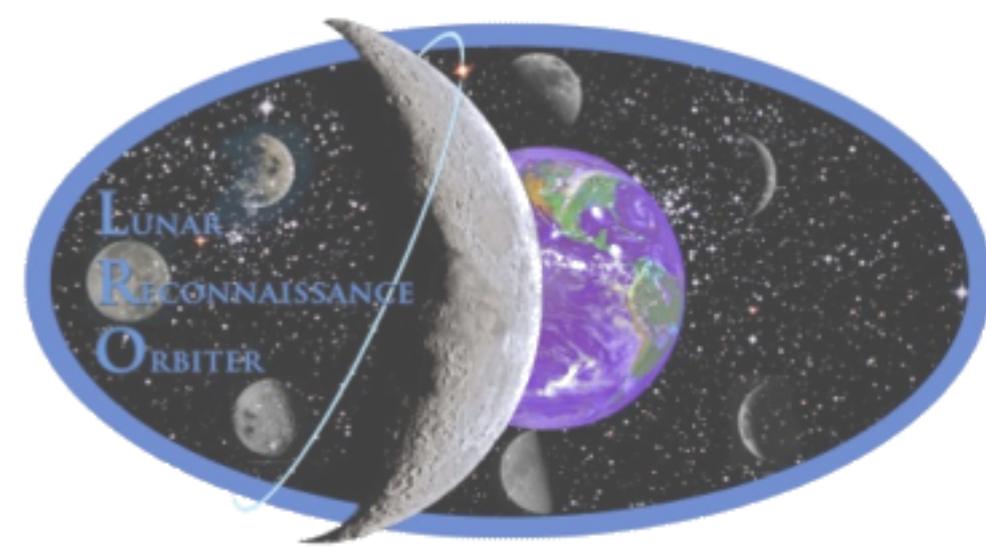
Interplanetary Laser Ranging: The Quest for 1 AU

Gregory A. Neumann¹, Michael H. Barker², Dandan Mao²,
Erwan Mazarico¹, Jan F. McGarry¹, David R. Skillman¹, Xiaoli
Sun¹, Mark H. Torrence³, David E. Smith⁴, Maria T. Zuber⁴

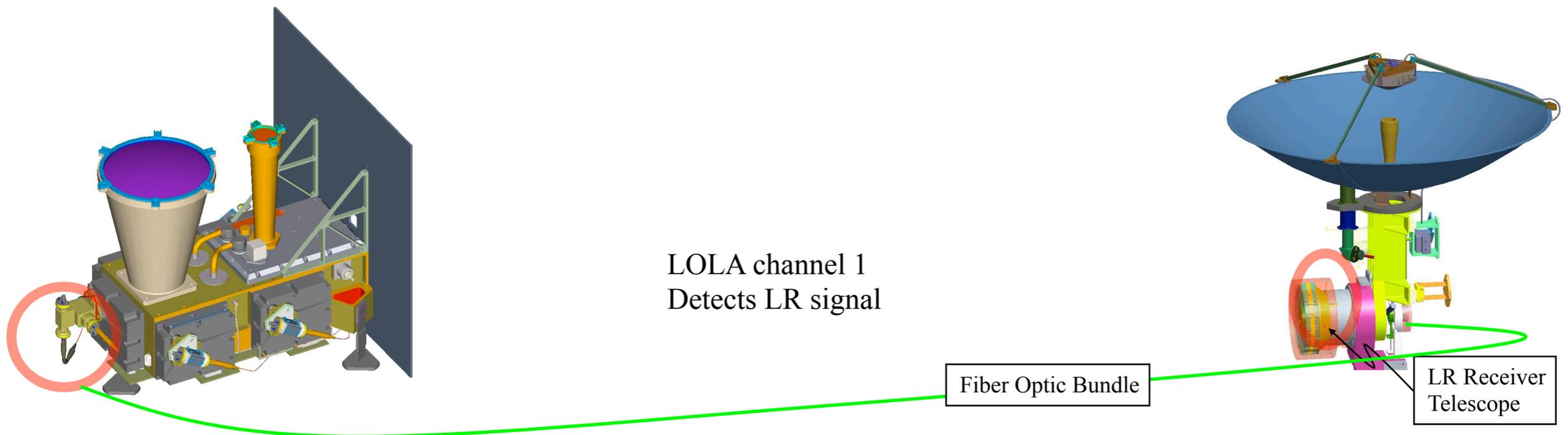
¹NASA GSFC, ²Sigma Space, ³Stinger Ghaffarian Technology, ⁴MIT



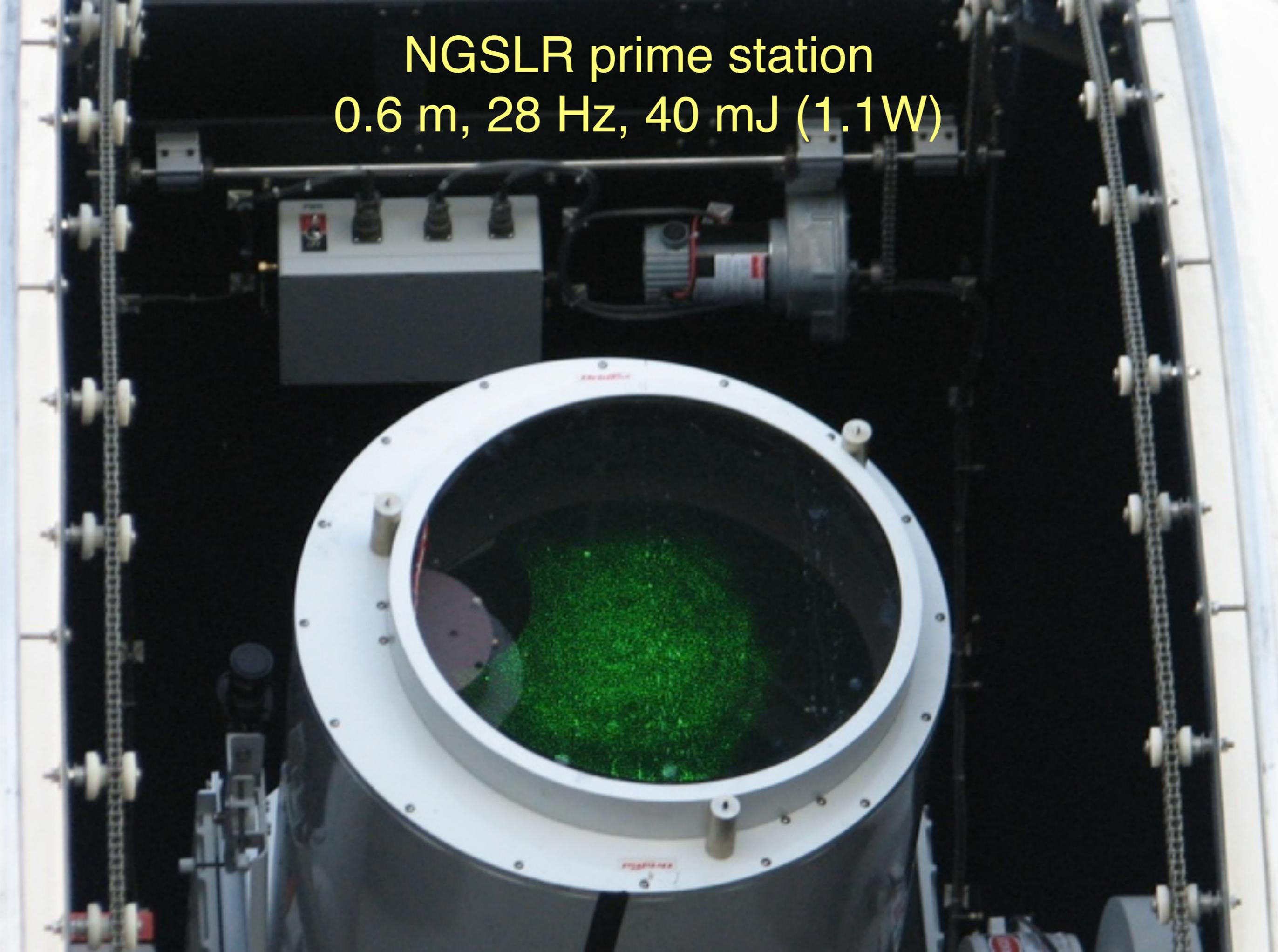
1-way Laser Ranging Experiments

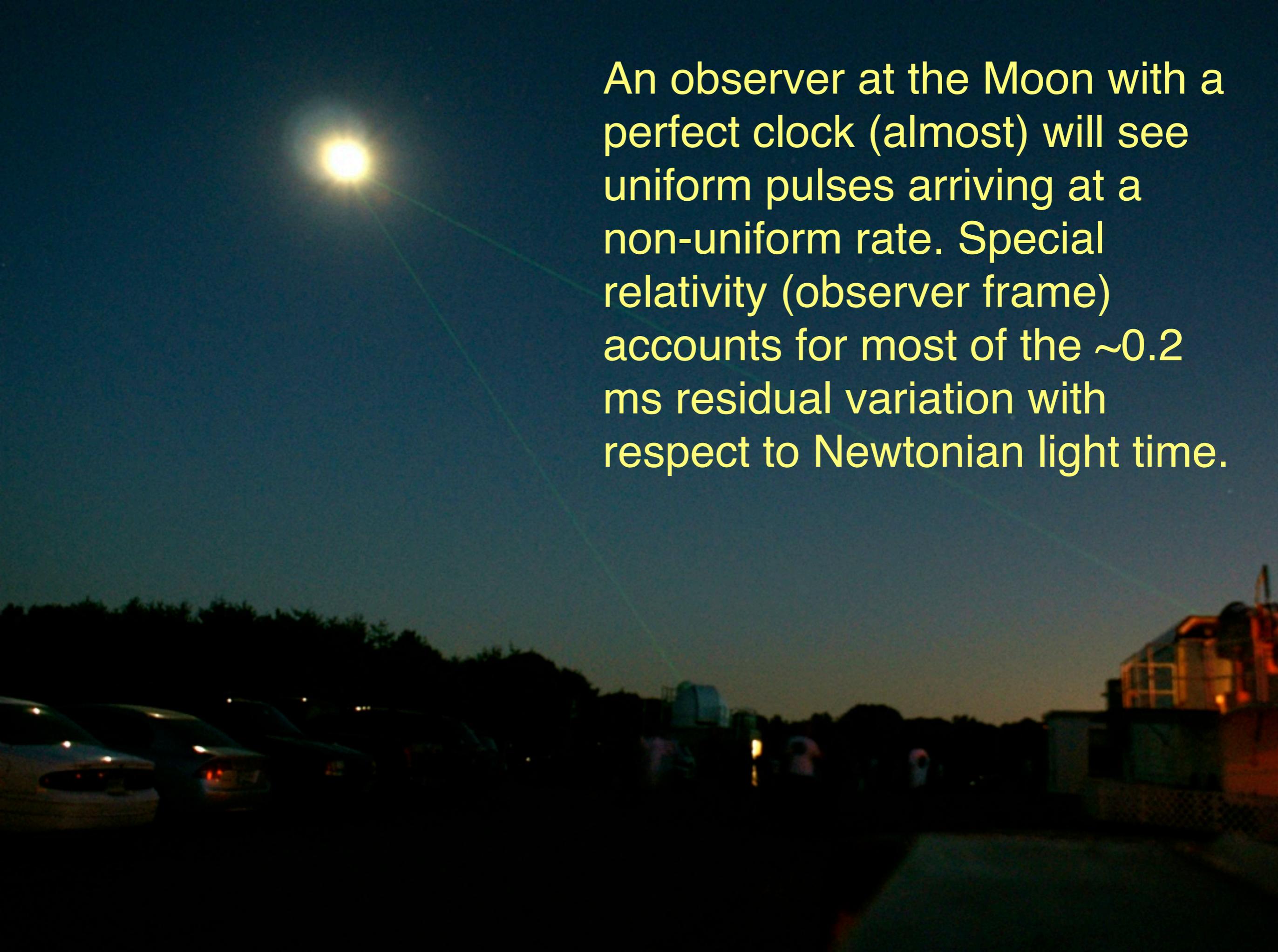


Lunar Reconnaissance Orbiter uses its precision oscillator and a 25-mm telescope connected to the LOLA receiver to time pulses fired from ground stations. A 28-Hz, 10-ms window is available for stations firing 532.1 nm pulses. Sub-ns relative timing is used for tracking and gravity model improvement. This experiment achieved its first success July 3, 2009 and concluded Sept. 30, 2014 with over 4,000 hours of tracking from 10 stations worldwide.



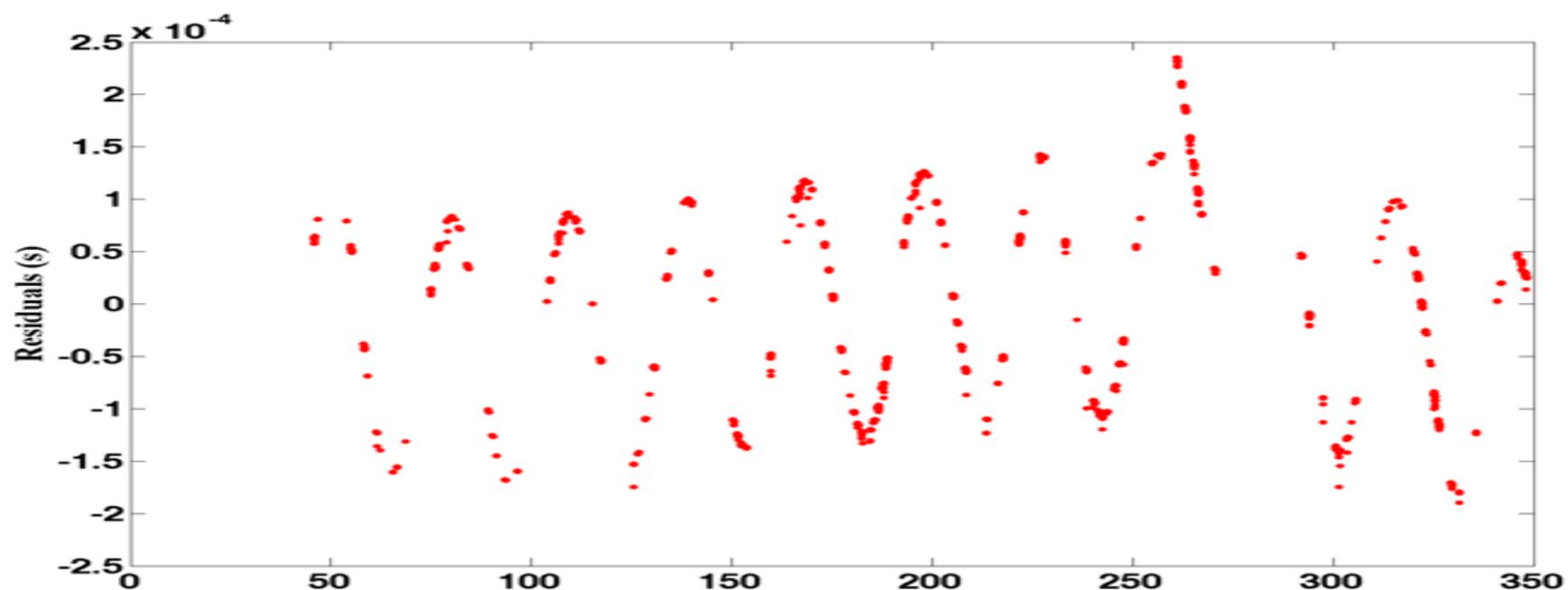
NGSLR prime station
0.6 m, 28 Hz, 40 mJ (1.1W)



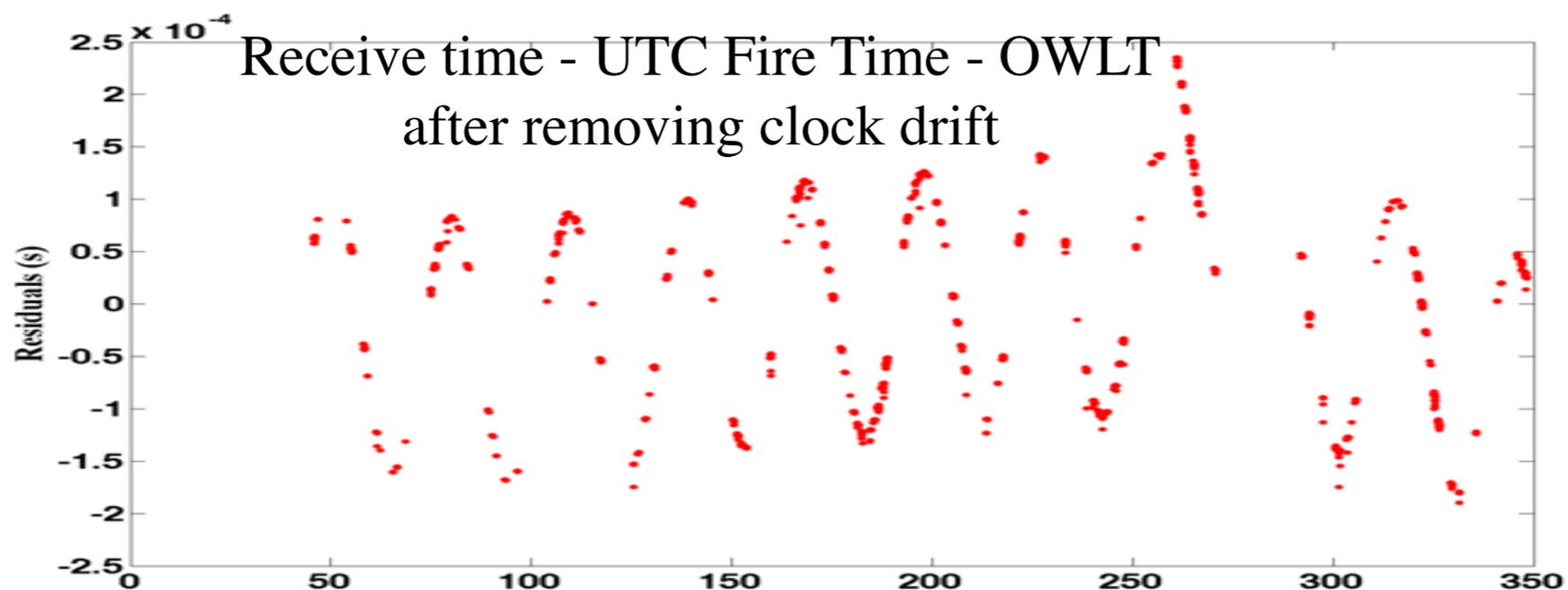
A photograph of a night sky with a bright star in the upper left. A green laser beam originates from the star and extends diagonally across the frame towards the bottom right. The background shows a dark sky with some faint stars and a silhouette of a building and trees in the lower half of the image.

An observer at the Moon with a perfect clock (almost) will see uniform pulses arriving at a non-uniform rate. Special relativity (observer frame) accounts for most of the ~ 0.2 ms residual variation with respect to Newtonian light time.

