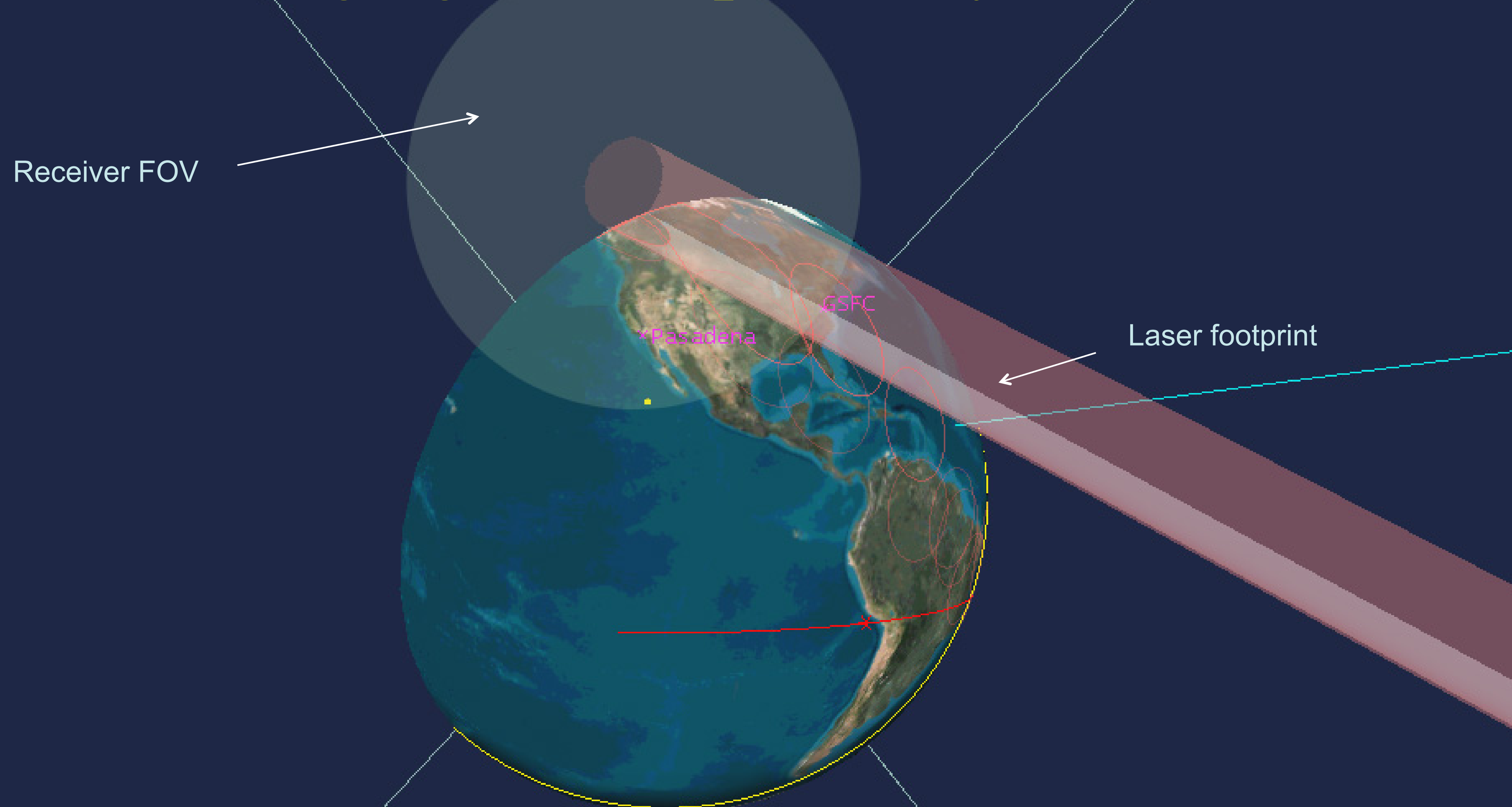
Laser Ranging at Interplanetary Distances



15th ILRS Meeting, Canberra, Australia

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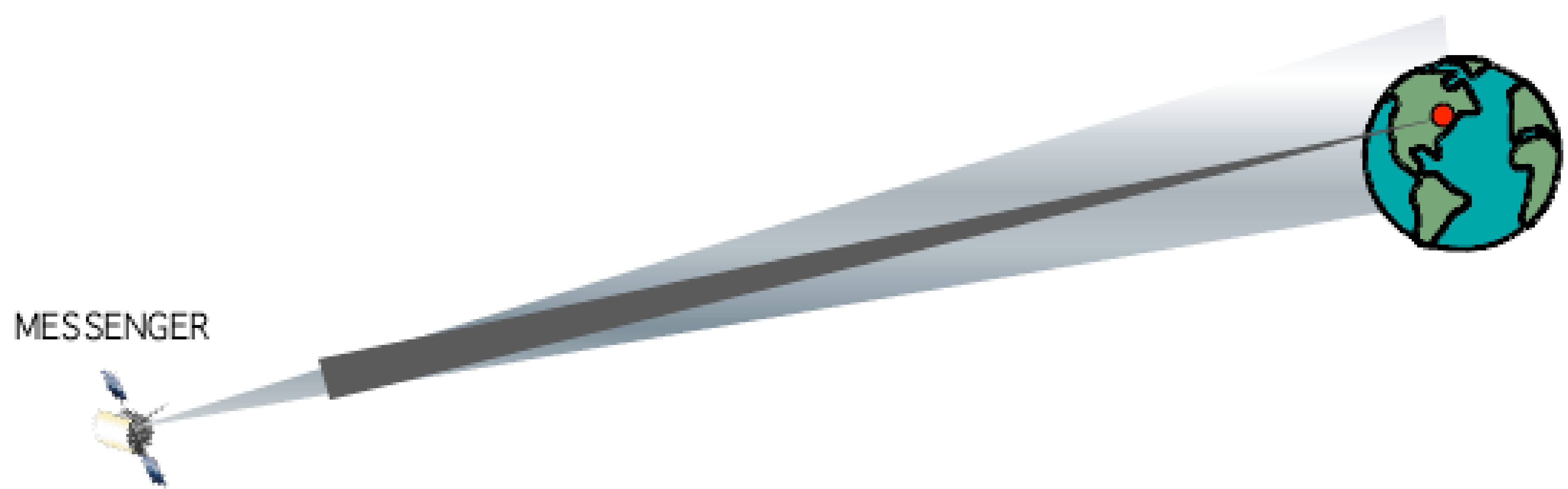
Laser Ranging Calibration Experiment: Test Objectives

- 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 Mercury Dual Image System (MDIS).

☑ Byproduct: Demonstrate interplanetary ranging and communication using an asynchronous transponder approach.



Ground Laser and Flight Terminal Parameters

Transponder required ~ 1/3 of MOLA laser energy

Performance of MLA laser matched predictions under colder-than-normal operating conditions.
HOMER laser testbed designed for high-rate, long duration operation, not specifically for ranging.