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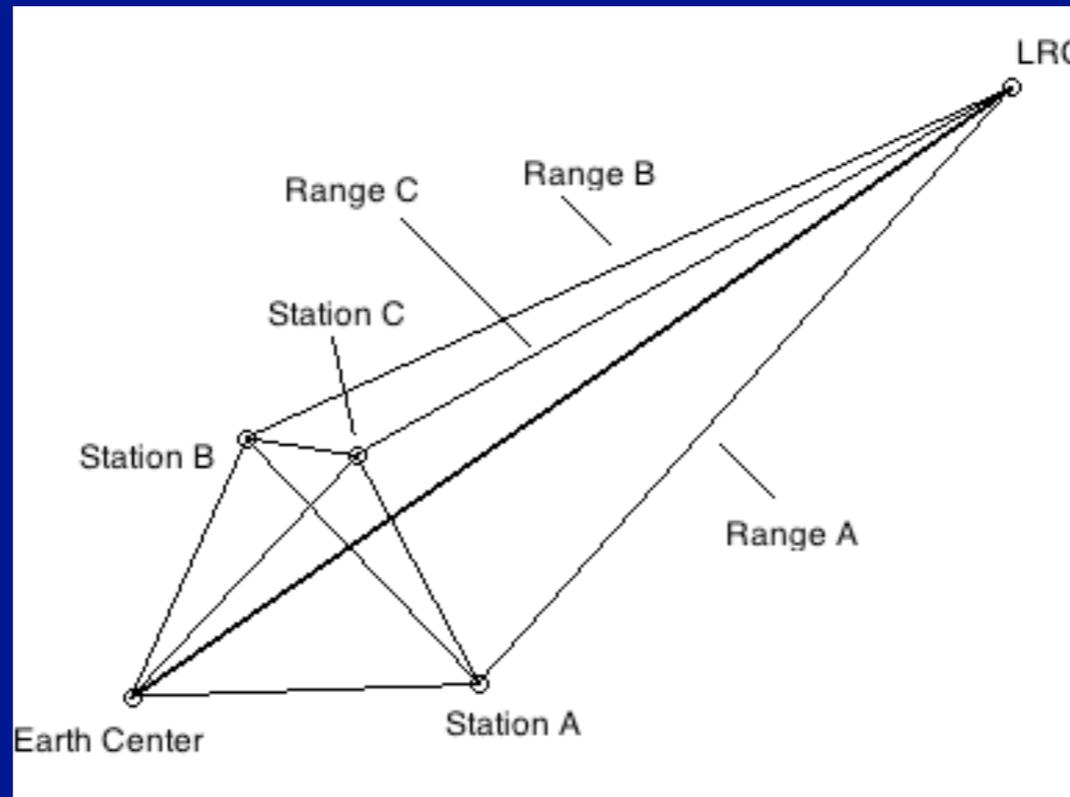
Ranging from multiple stations allows precise time transfer between stations over R_E baselines using arrivals at LRO-LR

See poster by D. Mao et al. Session 14: 3158

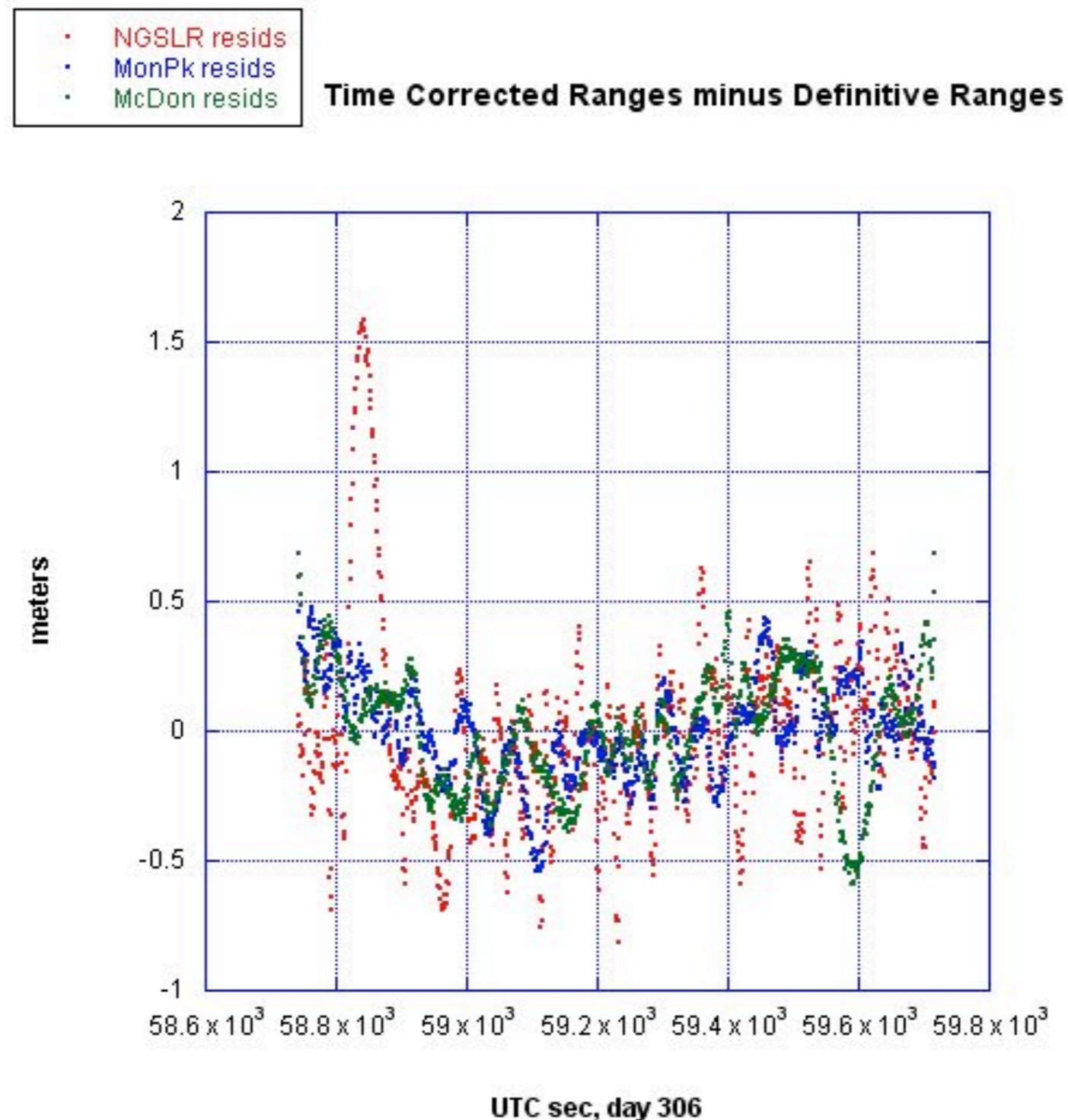
Dave Skillman (GSFC Code 694) has explored the feasibility of VLBI-like tracking of satellites using LRO-LR

LRO is at the tip of a long skinny general tetrahedron based on three Earth stations.

The geocentric inertial positions of the stations and the three ranges define the geocentric inertial position of the LRO spacecraft uniquely.

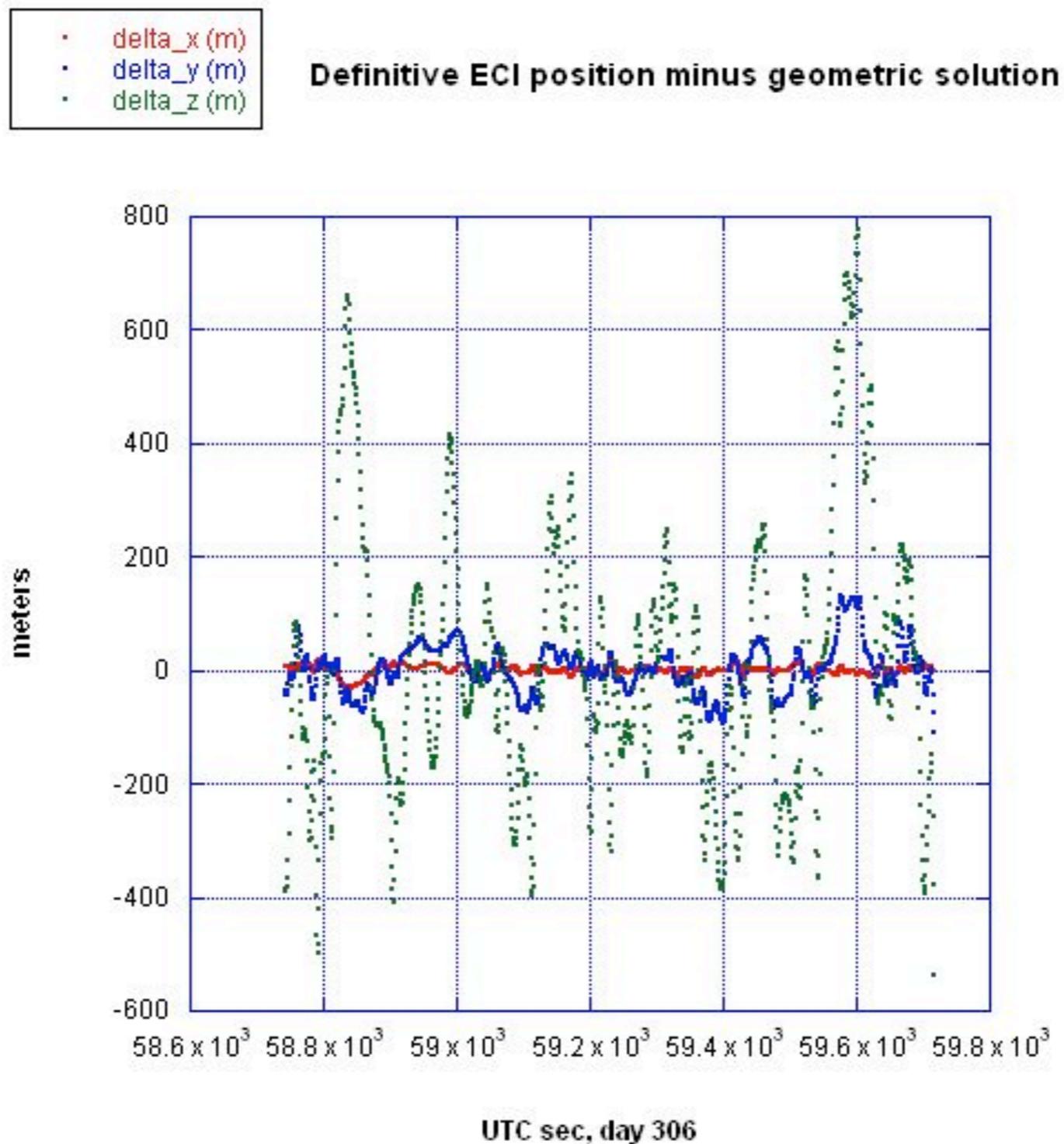


Using the linear fits to the time offsets, resampled ranges are corrected to get the best-estimate ranges, leaving residuals of about a meter when compared to the definitive ranges from LRO ephemeris.



Along- and across-track positions are constrained at the 100-m level, about the same precision as initially specified for LRO tracking. Simultaneous tracking has been intermittently successful with the cooperation of ILRS stations, although not baselined for LR.

ECI position of LRO compared to ephemeris positions, after correction for station time bias and drift.



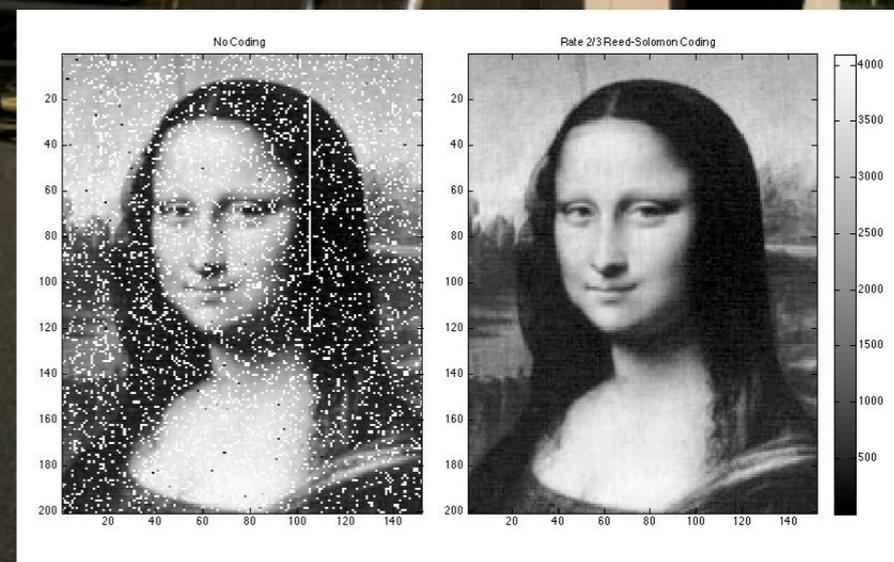
NGSLR communication experiment

Pulse position modulation

Feb. 17, 2012

~300 bps uplink with Reed-Solomon error-correction

Oct. 22, 2013-LLCD achieves 77 Mbps uplink to LADEE

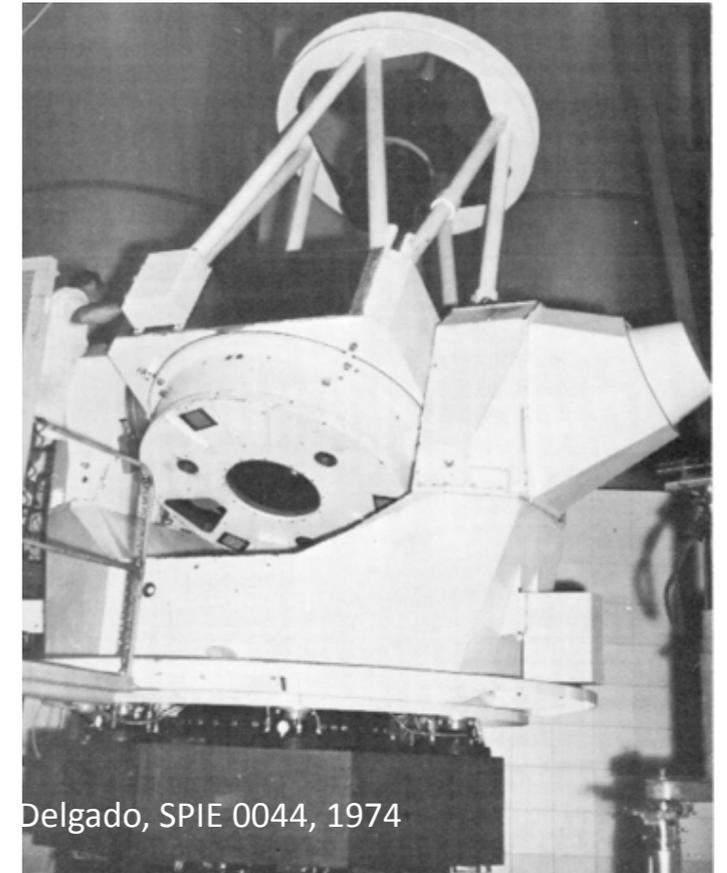




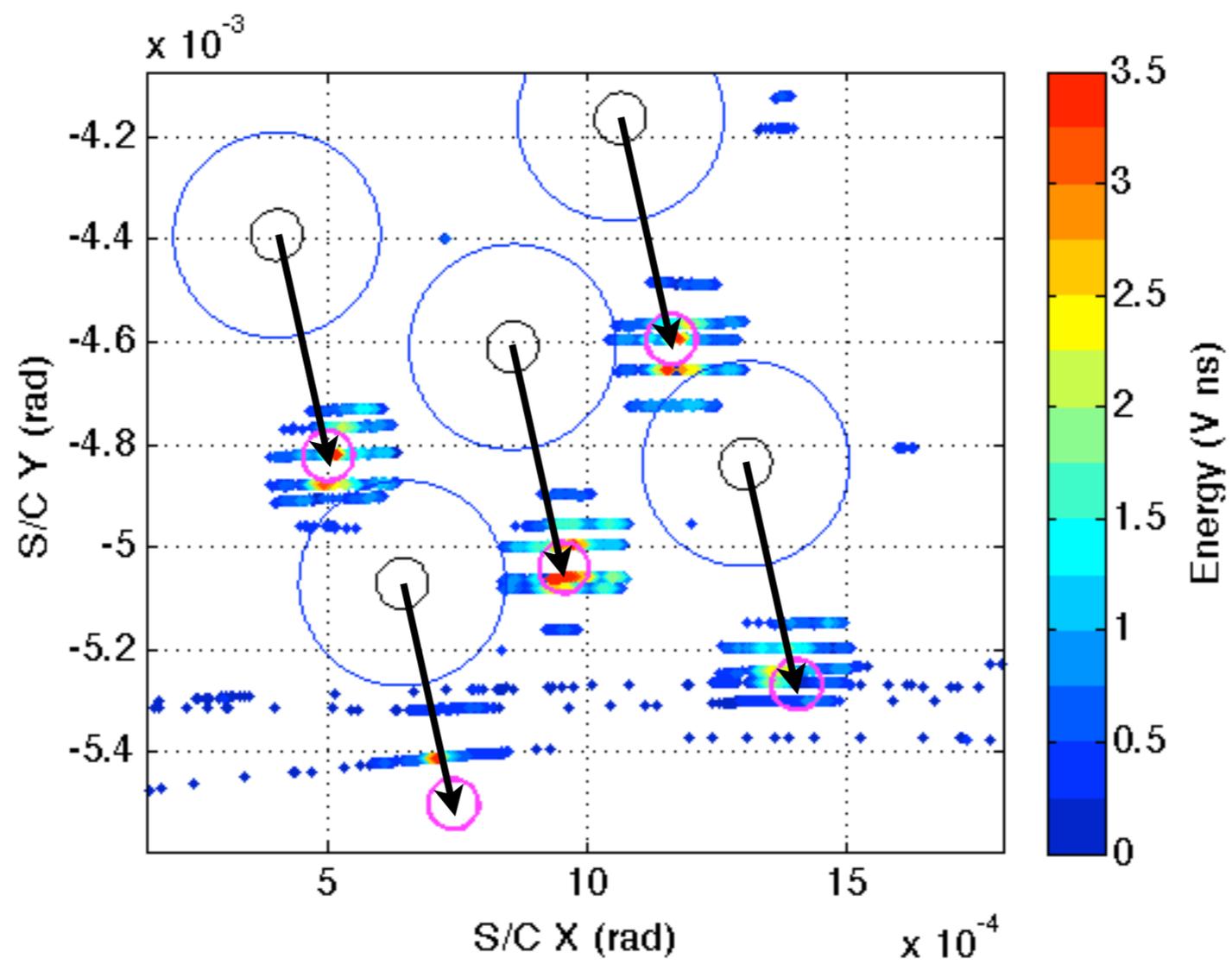
Measuring LOLA Laser Performance from Earth

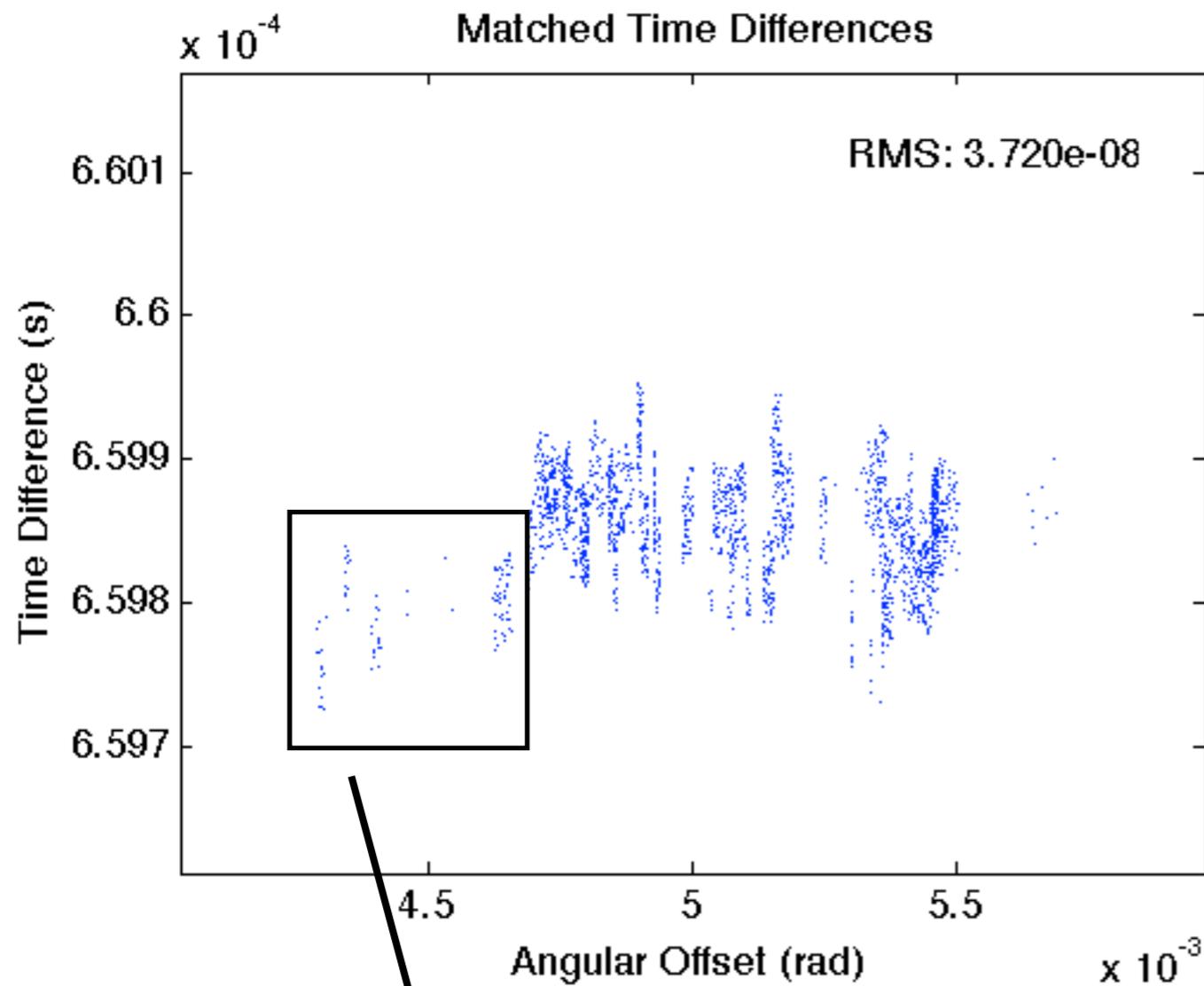


- Point and scan the LOLA laser at the 1.2-m telescope facility at Goddard, while firing lasers at each other, and recording the times of laser pulses at both ends.
- Solve for laser pointing, receiver FOV, and laser characteristics.
- Tests performed:
 - Aug 2009, failed.
 - Sep 2009, successful, two-way, with Laser 2, both 1.2 m and 5" telescopes.
 - Jul-Aug 2011, failed (downlink with a 5" dia. Telescope).
 - Jun-Aug 2013, failed (downlink with an 8" dia. telescope).
 - Jan 7, 2014, successful, down-link, Laser 2.
 - Jan 8, 2014, failed, down-link, Laser 1.
 - Mar 24, 2014, successful, two-way, Laser 1.



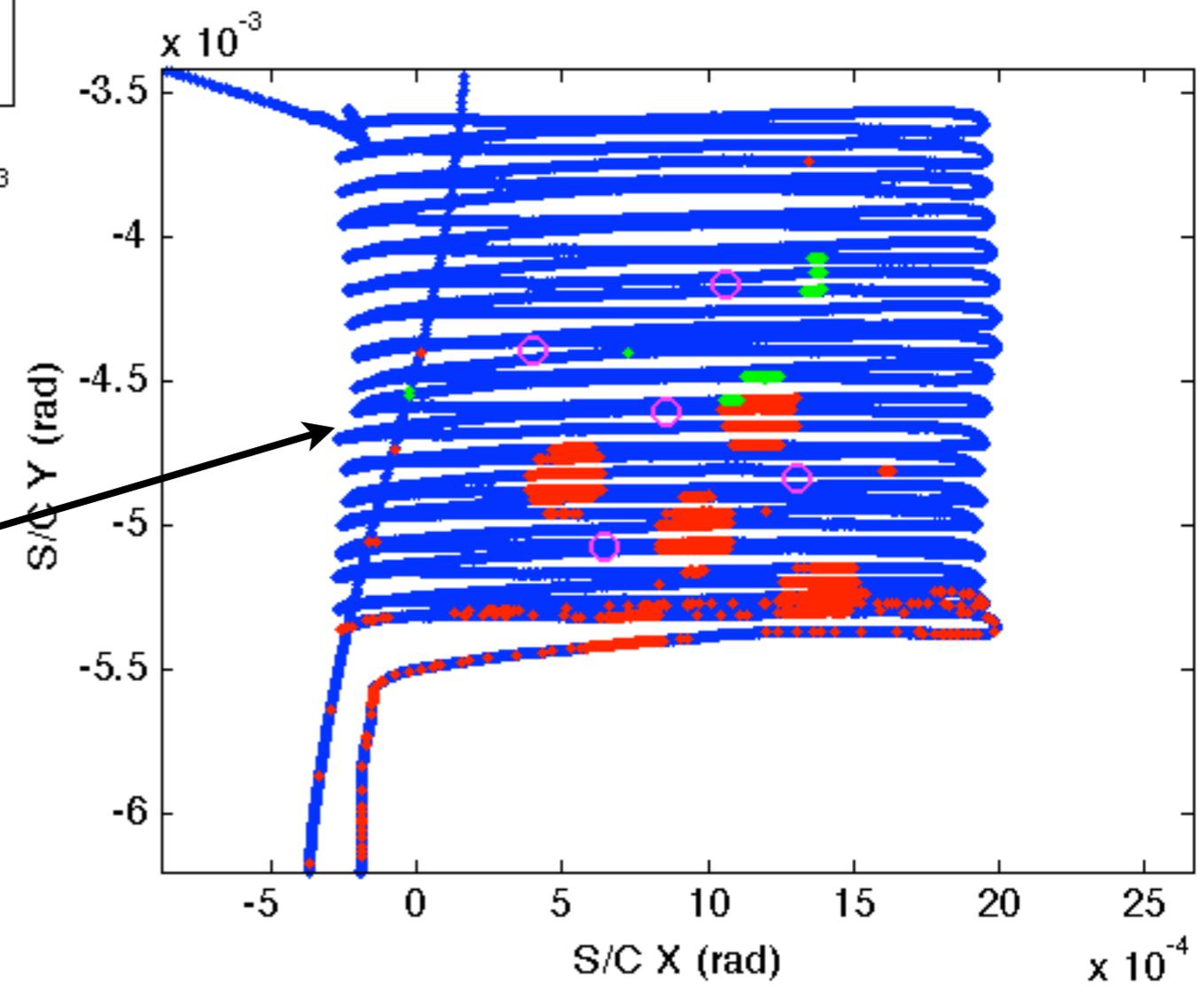
Nighttime shift ~450 urad mostly in Y





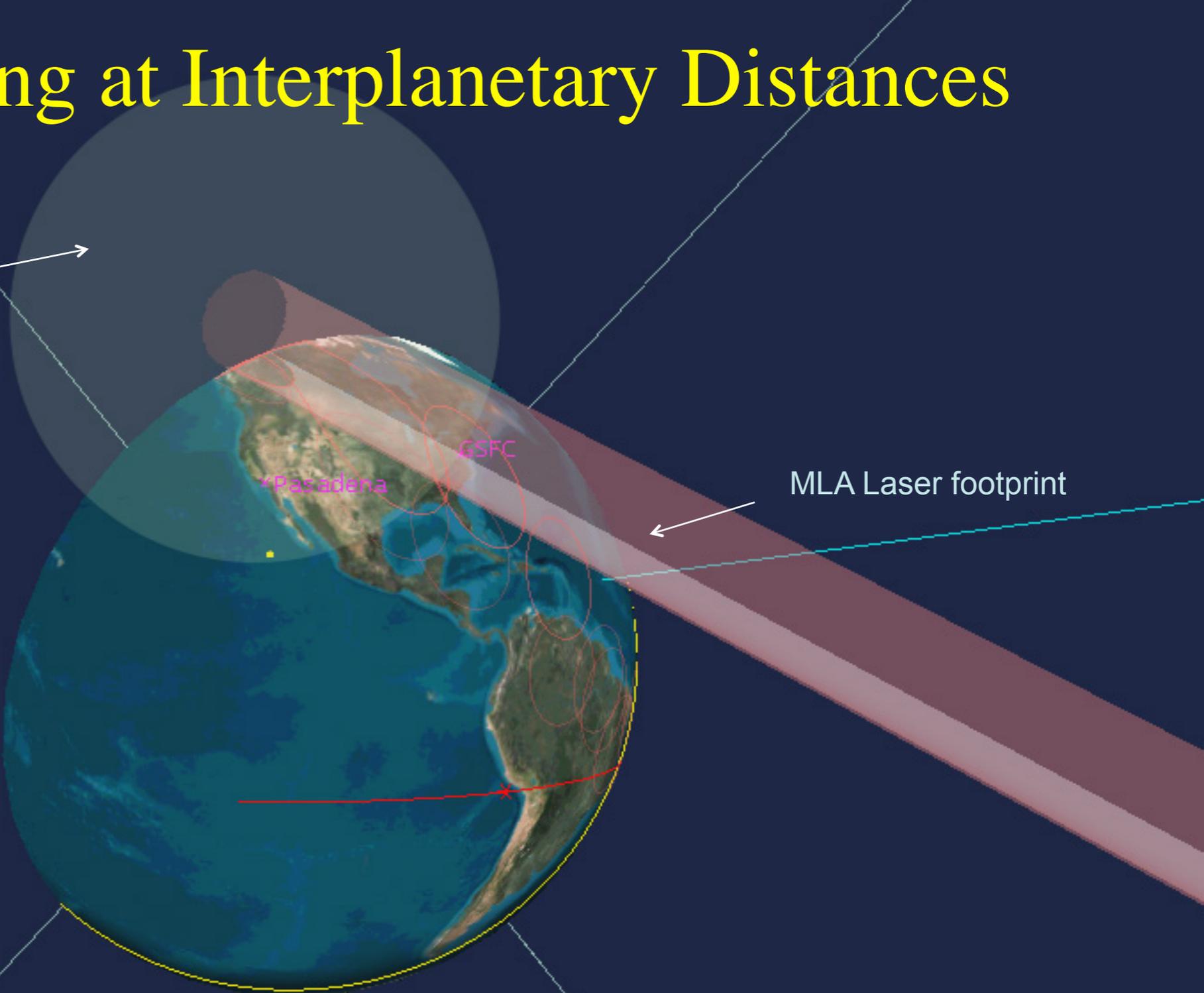
Match fire times with
rec. times accounting for
XLT+S.
Mean offset: 0.66 ms
RMS: 37 ns

Green dots



Laser Ranging at Interplanetary Distances

MLA Receiver FOV



MLA Laser footprint

15th ILRS Meeting, Canberra, Australia

Gregory A. Neumann¹, John Cavanaugh¹, Barry Coyle¹, Jan McGarry¹, David E. Smith¹,
Xiaoli Sun¹, Mark Torrence¹, Thomas W. Zagwodski¹, and Maria T. Zuber²

¹NASA Goddard Space Flight Center

²Massachusetts Institute of Technology

Power comparison:

DSS-14 Goldstone 70 m: 400 kW at S-Band (2320 MHz);
500 kW at X-Band (8560 MHz, wavelength 3.5 cm)



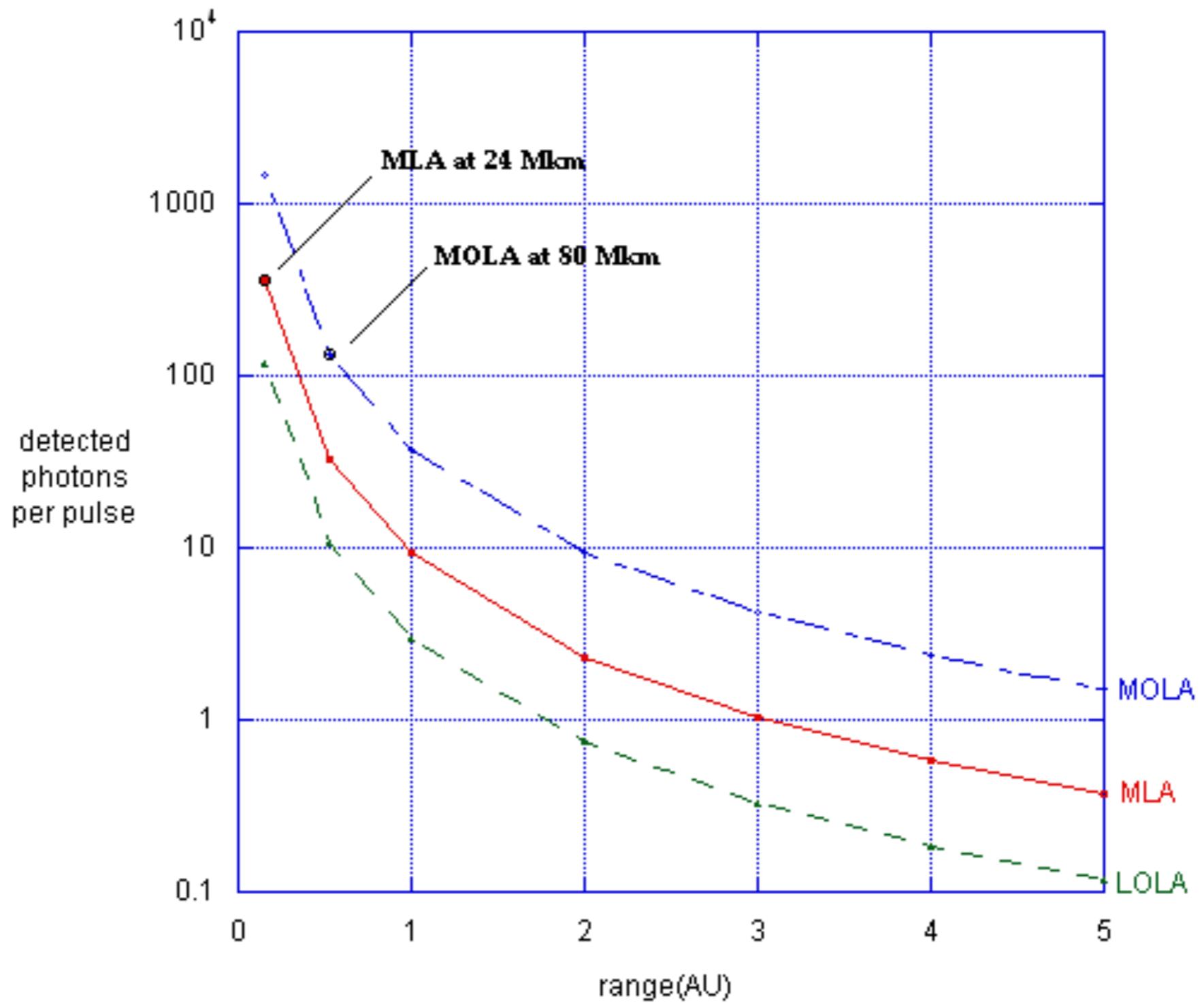
GGAO 1.2 m telescope: 1-5 W (wavelength 1.064 μ)
~5 orders of magnitude smaller power and wavelength

DSS-14 Goldstone
500 kW at



GGAO 1.2 m
~5 orders of magnitude

Detected Photons at Spacecraft vs Range
uplink, 48", 90 mJ pulse, 0.12 eff optics, 60 urad div



(Hz);

(u)

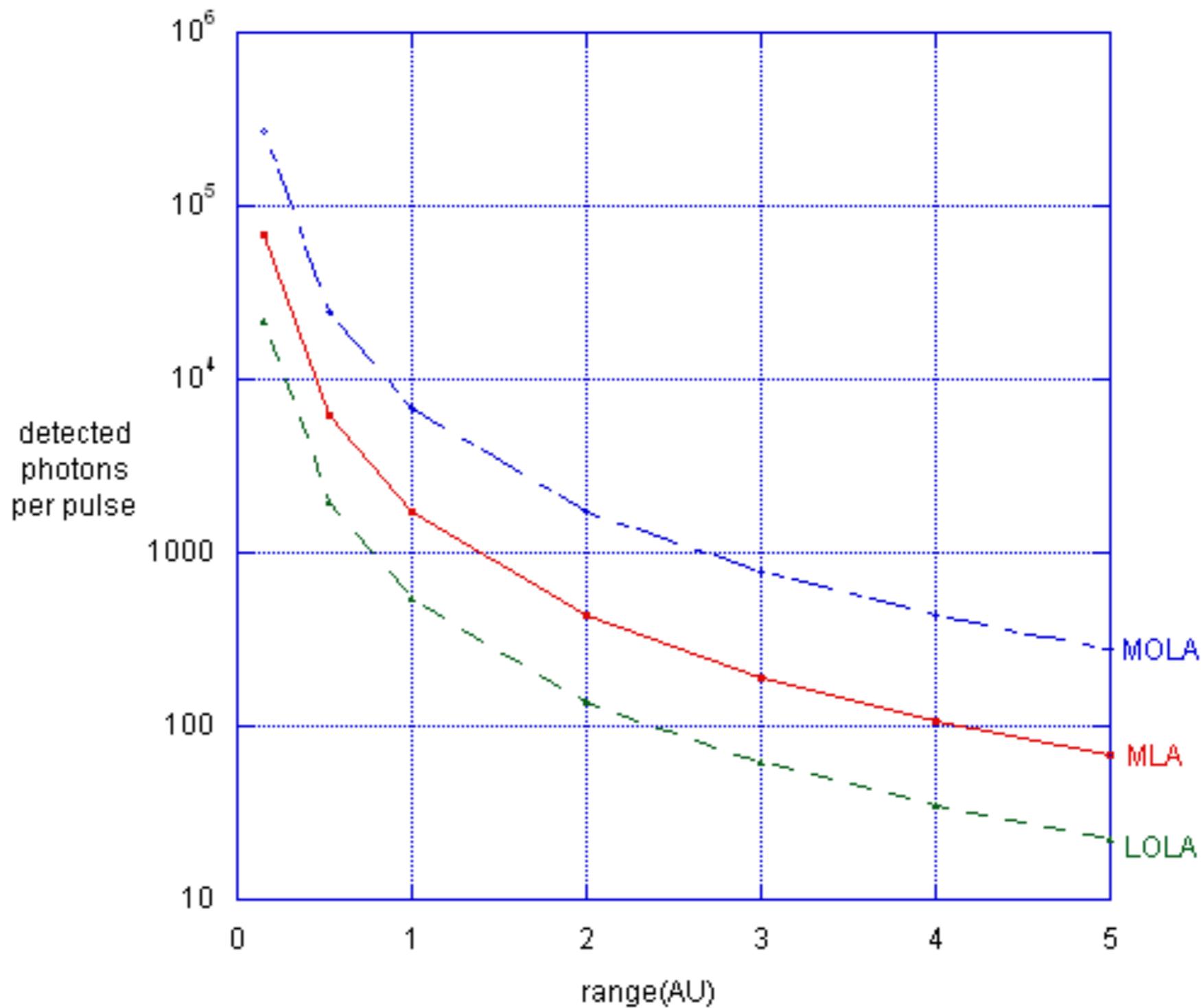
th

DSS-14 Goldstone
500 kW at



GGAO 1.2 m
~5 orders of

Detected Photons at Spacecraft vs Range
uplink, 48", 1 joule pulse, 0.5 eff optics, 30 urad div