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

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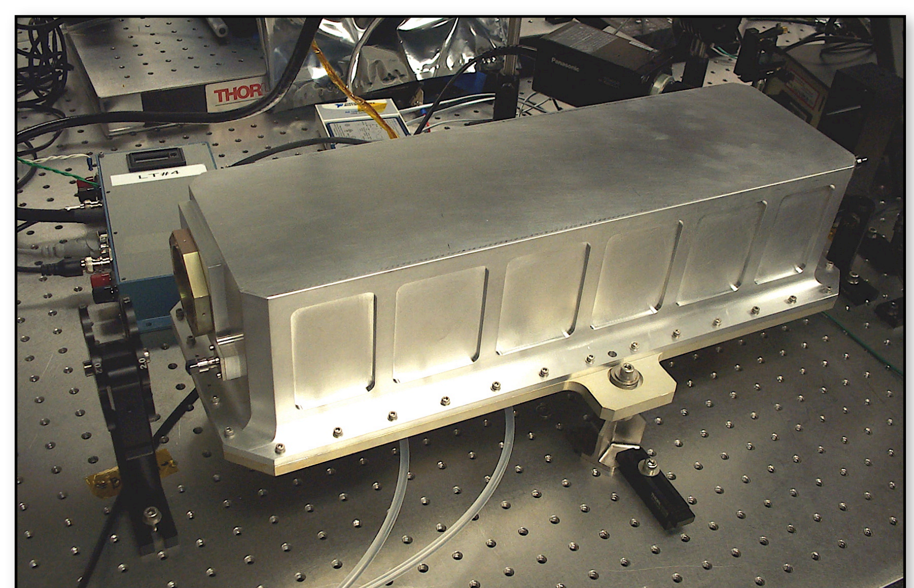
MLA



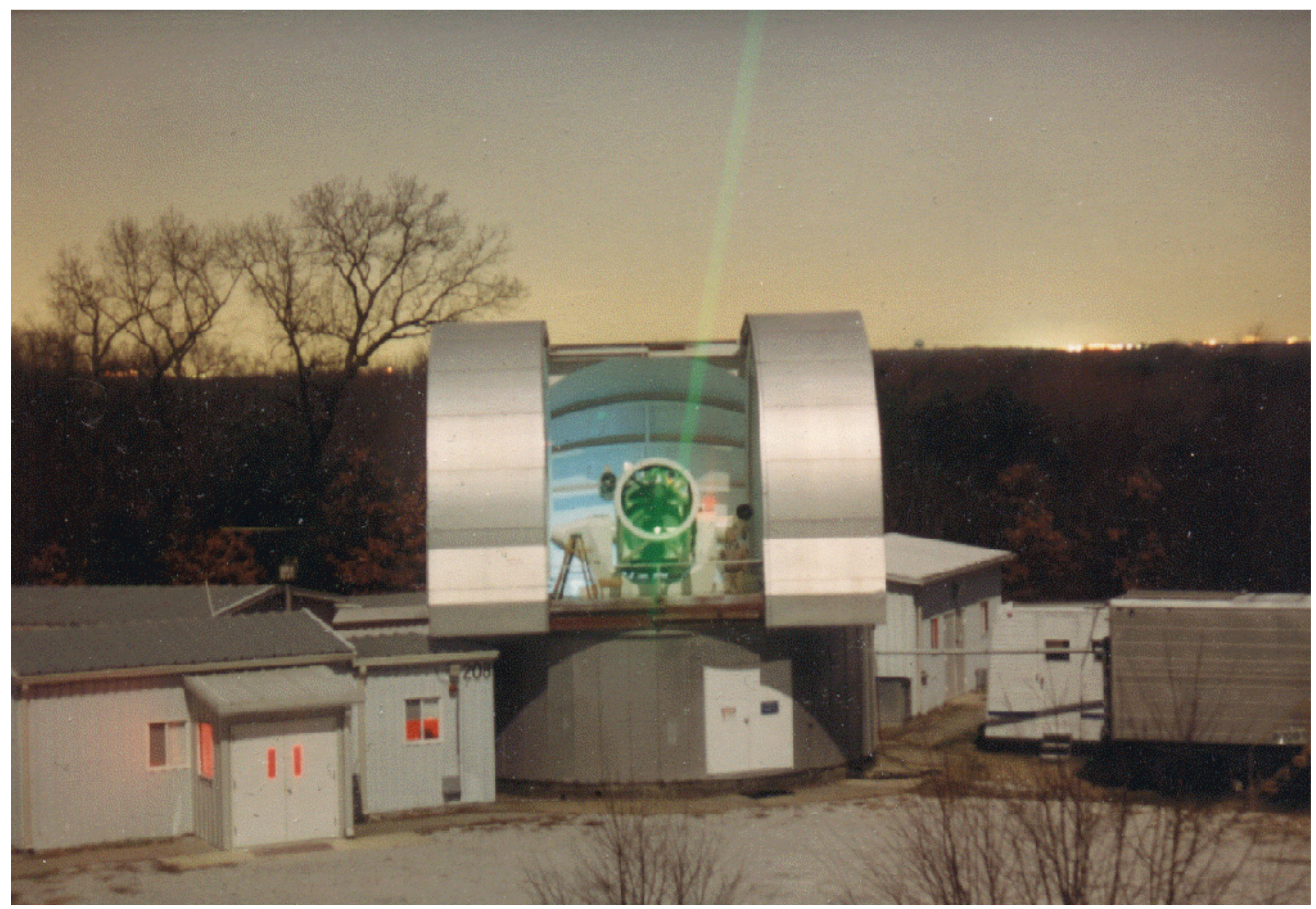
GGAO/
Homer-1

MLA - MESSENGER

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 μrad beam divergence
- 2-nm FWHM bandpass filter, 260 μrad receiver FOV for daylight operation
- Si APD photodetector, 0.05 fJ/pulse sensitivity

- GGAO optics and mount designed for LEO tracking.
- Mirrors were last coated in 1989. Overcoat peaked for UV-VIS operation!
- Estimated 70% transmission at each of 6 surfaces, implying 11% overall transmission at 1064 nm.



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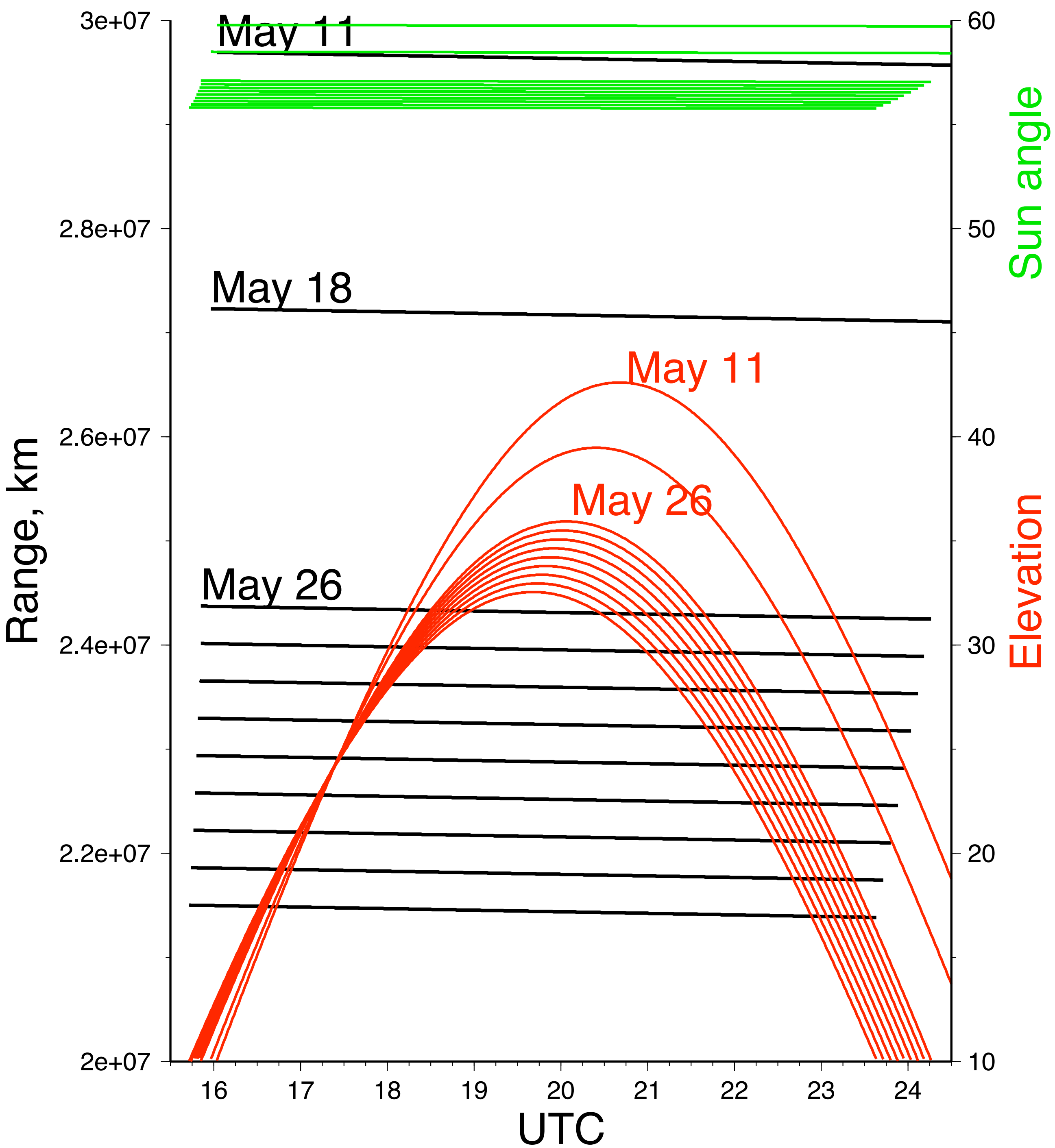
Pre-Earth-flyby Viewing Geometry



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.

Unfortunately, this was also a time when thick cumulus clouds were likely to form. An MLA Earth scan across a 3.2 x 3.2 mrad region was programmed for each of 5 days to ensure success.

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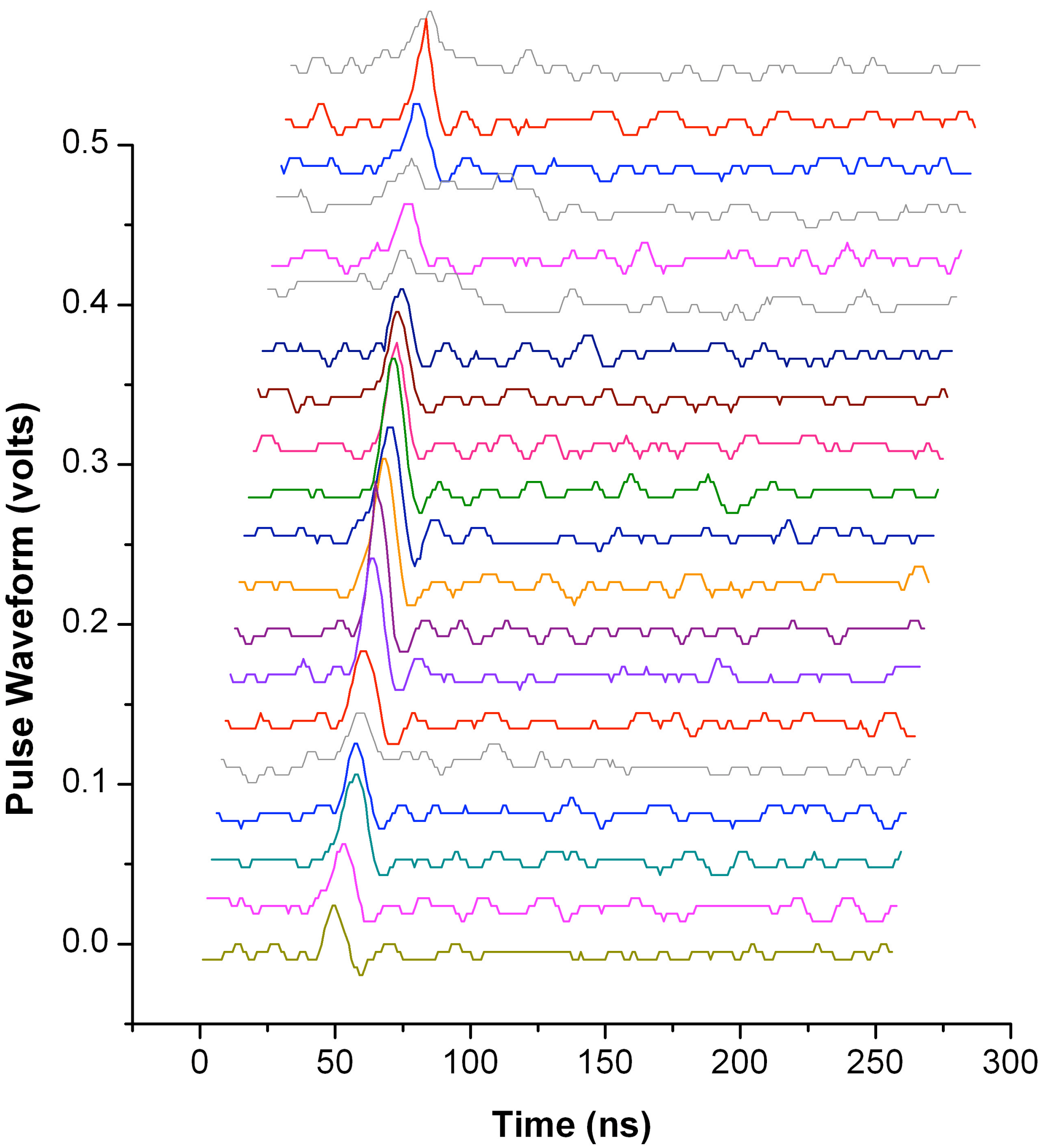
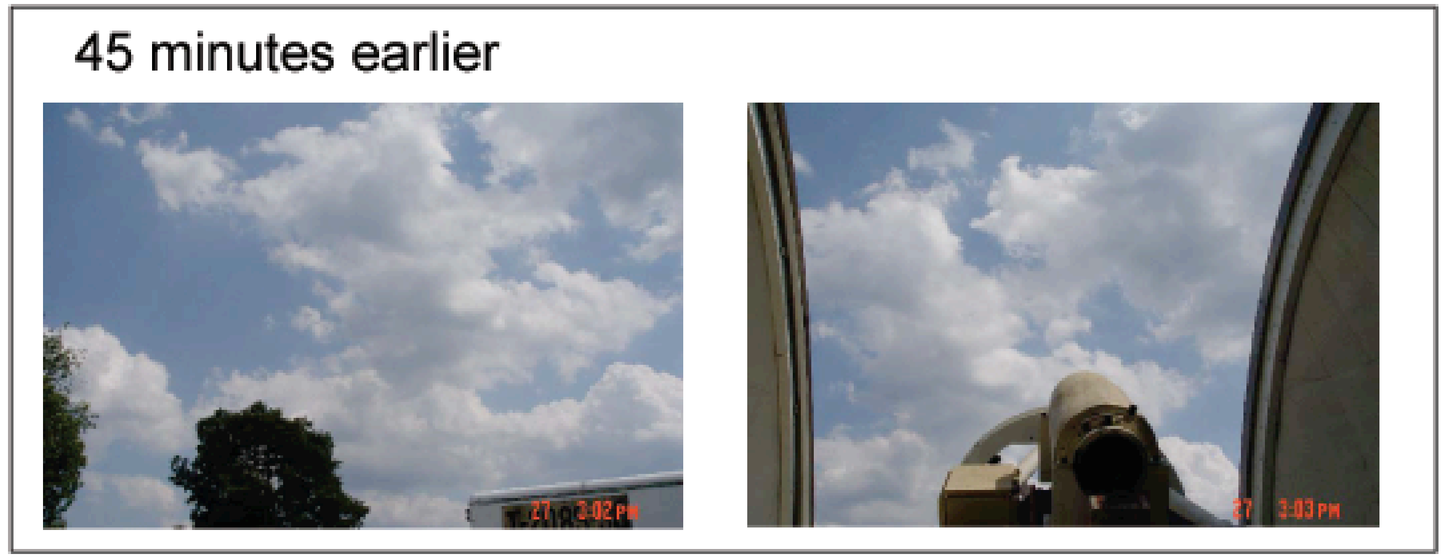
Weather - 05/27-05/31, 2005