(Hz);

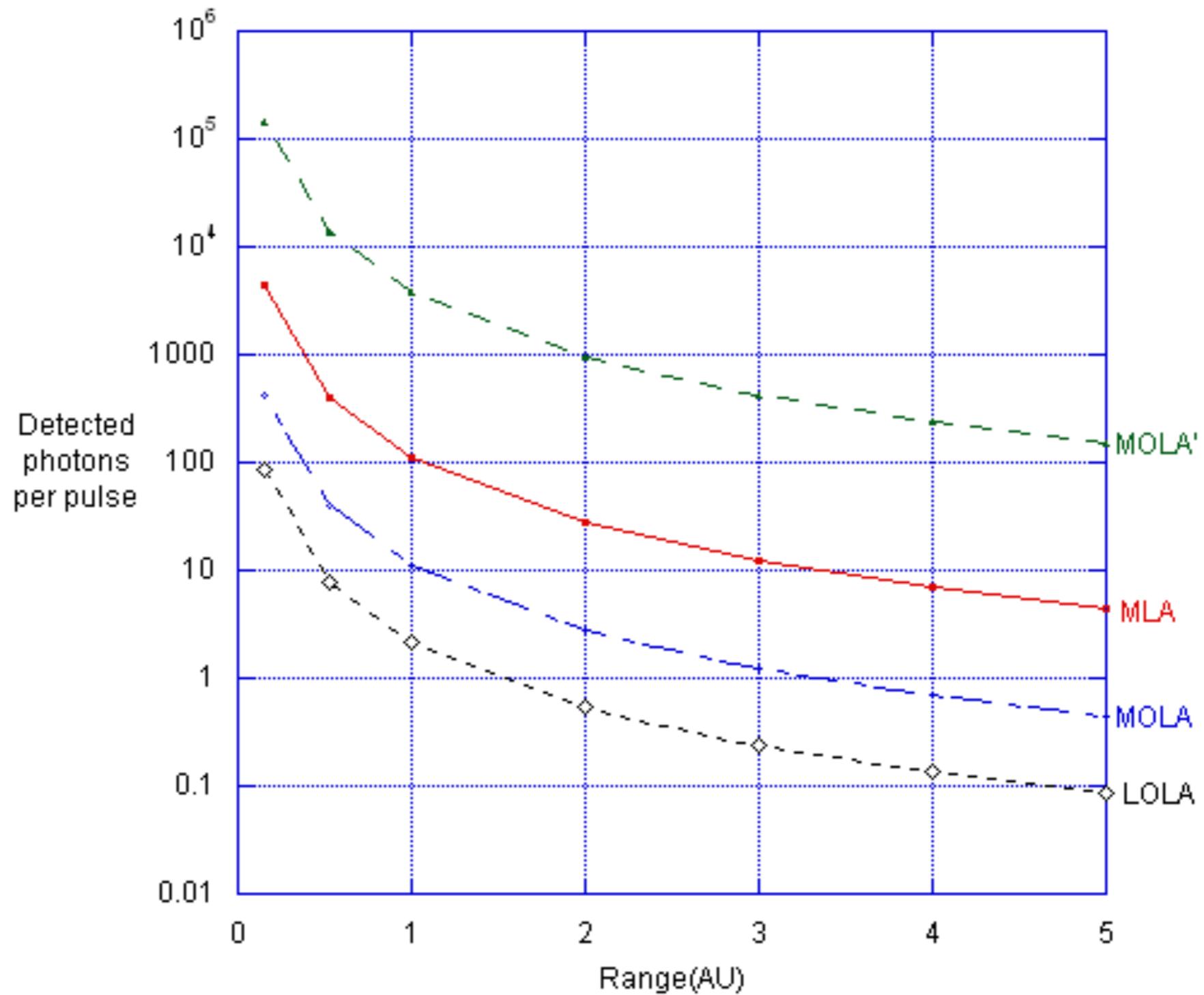
(u)
th

DSS-14 Goldstone
500 kW at



GGAO 1.2 m
~5 orders of

Detected Photons at 48" vs Range
48" at 0.5 throughput, MOLA' has 20 urad div



(Hz);

(u)
th

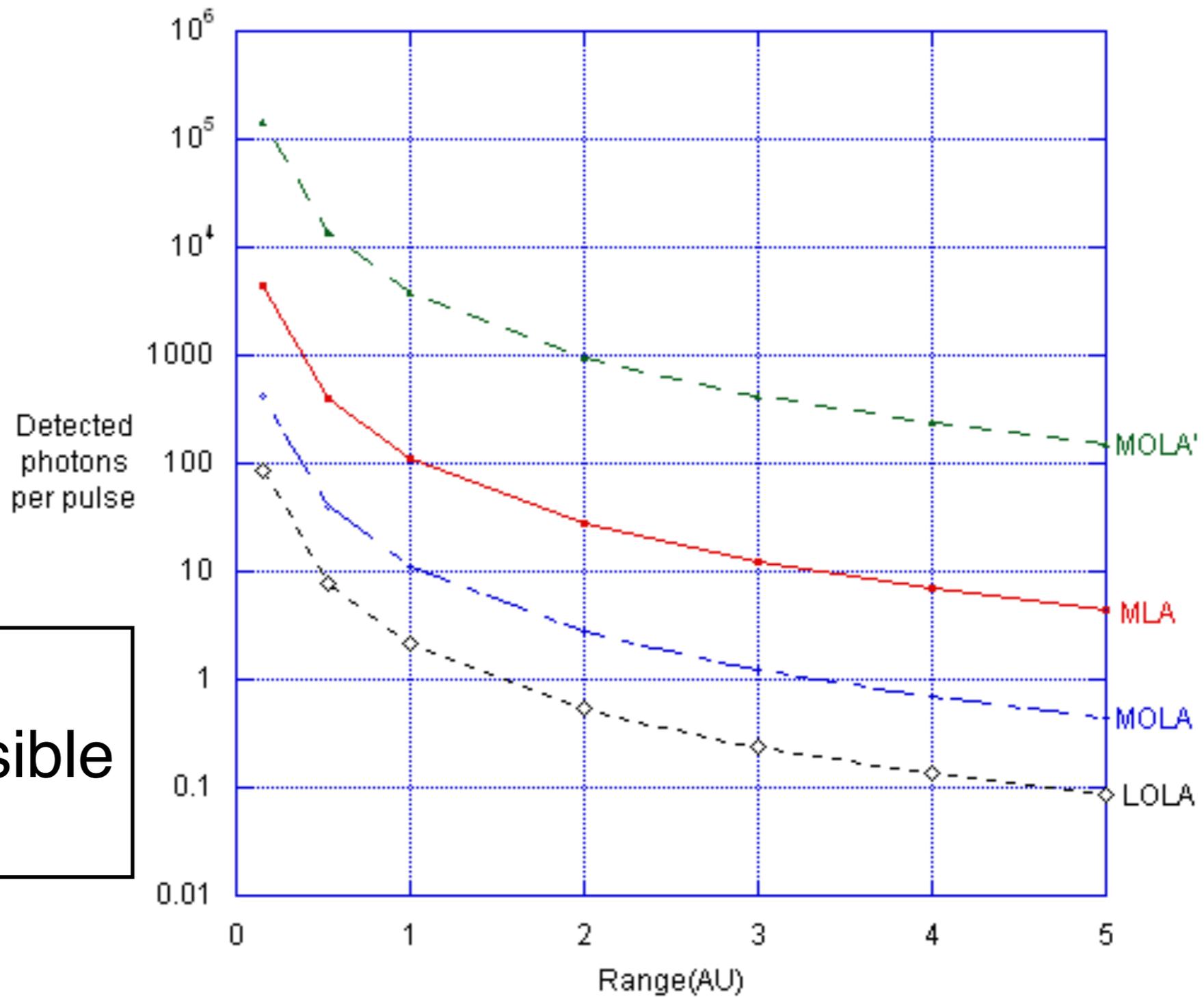
DSS-14 Goldstone
500 kW at



single-photon
detection possible
at several AU

GGAO 1.2 m
~5 orders of

Detected Photons at 48" vs Range
48" at 0.5 throughput, MOLA' has 20 urad div



(Hz);

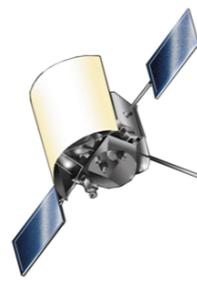
(u)
th

Asynchronous Transponders (Degnan, 2002)

- Ideal transponder receives a pulse and retransmits an echo (e.g., corner cube), and two-way light time is modeled in an appropriate inertial frame
- Passive transponder $1/R^4$ signal losses limit distance to Earth-Moon range at best
- Active transponder $1/R^2$ signal loss is manageable at interplanetary range
- Uses of interplanetary transponder measurements could include:
 - tracking and time transfer to orbiting satellites
 - deep space optical communication
 - improved planetary ephemerides and mass distribution within the asteroid belt
 - measurement of Astronomical Unit and AU-dot
 - Solar gravitational oblateness, by tracking of asteroids
 - Mars solid tidal dissipation from Phobos
 - tests of general relativity
- Asynchronous transponders (Degnan, 2002) require stability of the ground and spaceborne clocks and a communication channel in addition to a receiver/transmitter terminal.
- Several interplanetary spacecraft have implemented laser transponder experiments



Goddard Space
Flight Center
National Aeronautics and
Space Administration



MESSENGER



Laser Ranging Calibration Experiment: Test Objectives

- Verify laser performance; verify laser pointing and receiver boresight with respect to MESSENGER spacecraft coordinates.
- Verify MLA ranging function and receiver performance using a ground laser to simulate backscattered pulses.
- Calibrate MLA boresight offset with respect to spacecraft Attitude Control System.
- ☑ Byproduct: Demonstrate interplanetary ranging and communication using an asynchronous transponder approach.

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Ground Laser and Flight Terminal Parameters



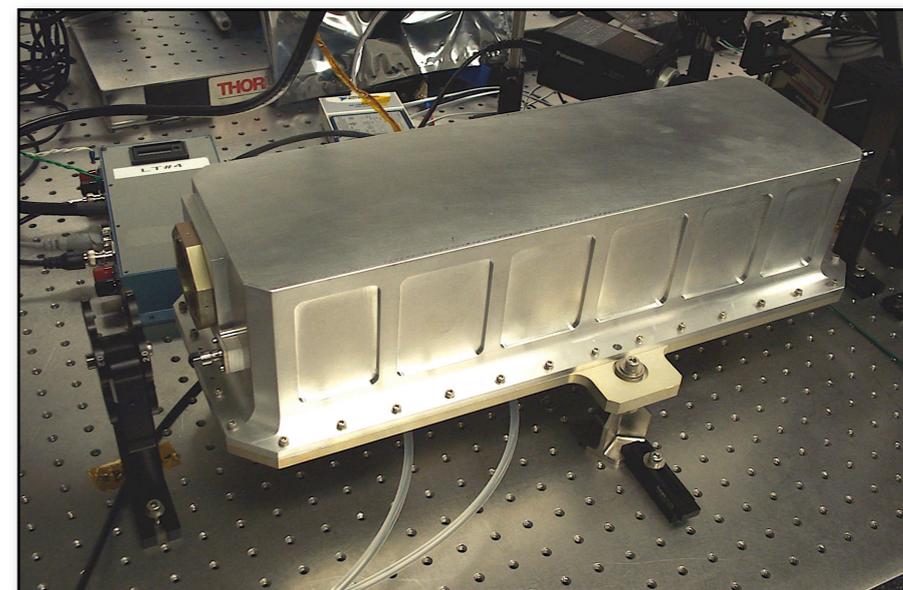
Transponder required ~20 mJ MLA laser energy

Performance of MLA laser matched predictions under colder-than-normal operating conditions. HOMER laser testbed designed for high-rate, long duration operation, as implemented on GEDI.

| Parameter | GGAO | MLA |
|---|------|------|
| <i>Transmitter:</i> | | |
| Wavelength nm | 1064 | 1064 |
| Pulse energy, mJ | 14 | 18 |
| Pulse repetition rate, Hz | 240 | 8 |
| Pulse width, ns | 10 | 6 |
| Beam divergence (FWHM), μ rad | 55 | 50 |
| <i>Receiver:</i> | | |
| Telescope diameter, m | 1.2 | 0.23 |
| Detector field of view, μ rad | 260 | 400 |
| <i>Alignment</i> | | |
| Transmitter-receiver boresight, μ rad | 25 | 50 |
| MLA alignment wrt s/c instrument deck, mrad | | 3.5 |



MESSENGER/
MLA



GGAO/
Homer-1



Ground Station at NASA GSFC



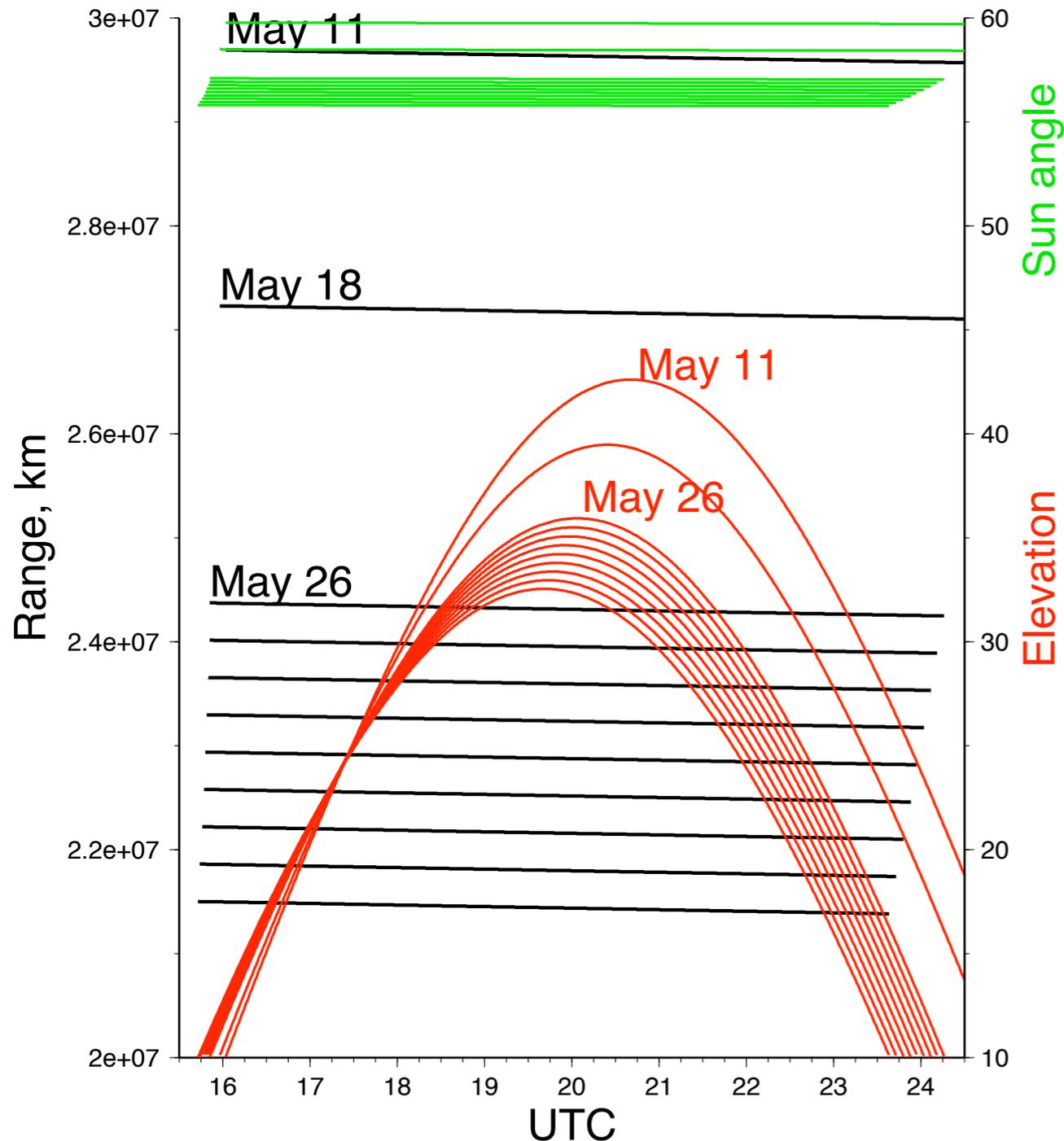
- The Satellite Laser Ranging (SLR) station at Goddard Geophysical Astronomical Observatory (GGAO), Greenbelt, Maryland, USA was built in 1973-74.
- 1.2 m diameter telescope, f/28, aperture shared transmitter and receiver optics
- Telescope open-loop pointing to MESSENGER S/C, with 55 μ rad beam divergence
- 2-nm FWHM bandpass filter, 260 μ rad receiver FOV for daylight operation
- Si APD photodetector, 0.05 fJ/pulse sensitivity at 1064 nm, a unique facility

- GGAO optics and mount designed for LEO tracking
- Estimated 70% transmission at each of 6 surfaces, implying 11% overall transmission at 1064 nm
- Mirrors have since been recoated.



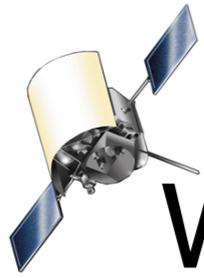
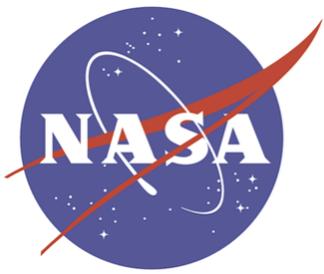
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Pre-Earth-flyby Viewing Geometry



Range to MESSENGER and decreasing elevation above horizon at Goddard 1.2-m telescope site constrained 1st experiment to mid-afternoon in late May, 2005 for elevation above 30° .

An MLA Earth scan across a 3.2×3.2 mrad region was programmed for each of 5 days to constrain boresight.