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

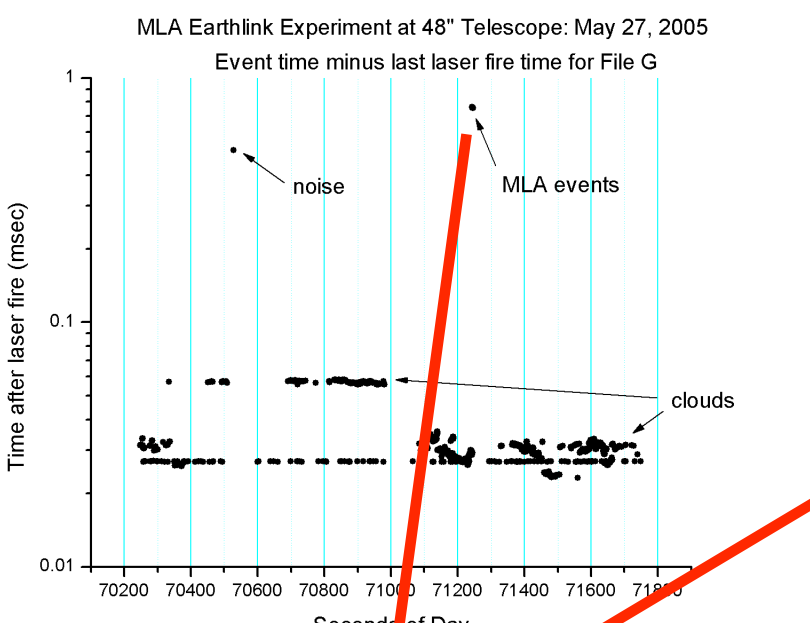


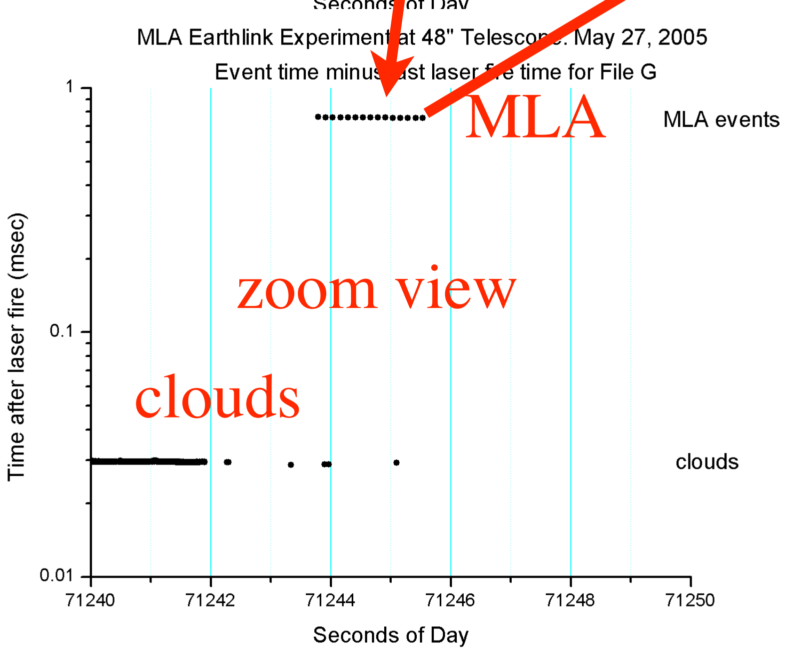
S/C and ground teams stood down for holiday weekend. May 31 clouds were similar, but 24 pulses were detected.

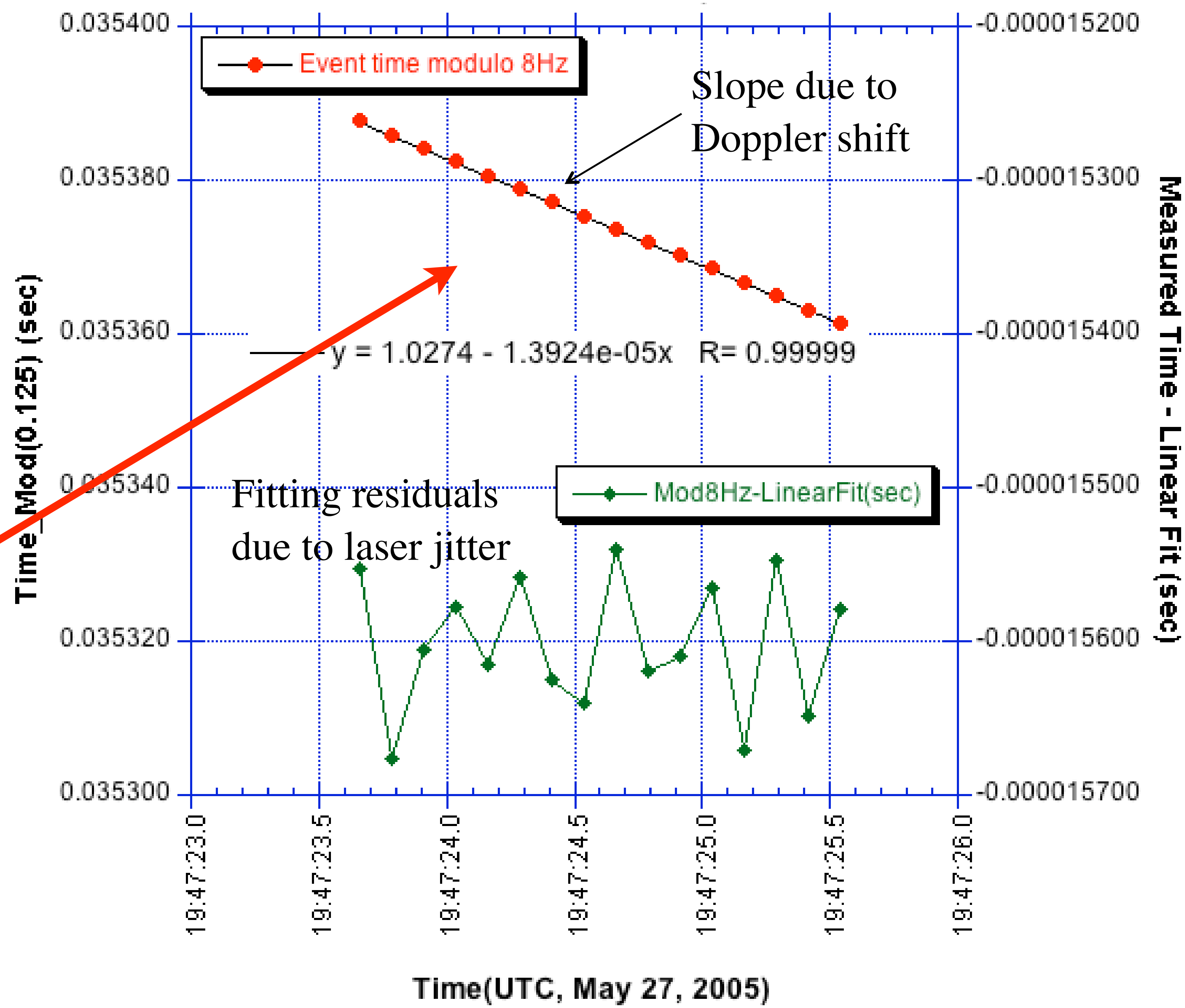


Pulse Arrival Times at GGAO

Arrival times confirm detection of MLA 8-Hz signal.