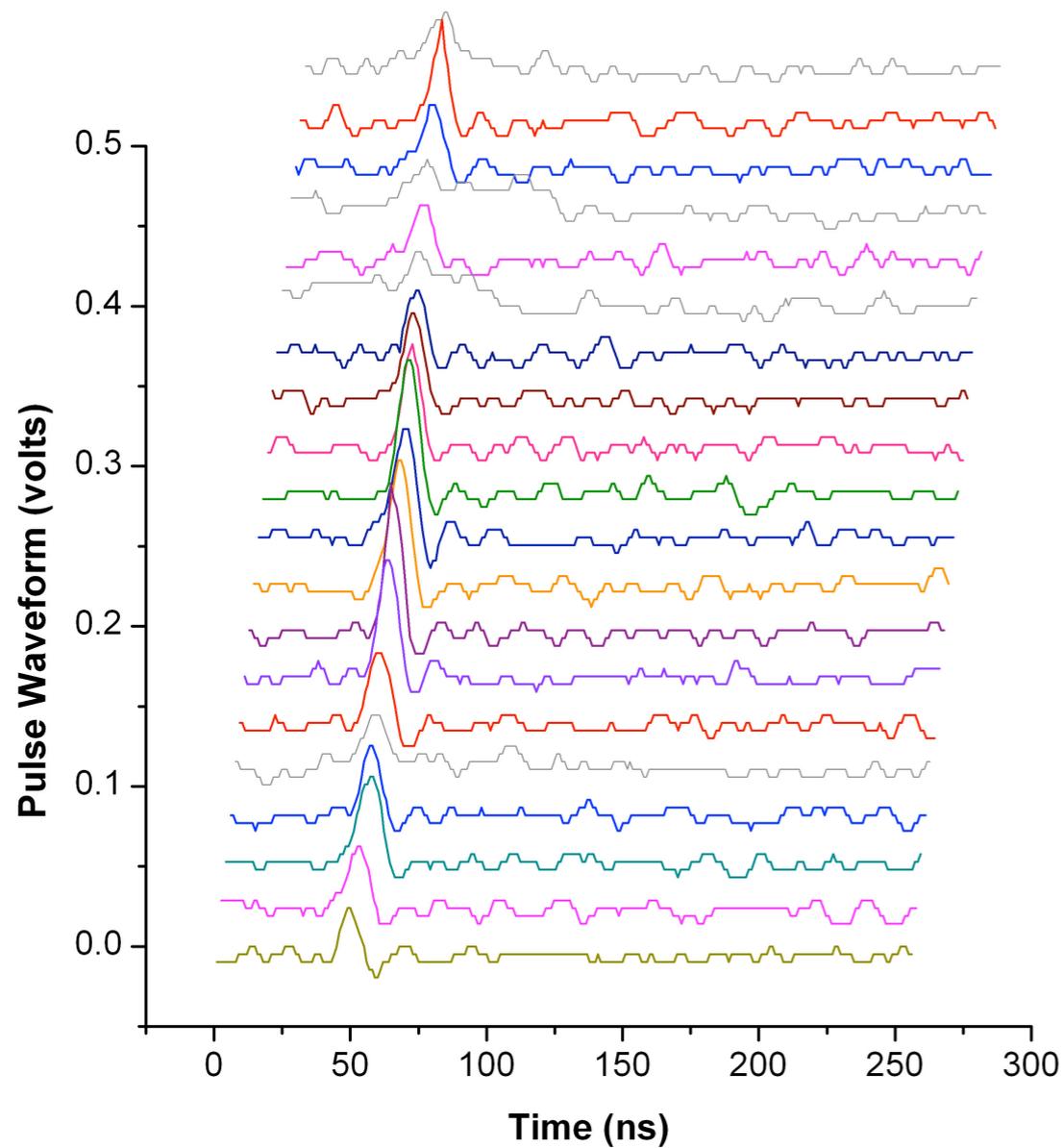
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Weather - 05/27-05/31, 2005



May 26 too cloudy. On May 27, GGAO detected 16 pulses at 8 Hz.

S/C and ground teams stood down for holiday weekend. May 31 clouds were similar, but 24 pulses were detected.



45 minutes earlier



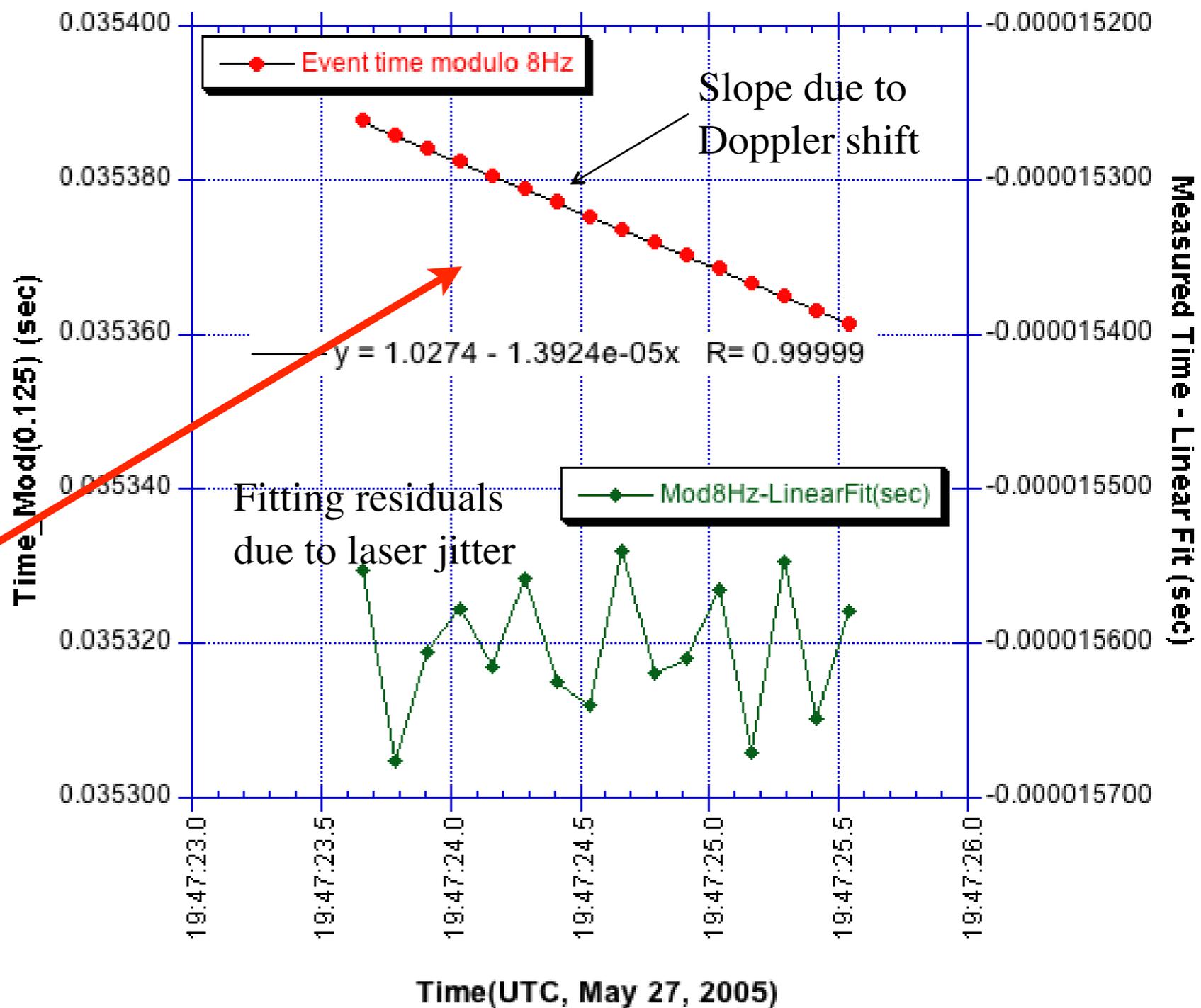
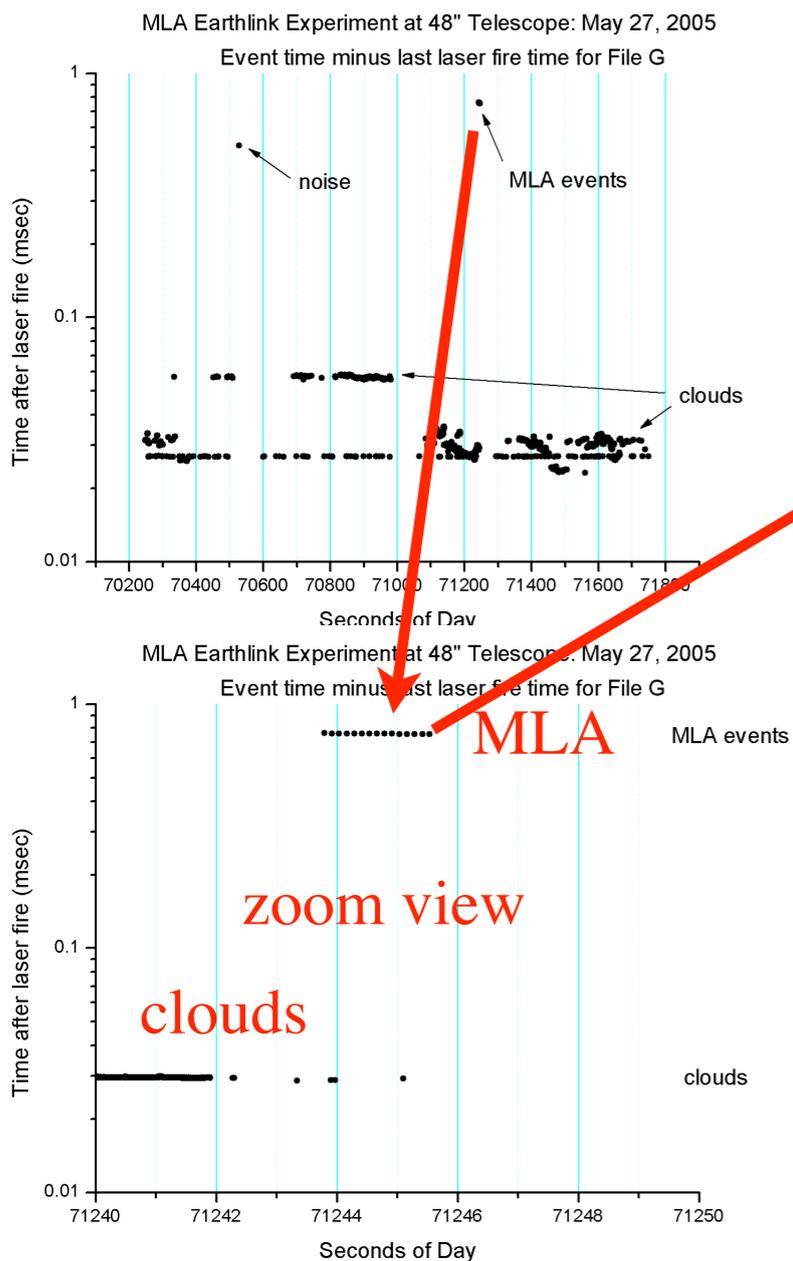
6 minutes later





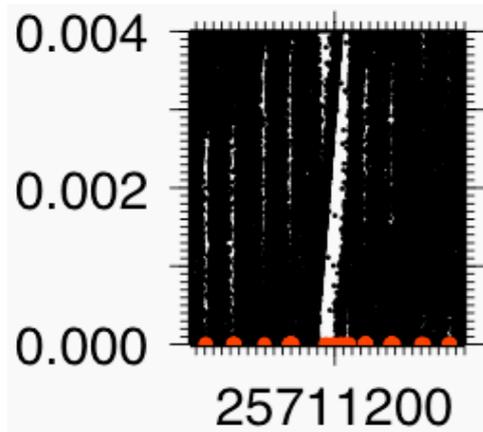
Pulse Arrival Times at GGAO

Arrival times confirm detection of MLA 8-Hz signal.



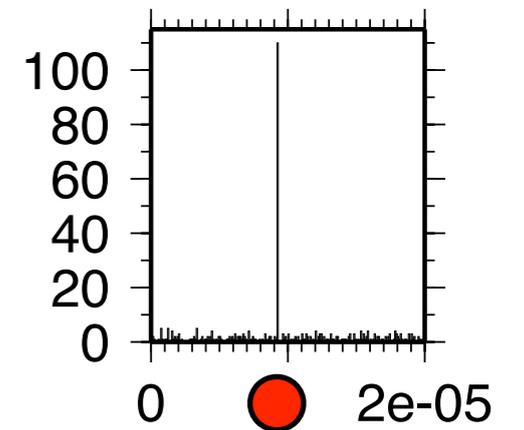
May 27 Uplink Pulse Detection

4 ms window

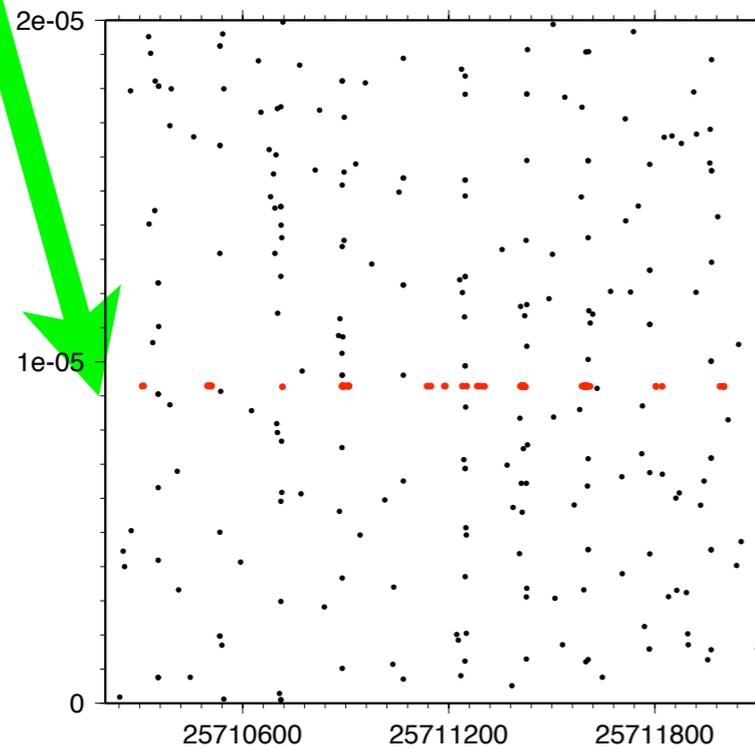


- Noise from earthshine masks signal
- Subtract predicted light time from MET
- Sort times, find nearest laser fire event
- Plot reduced 1-way times - search histogram
- fit “normal point” to MET times -----

histogram

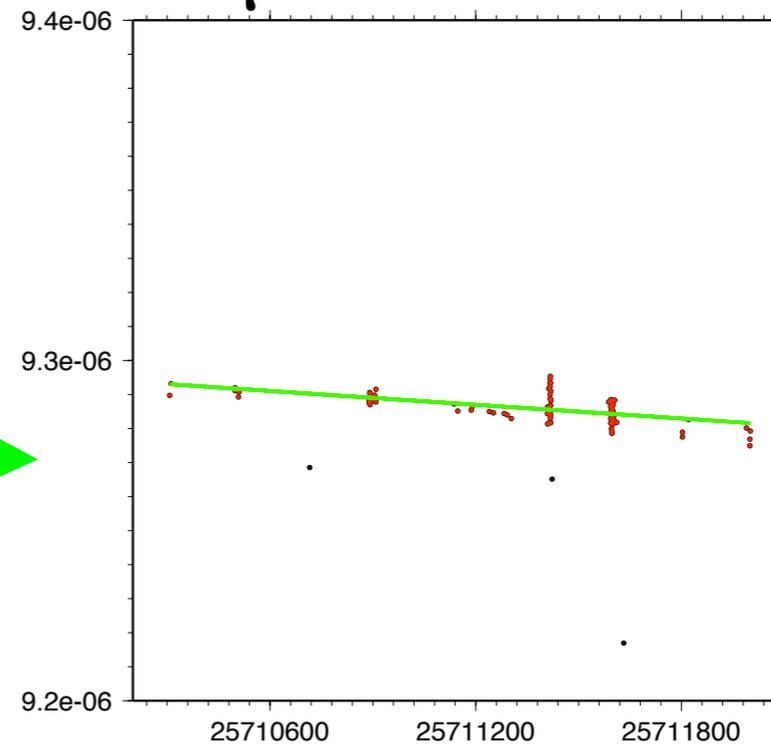


0.02 ms window



MET

0.2 μs window



MET

Asynchronous Transponder Approach

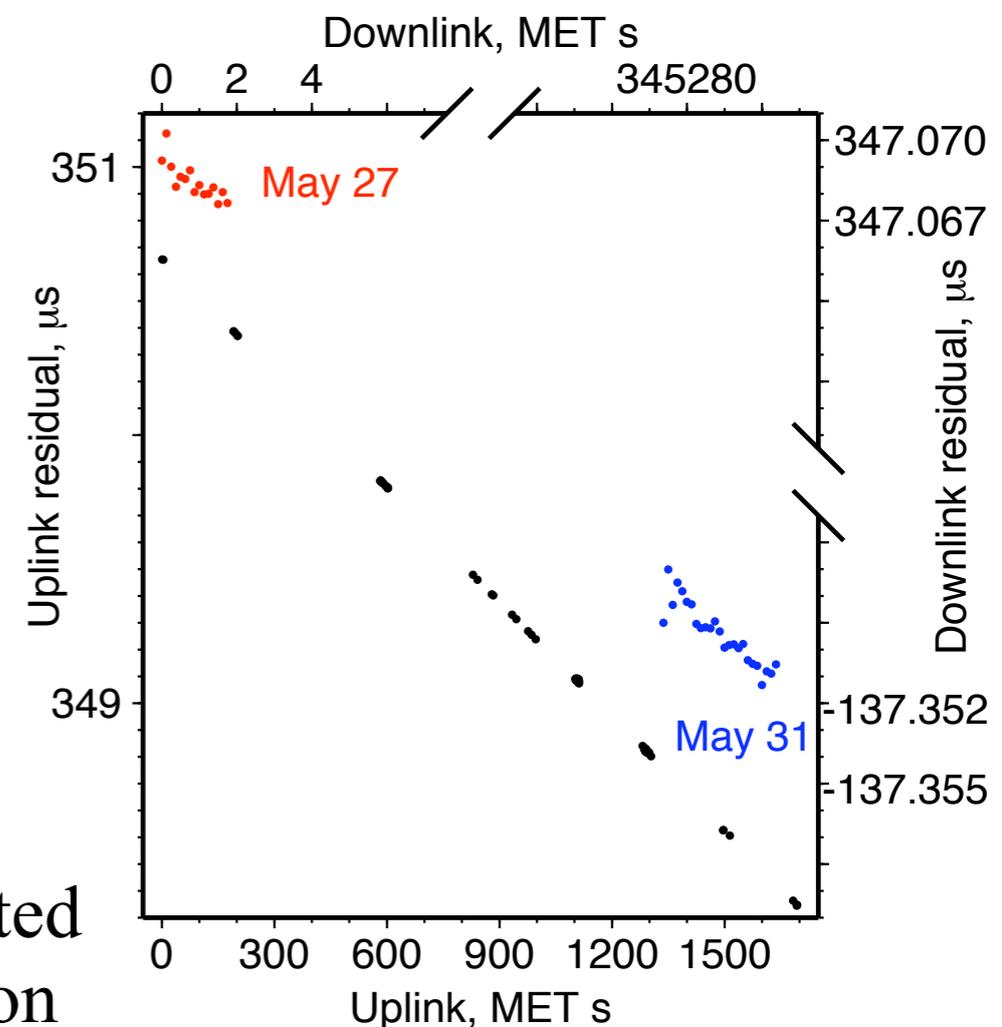
- Uplink events spanned 1/2 hour, while downlink events span 2-3 seconds
- We linearize 1-way light time $R(t)$ about S/C MET origin @25710307 s
- Subtract offset from Earth center $O(t)$ along LOS
- Estimate clock UTC offset and drift (p_1, p_2) at “transponder” MET time t
- Estimate S/C Range ($R=r/c$) at origin, range rate and Acceleration (p_3, p_4, p_5)
- Perform weighted LSQ fit to 16 downlink times τ_D and 107 uplink times τ_U

$$\tau_D = T_D + R(t) = p_1 + p_2 t + [p_3 + p_4 t + p_5 t^2 + O(t)]$$

$$\tau_U = T_U - R(t) = p_1 + p_2 t - [p_3 + p_4 t + p_5 t^2 + O(t)]$$

CAVEATS: $R(t)$ is a geometric 1-way range in a non-inertial system;
 Relativistic time delay ignored;
 But average of light times \approx range/c + Shapiro time delay.

Residual 1-way times using estimated trajectory and MET \rightarrow UTC function



Results: MLA vs. Radio Tracking Solution

Ranges compared to MESSENGER SPICE ephemeris (Newtonian light time) plus solar central-body relativistic time delay (equivalent to 486.6 m added range)

- ✓ Downlink RMS residual = 0.39 ns, uplink RMS = 2.9 ns, => 0.67 ns solution S.D.
- ✓ Doppler rate and acceleration agree within formal errors
- ✓ Timing offset of USO (0.349 ms) well within 1 ms mission requirement.

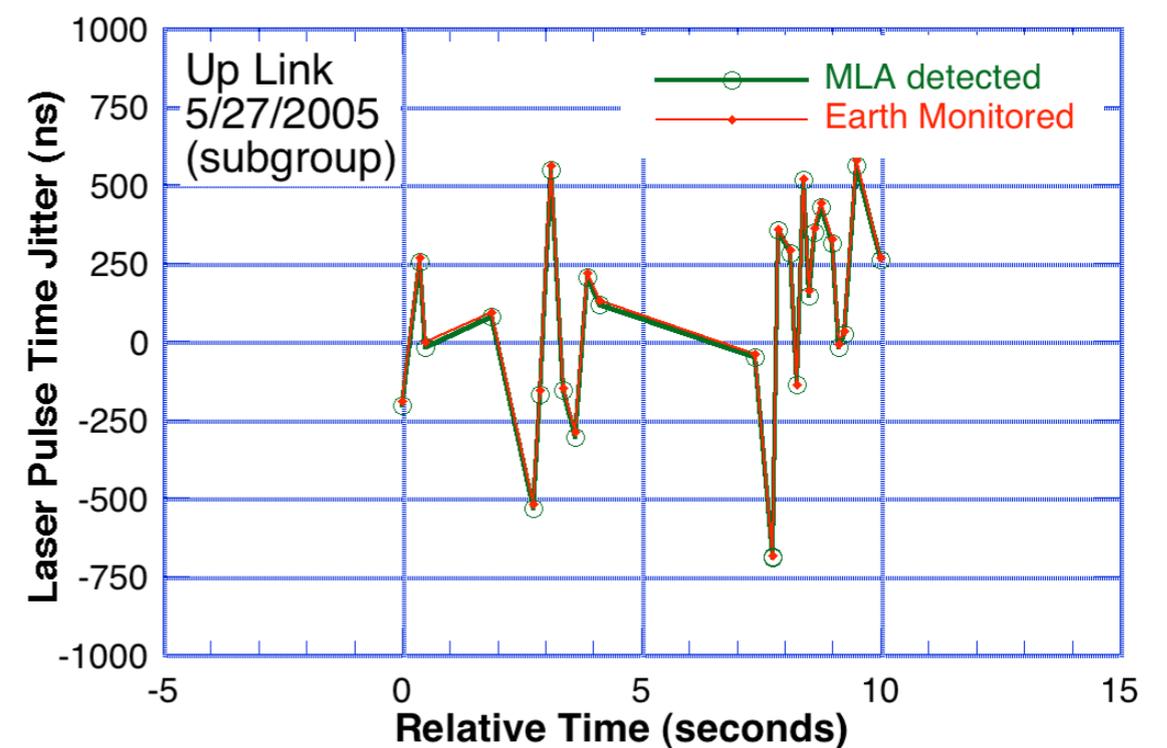
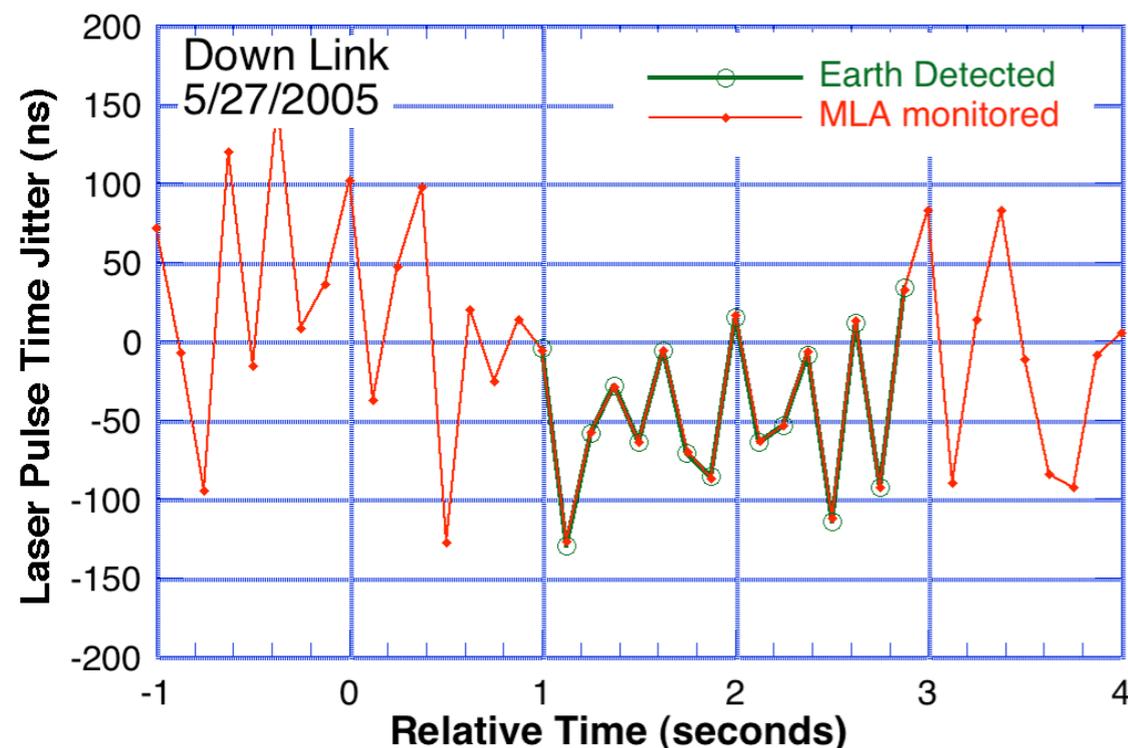
Range discrepancy is much smaller than relativistic light time effects. With better modeling of system delays, discrepancy could be further reduced.

| Parameter | Laser Link Solution | Predicted Spacecraft Ephemeris | Difference |
|----------------------------------|---------------------------------------|--------------------------------------|------------------------|
| Range, m | 23,964,675,433.9±0.2 | 23,964,675,381.3 | 52.6 |
| Range rate, m s ⁻¹ | 4154.663±0.144 | 4154.601 | 0.062 |
| Acceleration, mm s ⁻² | -0.0102± 0.0004 | -0.0087 | -0.0015 |
| Time, s of UTC day | 71163.729670967±6.6x10 ⁻¹⁰ | 71163.730019659 | 0.000348692 |
| Clock drift rate, ppb | 1.00000001533±4.8x10 ⁻¹⁰ | 1.00000001564 | -0.5x10 ⁻¹⁰ |

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Pulse position modulation

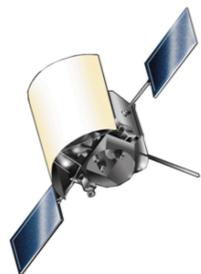
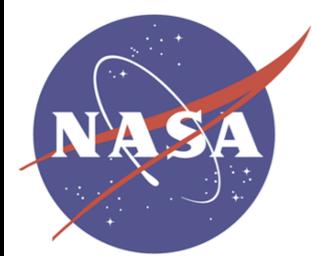
- MLA is passively Q-switched, leading to ~ 100 ns random jitter in fire times.
- This pattern is observed precisely on the ground.
- HOMER is actively Q-switched with precise fire time control, but the pulse generator produced ~ 300 ns random jitter.
- This pattern is observed precisely at MLA and relayed to the ground.



MLA-Earth Ranging Experiment 2007

- MESSENGER was commanded to scan MLA boresight across the face of Earth for ~32 minutes on 3 successive passes during twilight at Goddard Geophysical Astronomical Observatory, while MLA was firing during 5 days Jun. 17-24.
- GGAO pointed 1.2-m telescope at MLA, firing 0.25 J laser at 48 Hz when permitted by aircraft safety and DOD clearance.
- Distance to MLA was ~100 M km, 330 s light time.





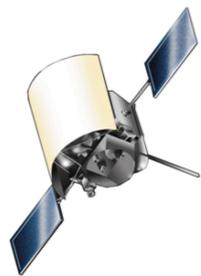
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Ground crew at GGAO



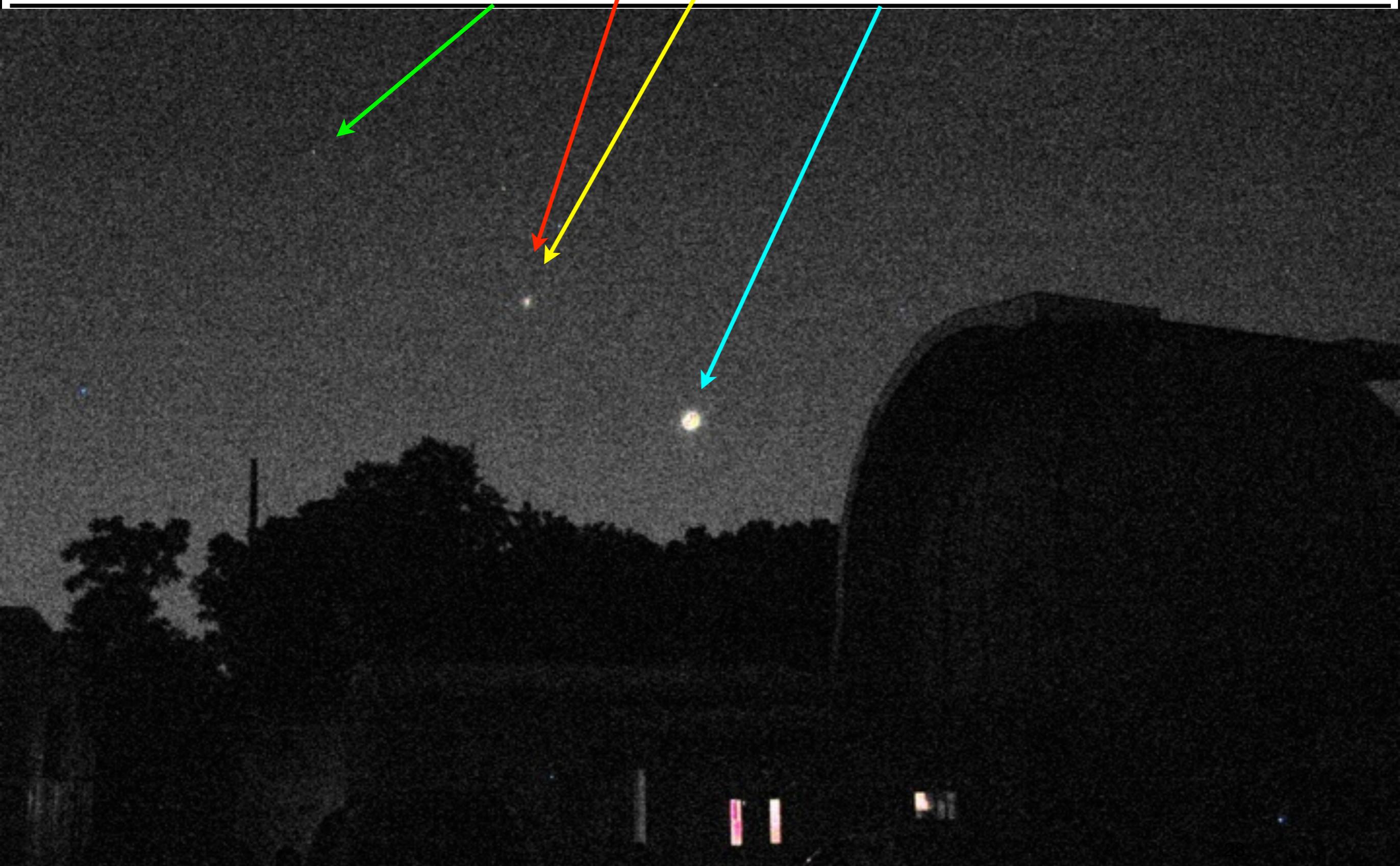
2007-06-18, 103,408,600 km

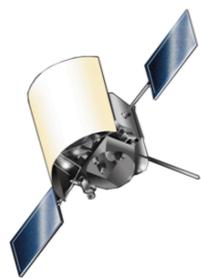




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Saturn, Venus, Moon



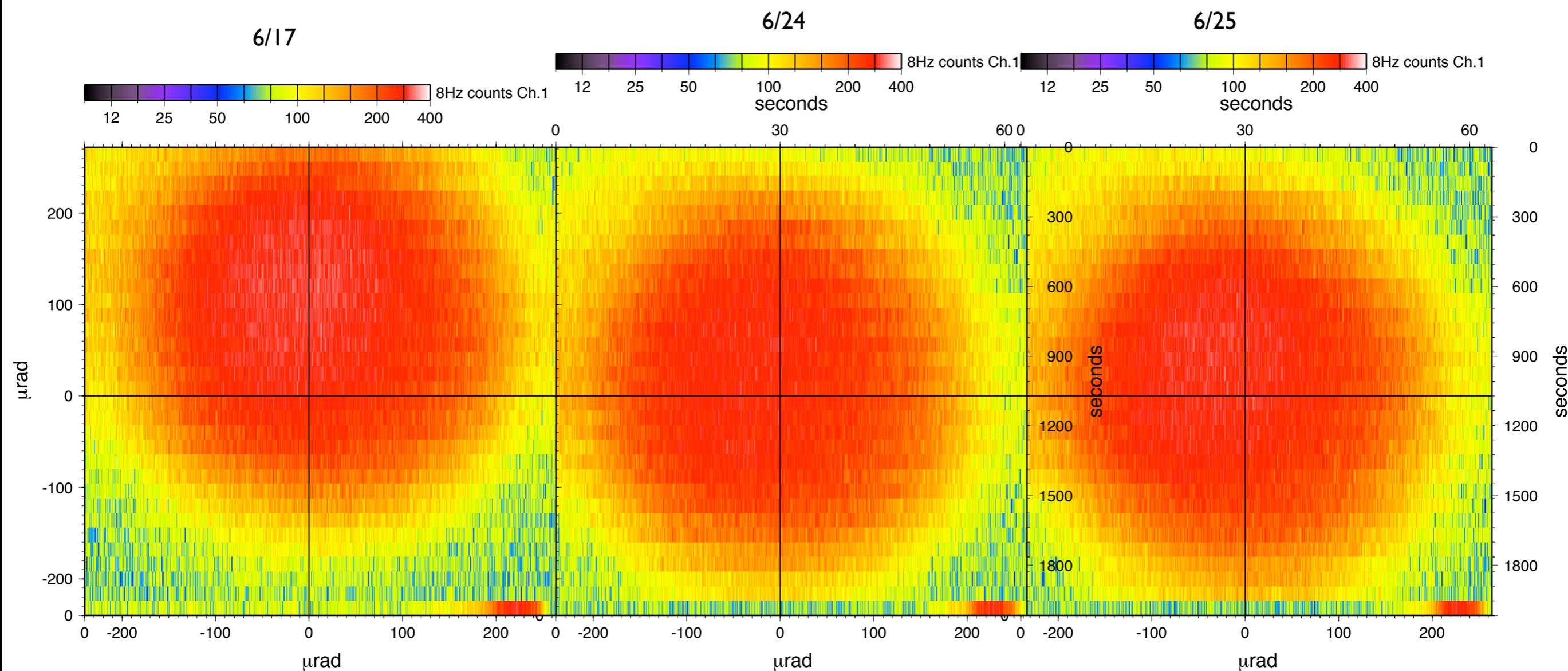


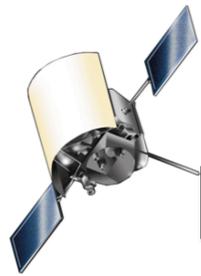
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MLA passive scan results



- Earthshine counts vs time (end of scan crossing Earth at LR corner).
- Detector boresight stayed within 0.48×0.48 mrad (99 arcsec) scan.
- G&C control approached nominal aimpoint over course of week.



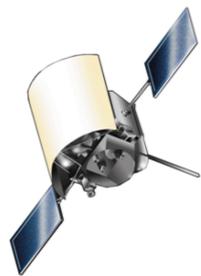


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Earth-MLA experiments 2009-2010



- MLA boresight was within 100 microradians of aimpoint.
- All instrument data were received as expected.
- Event timing on ground within 20 ns of UTC.
- Link margin was nominally sufficient to trigger single-photon detectors at GGAO.
- Atmosphere was sufficiently clear to permit ranging on 4 of 5 nights, and ground laser had sufficient power to communicate a position-modulation-encoded message to MLA.
- No signal above background was confirmed at either end.
- Telescope alignment was believed to have been a problem.
- Two attempts in Feb 2010 to use GLAS as a receiver terminal also failed, likely due to misalignment of ICESAT spacecraft.