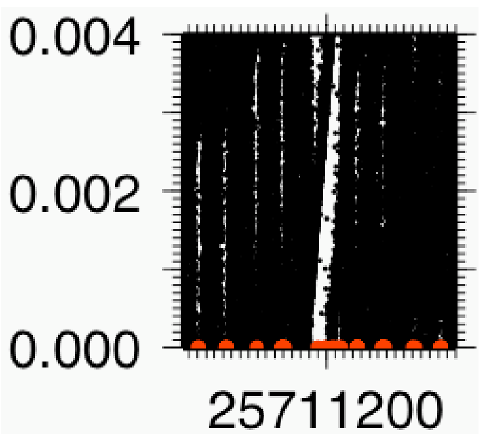






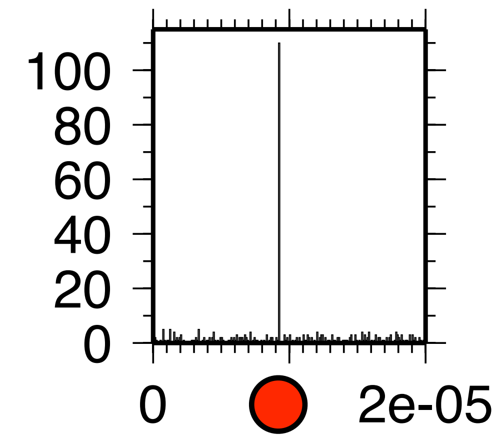
May 27 Uplink Pulse Detection Algorithm

4 ms window

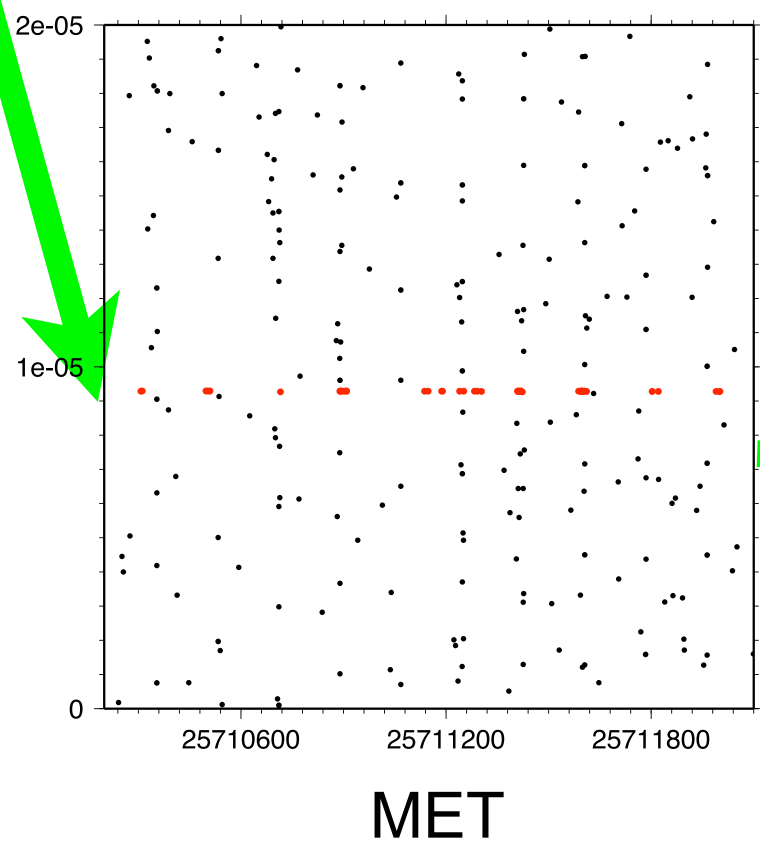


- Noise from earthshine masks signal
- Subtract predicted light time from MET
- Sort times, find nearest laser fire event
- Plot reduced 1-way times - search histogram
- fit “normal point” to MET times ------------------

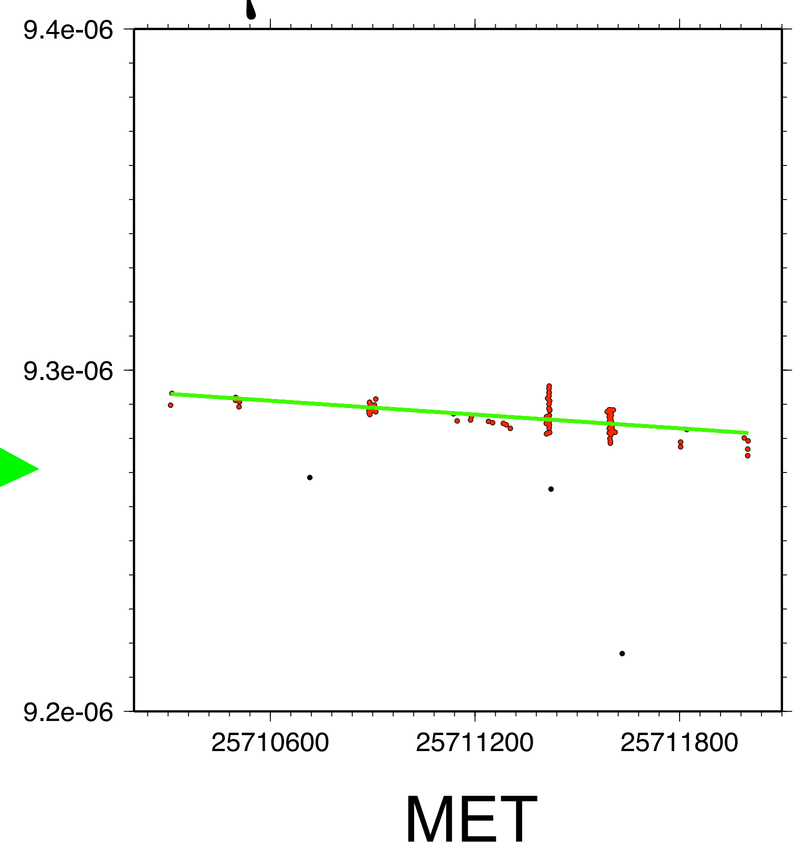
histogram



0.02 ms window



0.2 μs window



Factors contributing to success/failure

Positive

- Experience and dedication of staff
- Smooth S/C G&C operation
- Ground station pointing and laser alignment (arcsecond accuracy)
- 100 ps event timer precision and 1-ns waveform digitizer, tied to GPS UTC clock within 100 ns
- MLA's 400 ps pulse centroid precision and spacecraft USO stability
- Good preliminary S/C calibration and rehearsal (May 11-18), shortening scan durations.

Negative

- Low elevation, long atmospheric path at GGAO
- Cloudy skies, forward scattering
- Relatively weak uplink margin (1.5 mJ effective energy)
- Poor initial boresight model, requiring 3+ mrad correction and hours of scanning
- Strong earthshine background noise, preempting many returns
- Need to calibrate absolute time delays and atmospheric delay (no path calibrations applied).

Interplanetary laser ranging is achievable!

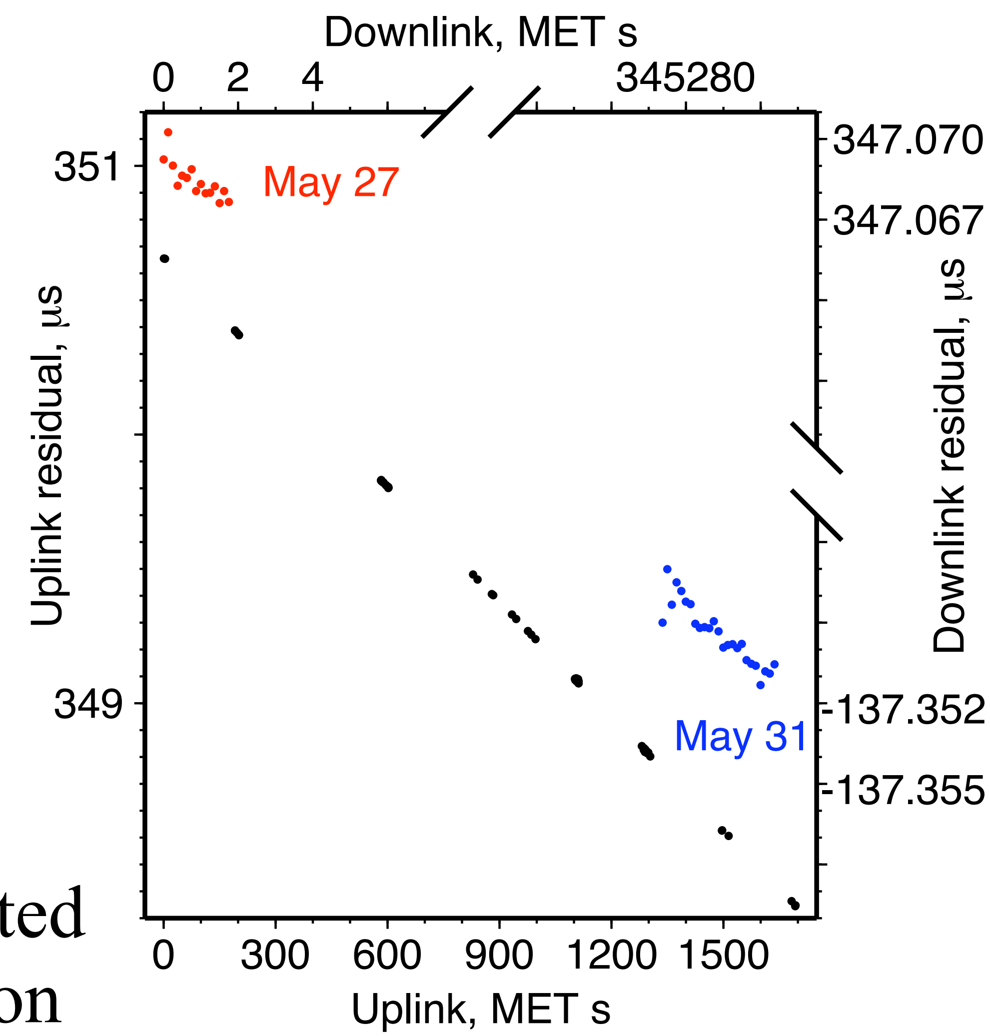
Asynchronous Transponder Analysis

- Uplink events span 1/2 hour, while downlinks occur for 2-3 seconds
- Linearize 1-way light time ("Range") about S/C Mission Elapsed Time 25710307 s
- Correct for offset from Earth center O(t) along LOS (azimuth is relatively constant)
- Estimate clock UTC offset and drift (p_1 , p_2) at "transponder" MET time t
- Estimate S/C Range at origin, Range Rate and Acceleration (p_3 , p_4 , p_5)
- Weighted LSQ fit 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) not a true geometric 1-way range in a non-inertial system; Relativistic time delay ignored; But average of light times ≈ range + Shapiro time delay.



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

Comparison with 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 improved calibration for 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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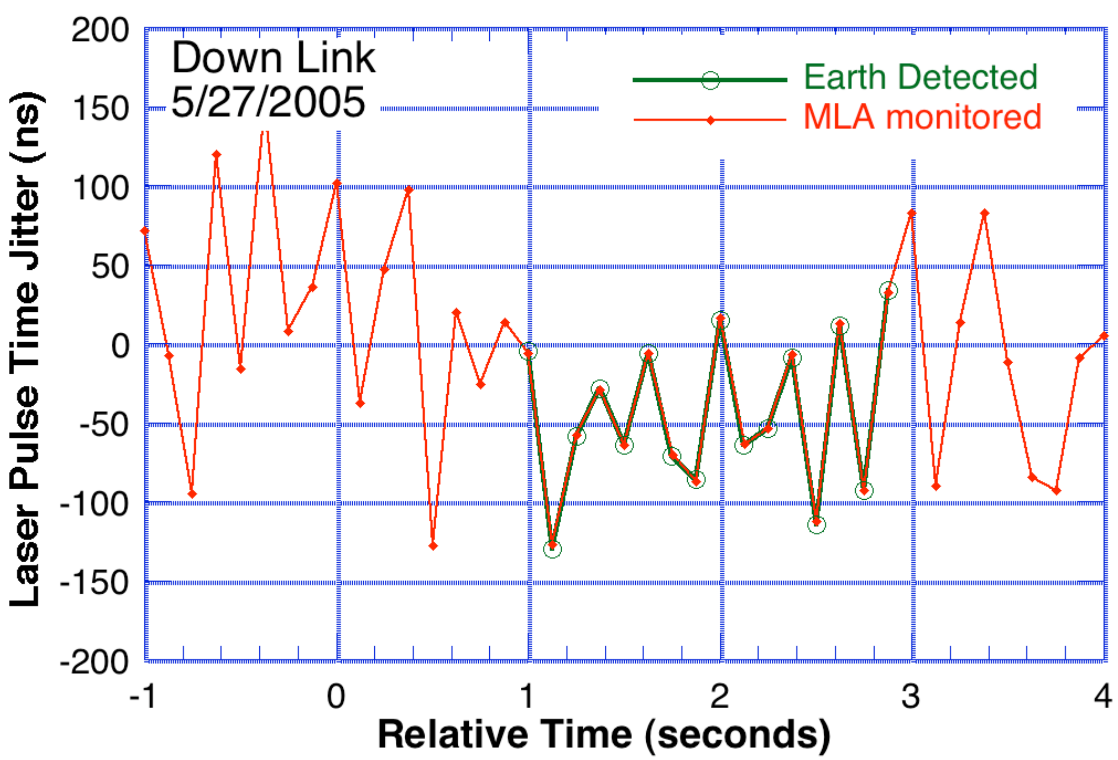
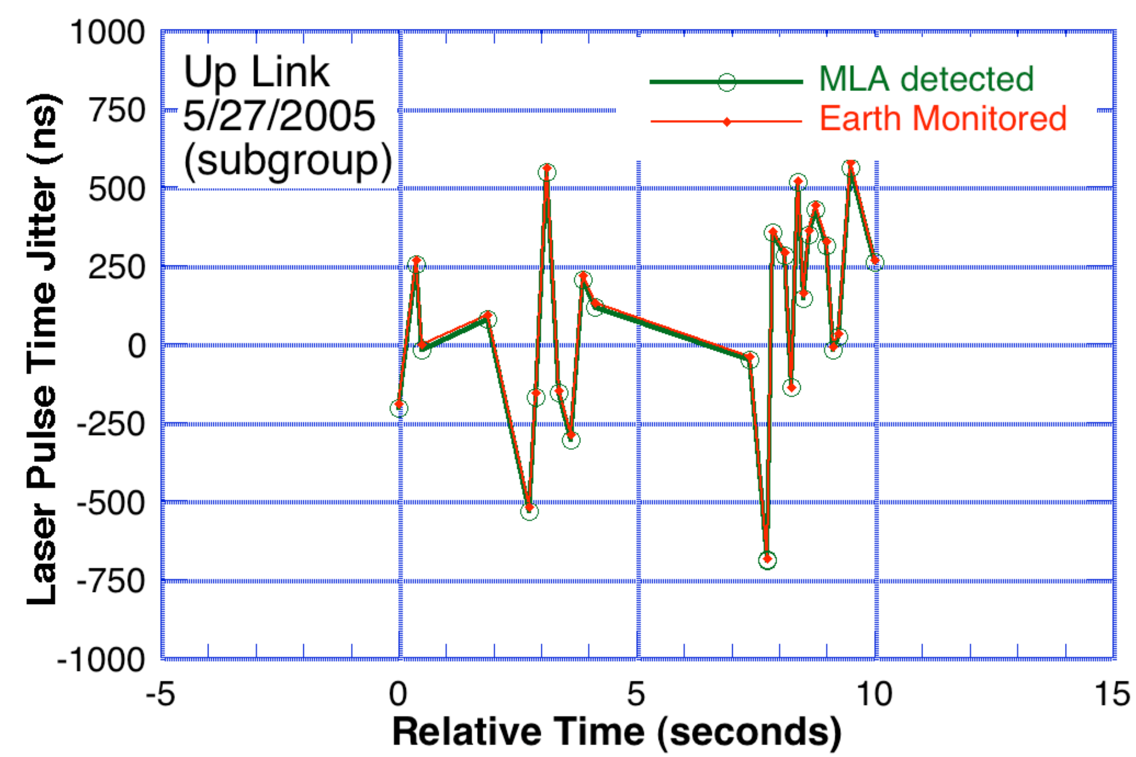
2-way Laser Communication (sort of)