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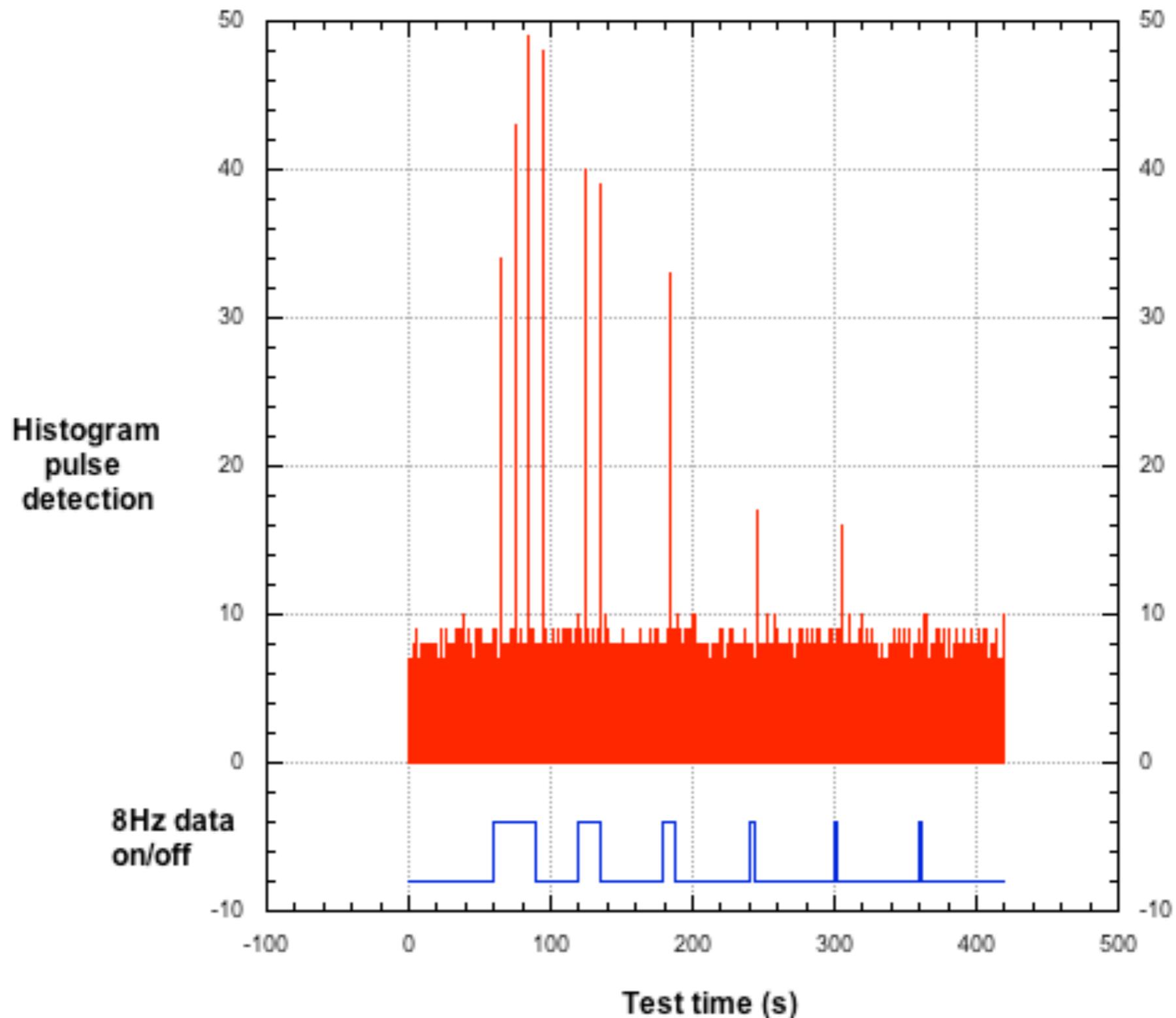
MLA-Earth 2014 Experiment at 1.02 AU



- New tracking encoders, electronics installed at 48" telescope together with improved finder telescope CCD.
- 1 Joule, 50-Hz laser refurbished and collimated.
- Visibility marginal, elevation low, and weather precluded full mount calibration, but Mercury was tracked in finder.
- Higher-than-expected background from illuminated Earth may have blocked MLA detections. No strong triggers identified. Receiver boresight verified with passive scans.
- Single-photon detection should have picked up 8-Hz MLA signal, with $100 \mu\text{s}$ timing reconstruction. Search results were not convincing, compared with predictions. MLA beam quality and output is a possible cause.

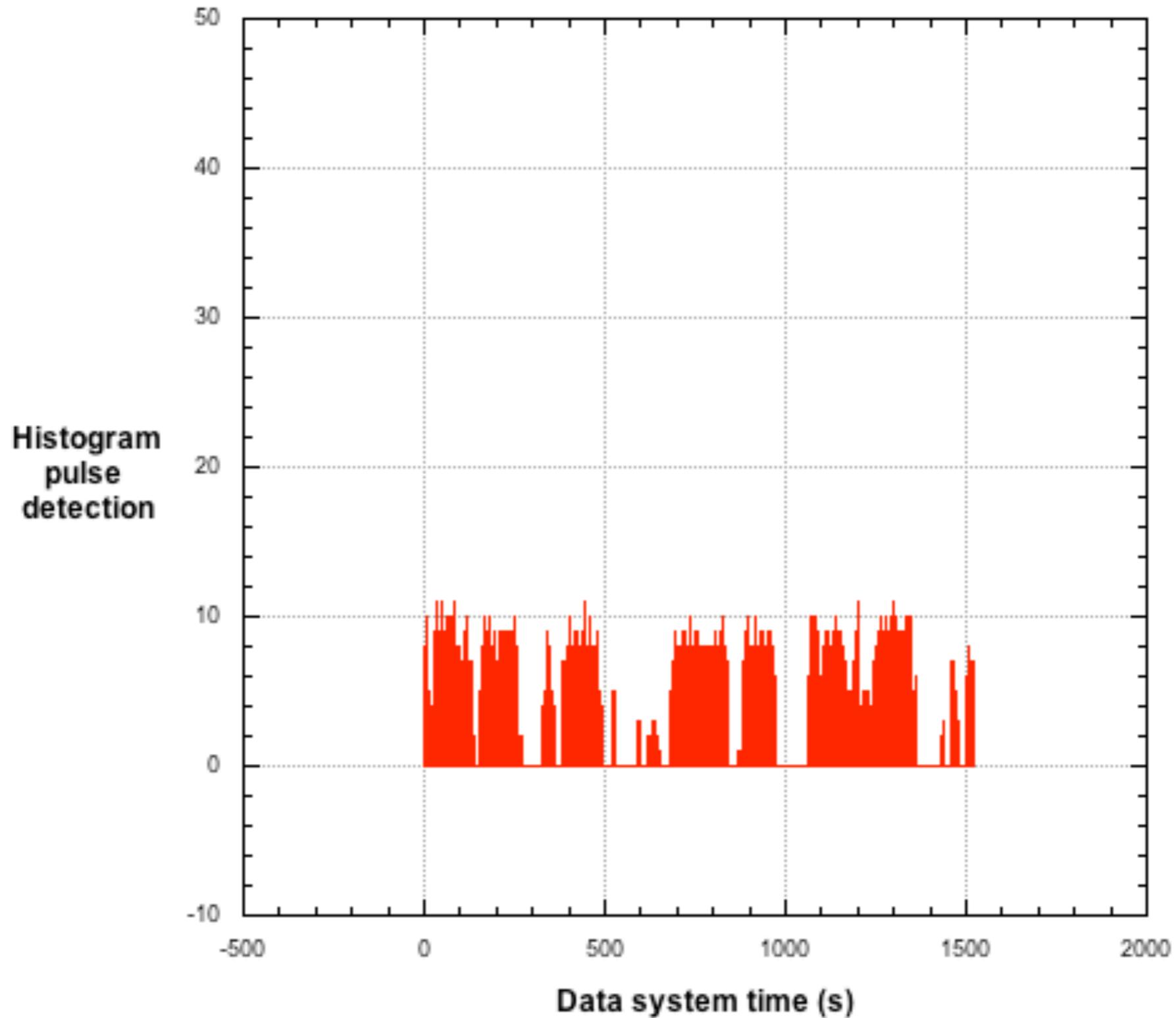
This is a plot of 42 histograms set side-by-side to emulate a spectrum analyzer

Lab data run 007 May 12, 2014
2.4 MHz noise plus various
intervals of 8Hz data (blue line)
10ns resolution histograms taken every 10s



Same analysis as previous slide – but now against downlink data day 139

MLA downlink experiment Day 139 10ns resolution histograms taken every 10s

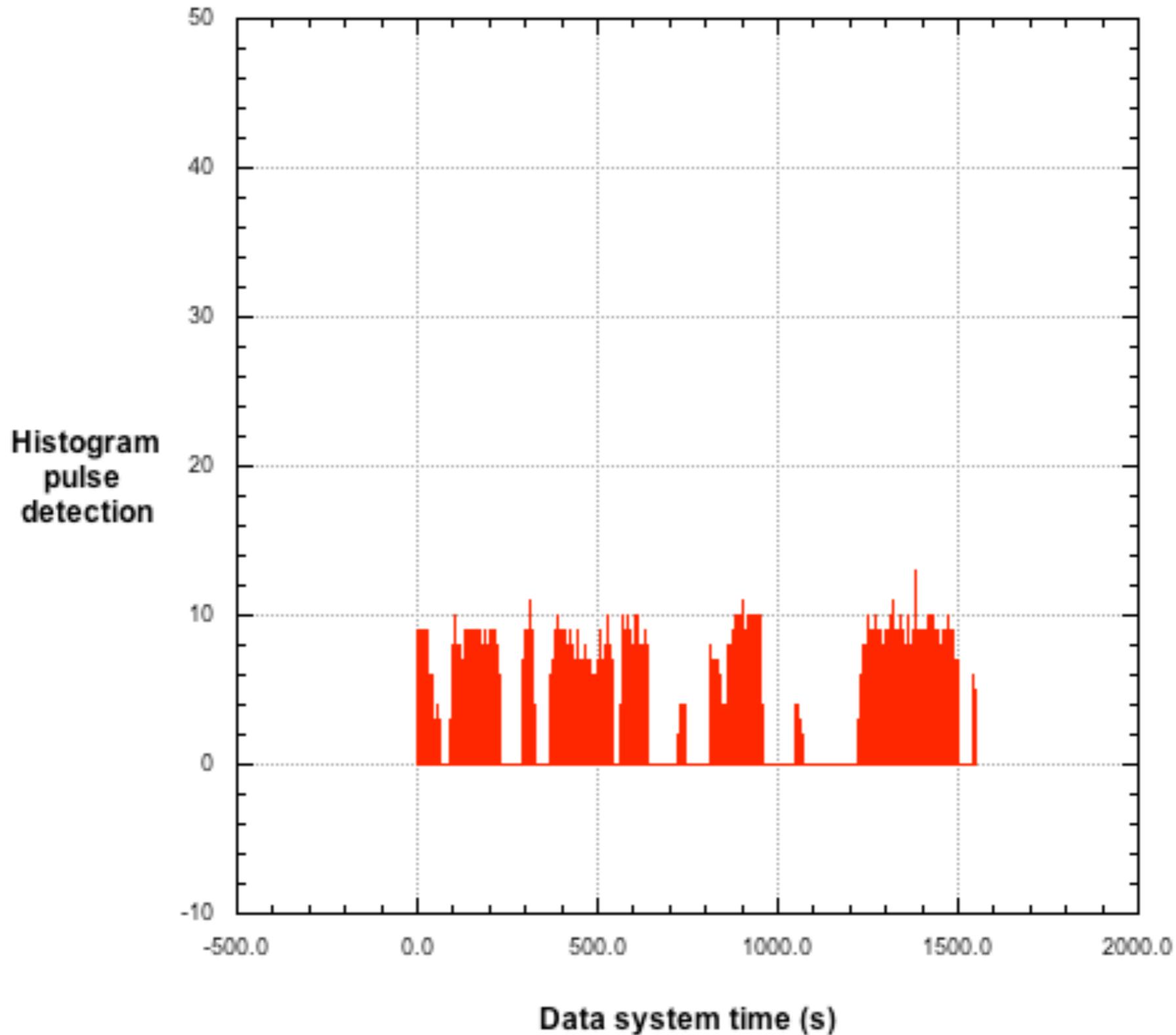


Data dropouts are due to MLA start pulse reporting problems

No signal seen

Same analysis as previous slide – but now against downlink data day 143

MLA downlink experiment Day 143 10ns resolution histograms taken every 10s



Data dropouts are due to MLA start pulse reporting problems

No signal seen

Search for MLA pulses
in the downlink data
taken at the 48" telescope
Days 139 and 143, 2014

Dave Skillman
Xiaoli Sun
June 12, 2014

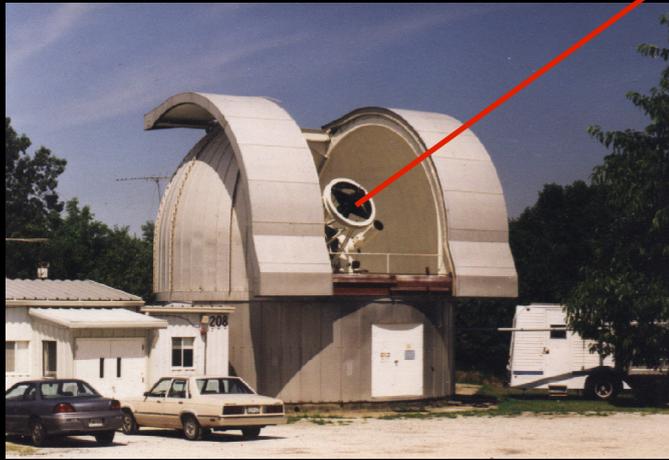
Search Summary:

Day 143 has been searched with all techniques out to $\pm 1100\mu s$
- no convincing MLA events found

Day 139 has been searched with all techniques out to $\pm 100\mu s$
- no convincing MLA events found

Lab simulation data has been searched with all techniques out to $\pm 100\mu s$
- 8Hz events easily seen with all search software techniques

Earth-Mars 1-way Experiment Sept. 2009 (not to scale)

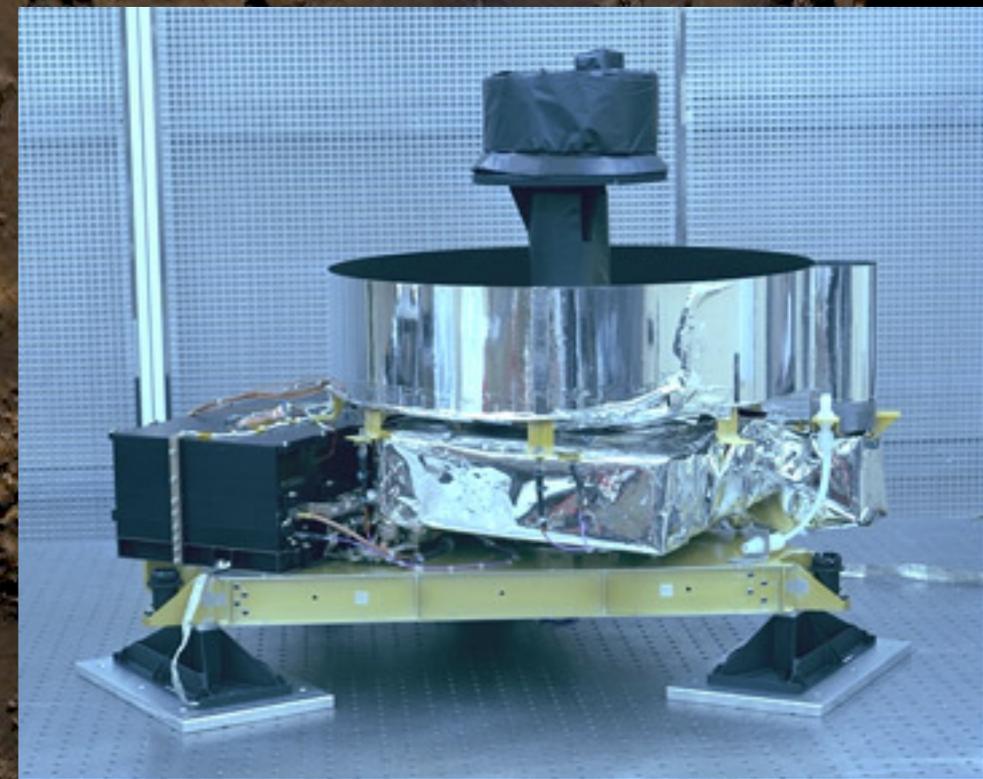


81 Mkm



~ 560 laser pulses detected

Mars Orbiter Laser Altimeter (MOLA) 1996-2001



| | |
|-------------------|-------------------|
| ranging precision | 37.5 cm |
| range | 785 km |
| Accuracy | ~1 m |
| pointing control | 200 arcsec |
| firing rate | 10 Hz |
| Shots | 700×10^6 |