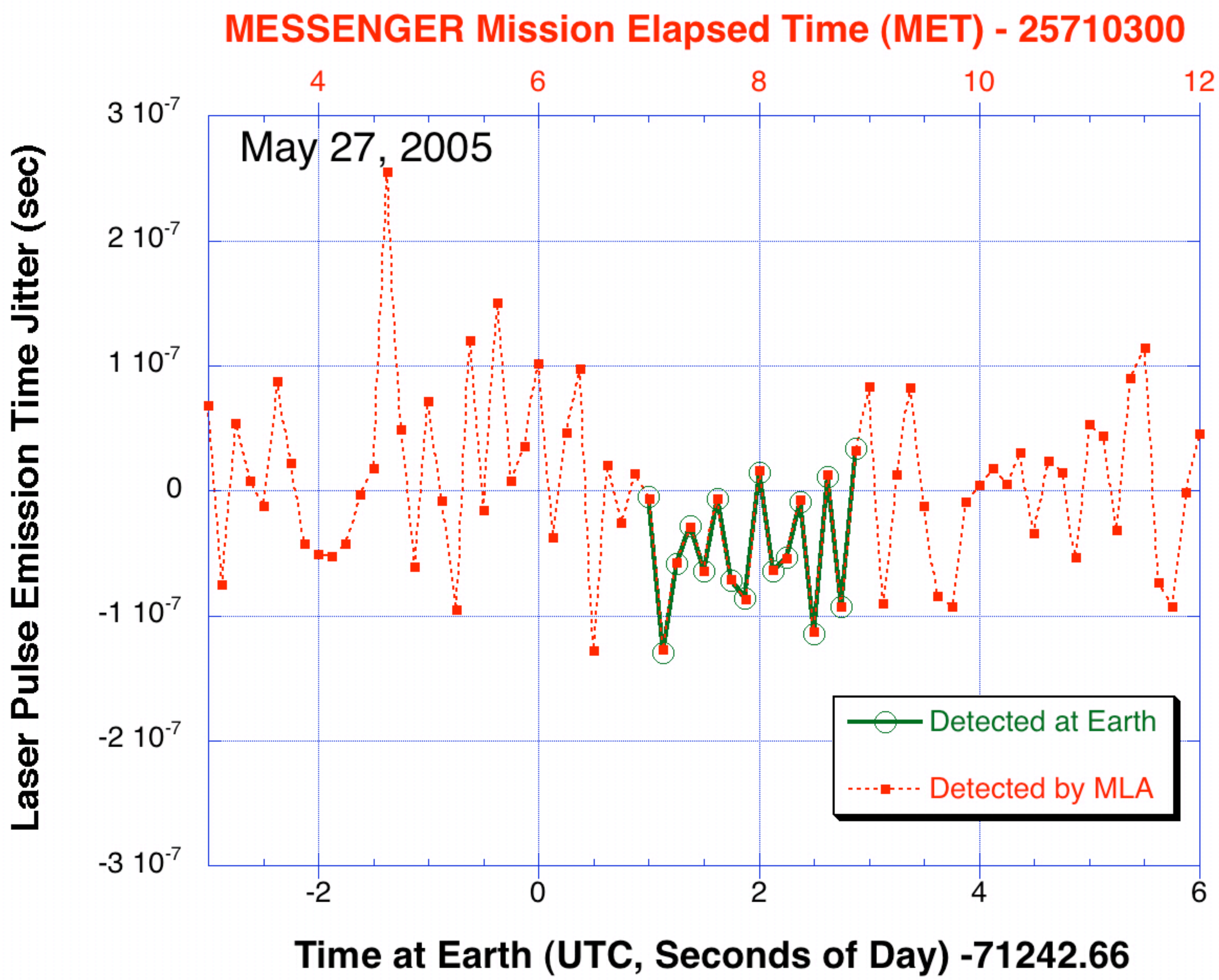
- MLA is passively Q-switched, leading to ~100 ns random jitter in fire times.
- This pattern is observed precisely on the ground.

- 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.





Detection of Laser Time Jitter



The MLA laser shot-to-shot jitter pattern may be used to synchronize the spacecraft MET to UTC and simulate a transmitted signal.

☑ Difference between GGAO detected and MLA recorded laser jitter was 0.35 ns S.D., corresponding to a 100:1 signal-to-noise ratio (SNR).