SVS/MOLA Science Team

Photographs of Telescope Setup

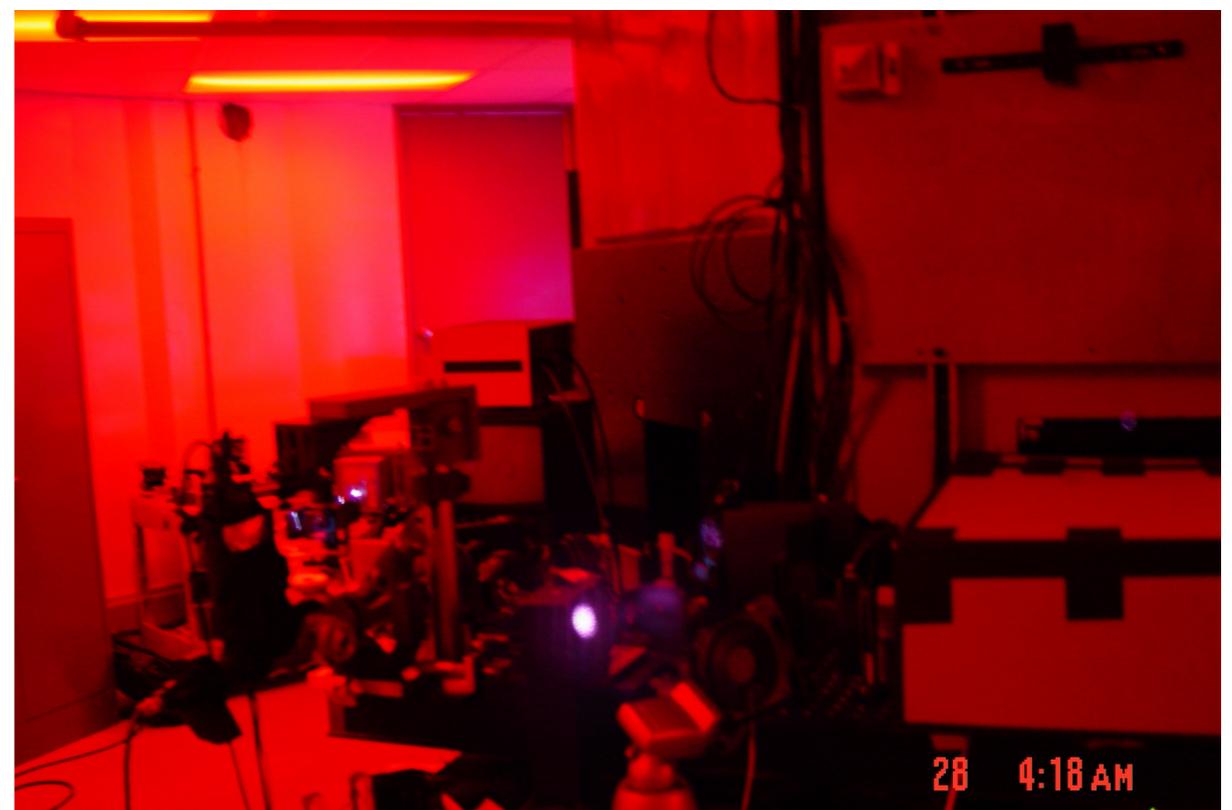
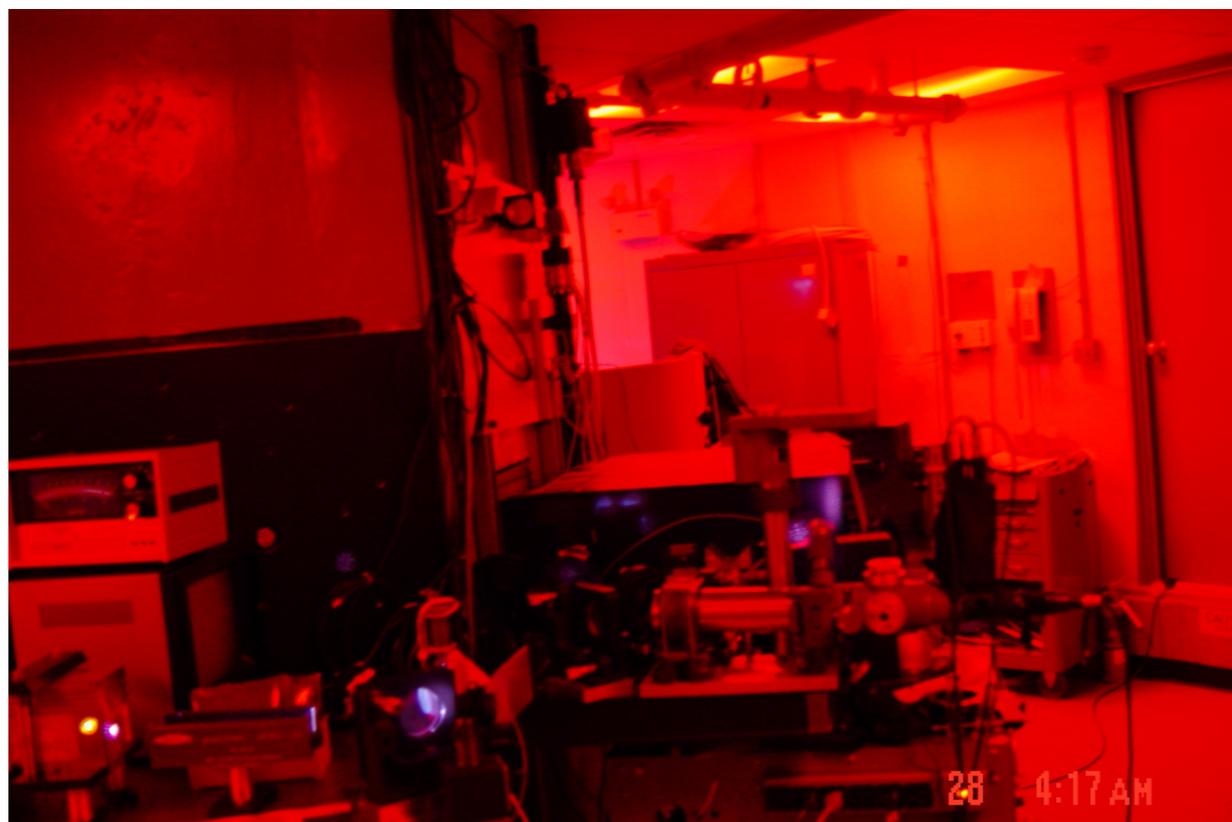
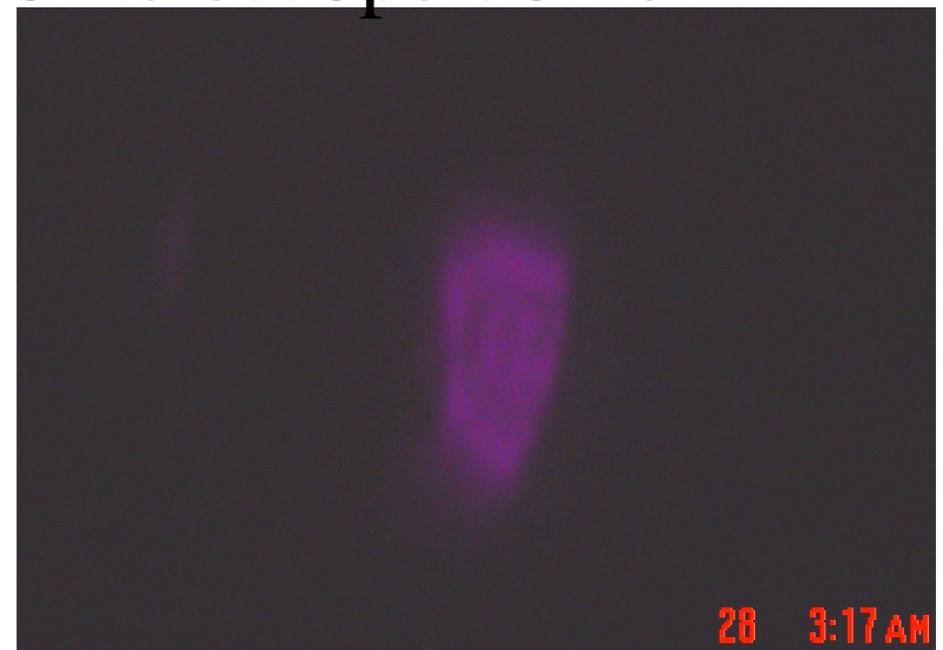
9/28/05 (Clear)

Mars



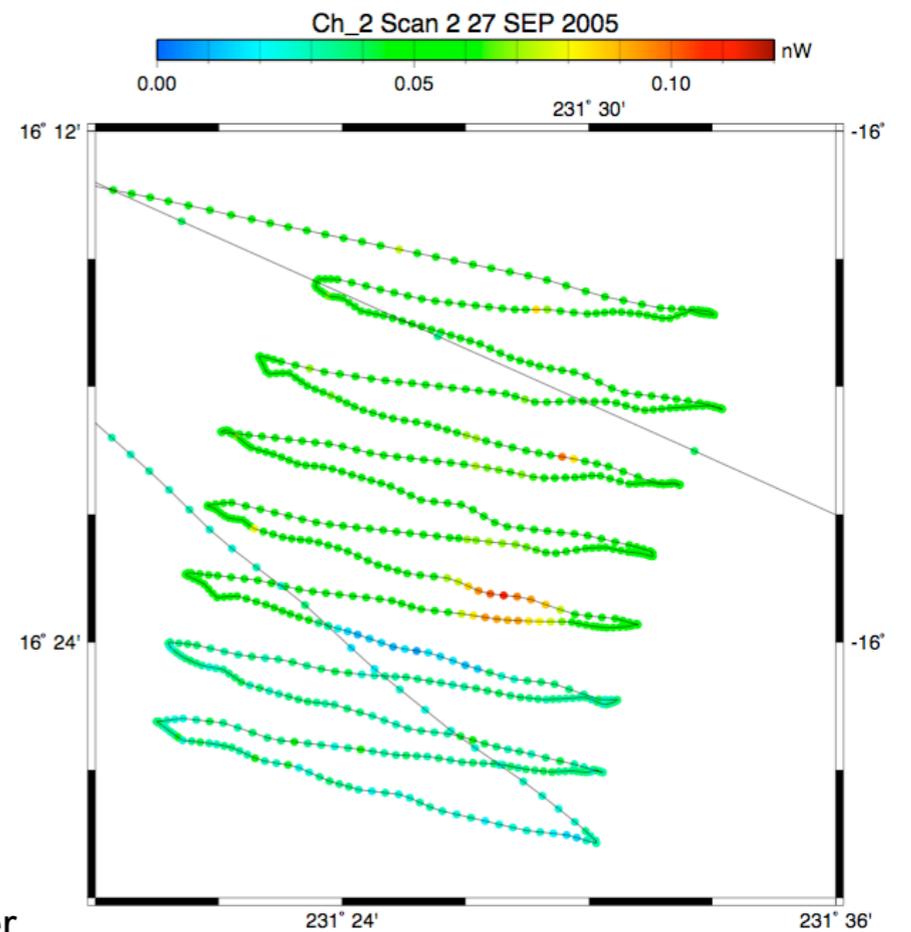
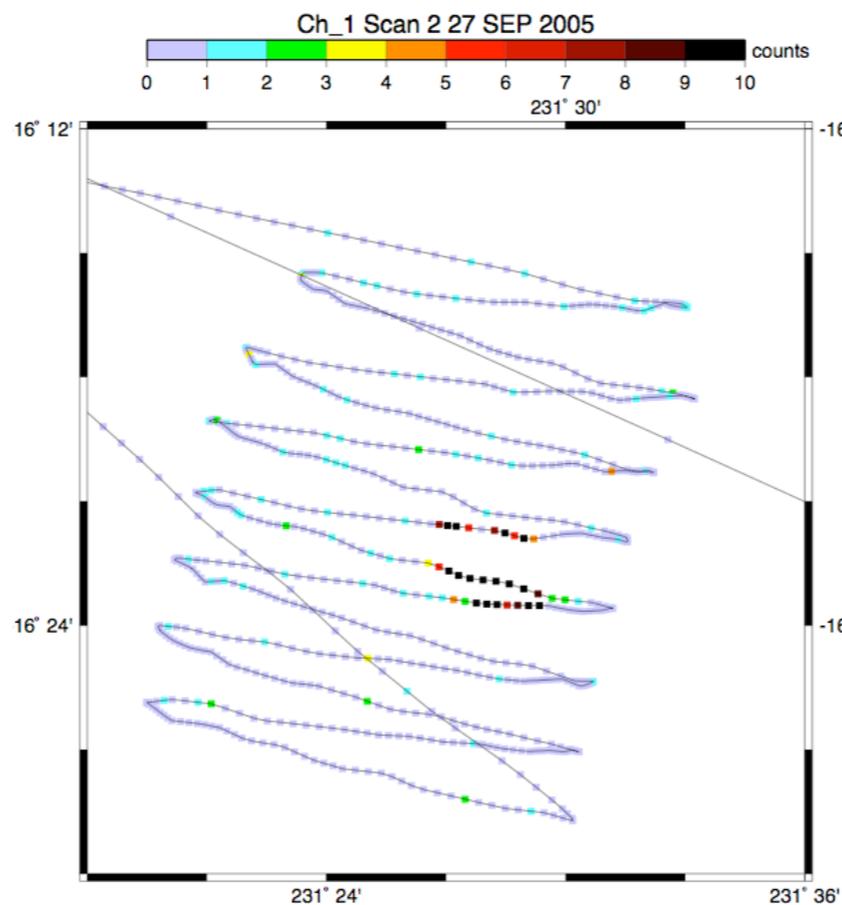
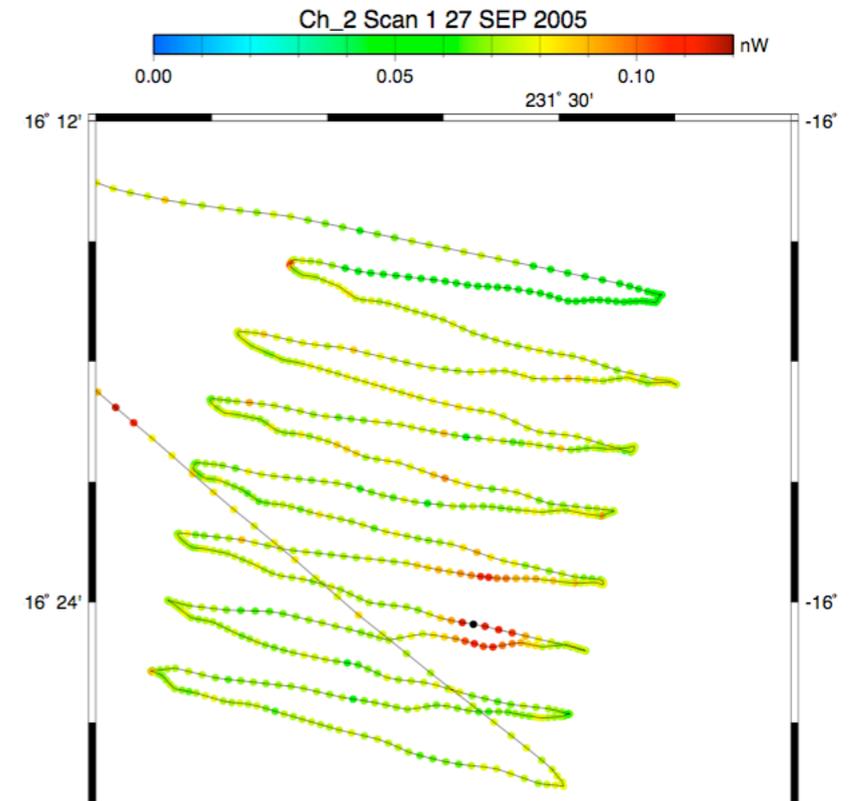
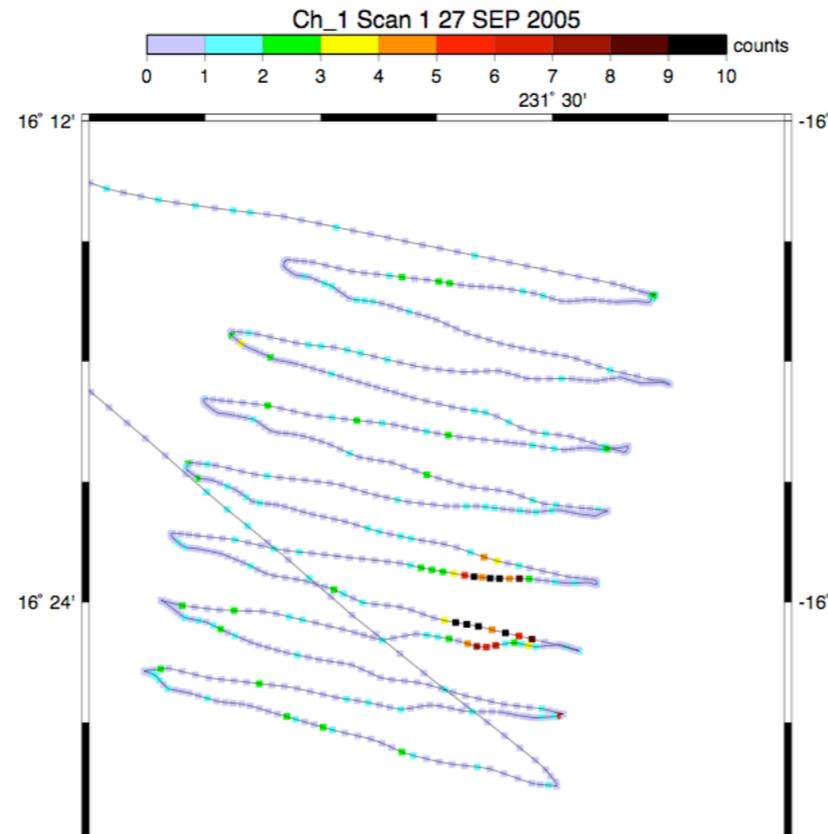
Chopped (6 on, 6 off) and unchopped 49-Hz laser

Laser Beam patterns on inside of telescope dome



Laser Pulse Detection (clear sky on 9-28-05)

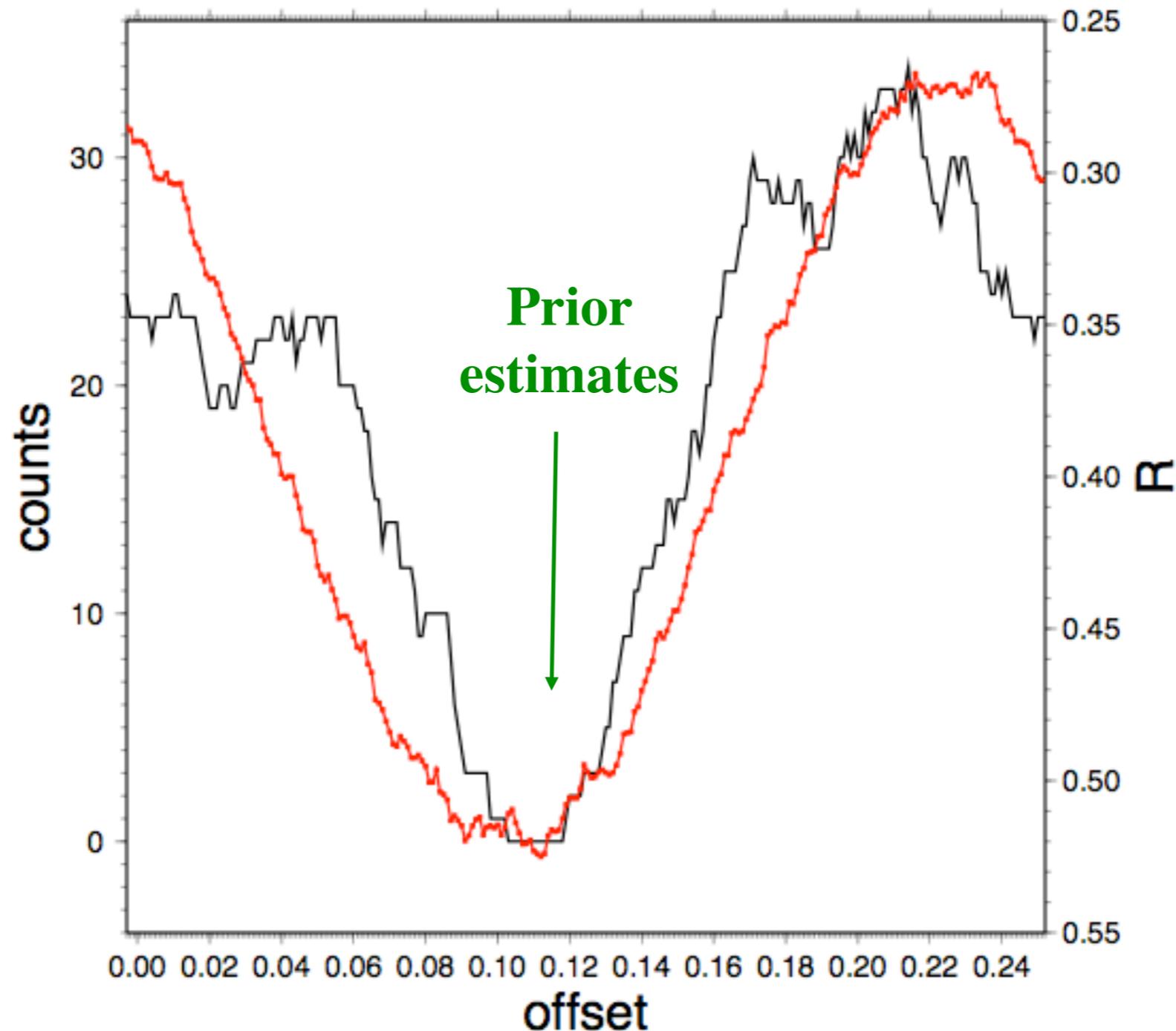
MGS Scan
pattern & MOLA
receiver counts
(Ch1) and
Power (Ch2)



Timing Offset Determination

Using detected pulses from Ch1 on First Scan

Cross-Correlation (inverted scale, red) & Excess pulse count* (black)



*- # of pulses detected by MOLA in excess of # transmitted from Earth laser

The quest for 1 AU:

Factors contributing to success/failure

Positive

- Staff experience and dedication
- Smooth S/C G&C operation
- Ground station pointing and laser alignment (arcsecond accuracy), years of practice
- Powerful laser/telescope
- 100 ps event timer precision and 1-ns waveform digitizer, tied to GPS UTC clock within 100 ns
- Spacecraft USO stability
- Preliminary S/C calibration and rehearsal.

Negative

- Low elevation, long atmospheric path at GGAO
- Cloudy skies; forward scattering
- Relatively weak uplink margin; poor initial boresight model, requiring hours of scanning
- Strong earthshine background noise, preempting many returns; Mercury background counts.
- Time needed to calibrate system time delays and telescope pointing.

Thanks to MESSENGER, LRO, and Mars Global Surveyor!