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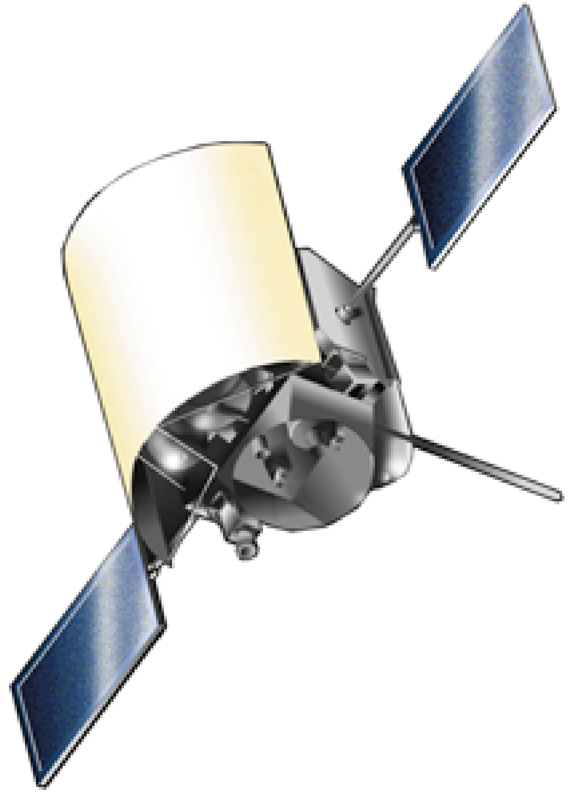
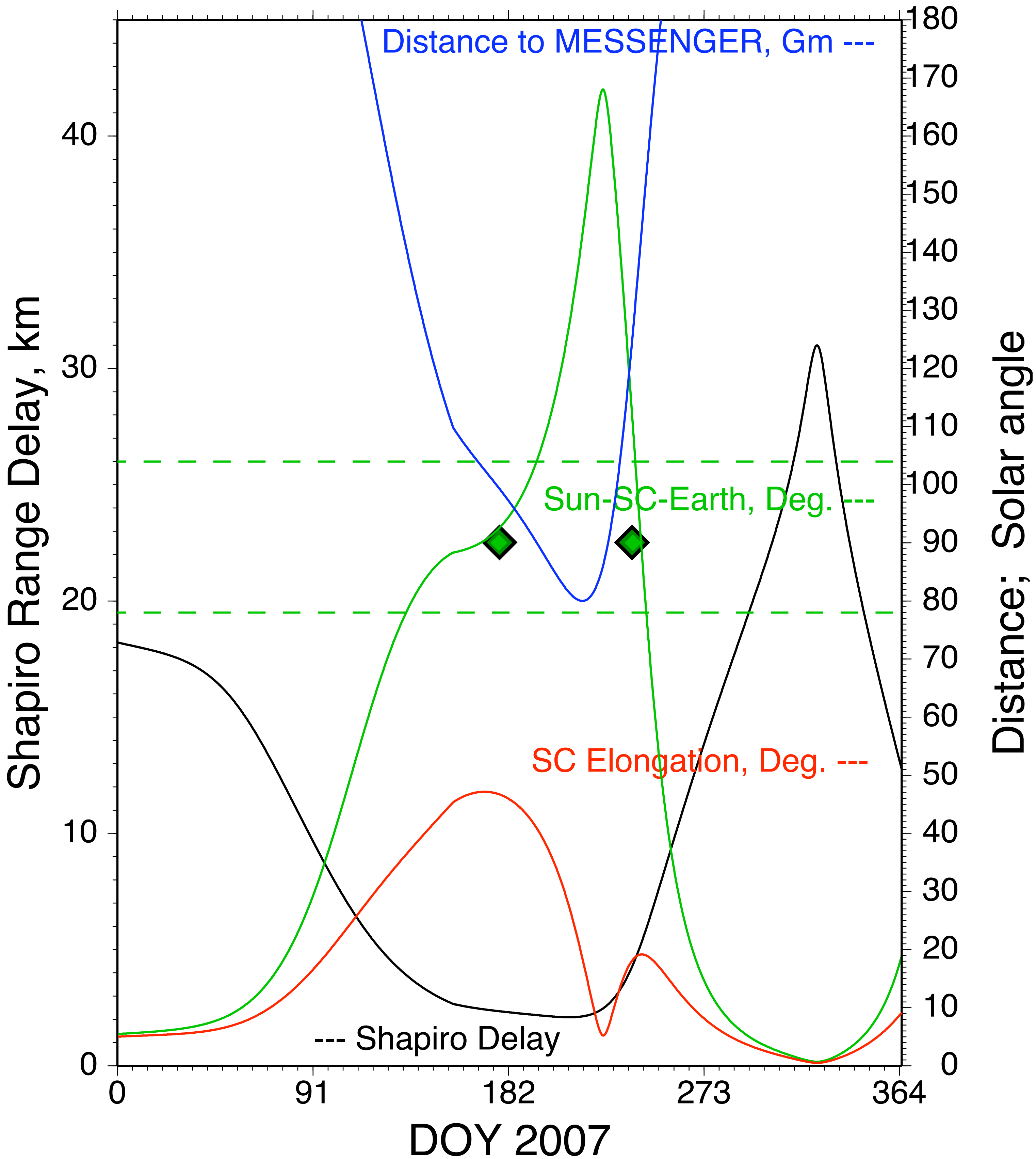
Two ranging opportunities in 2007





Sunshade axis perpendicular to instrument platform requires Sun-S/C-Earth angle ≈ 78–104°

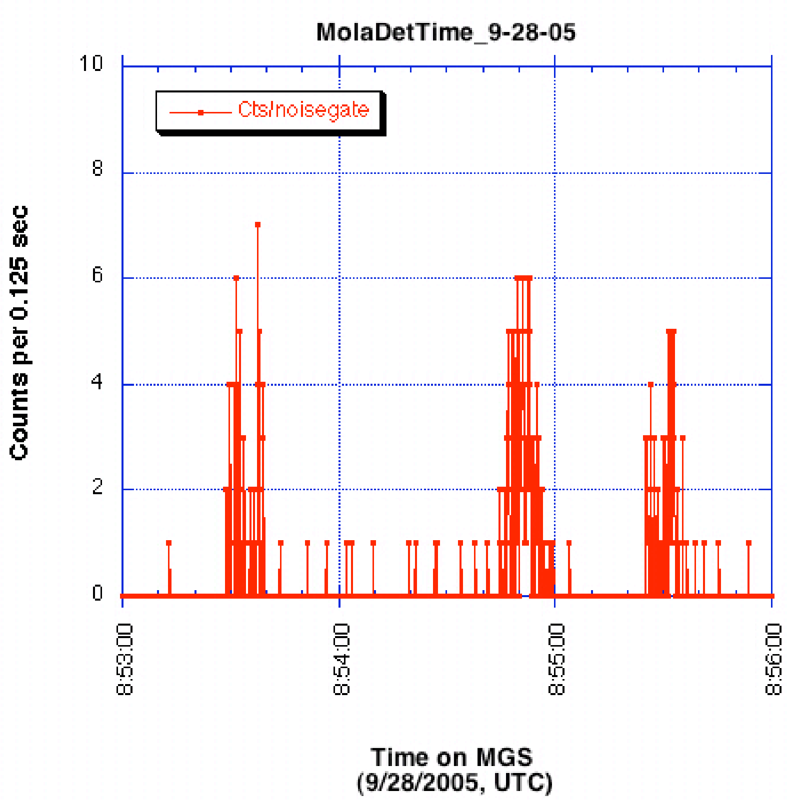
S/C elongation from Sun and ranging distance drive ground station requirements.

Relativistic effects (Shapiro time delay) peak at solar conjunction.

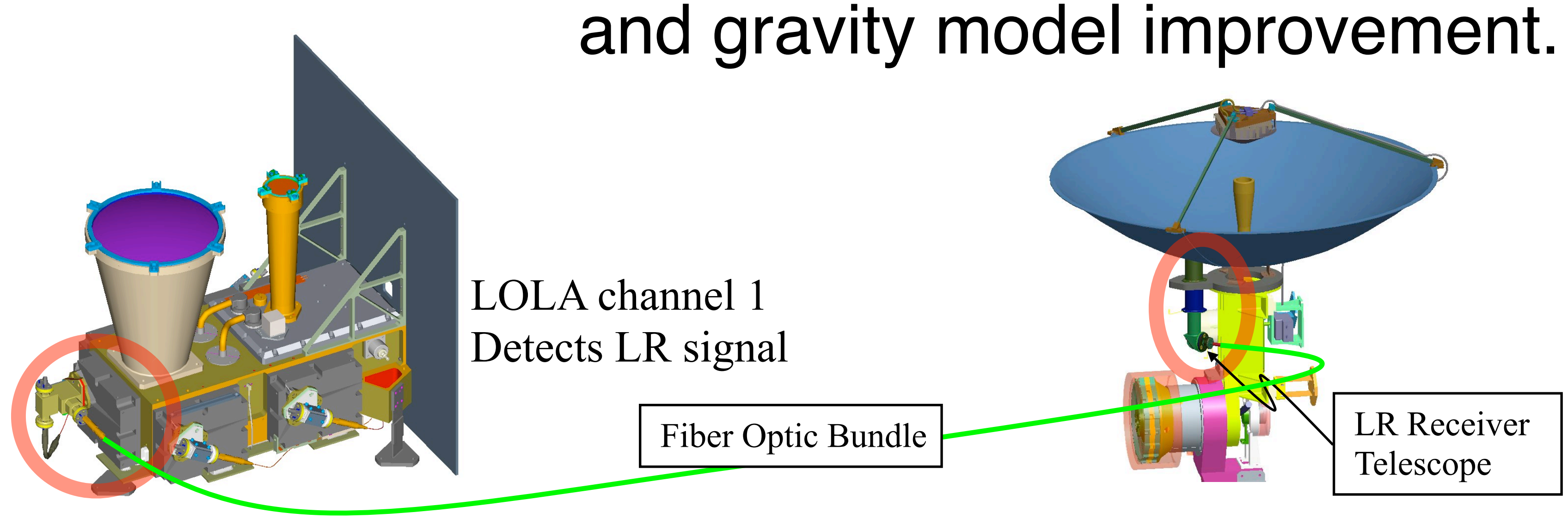
☑ LOLA-LR optical design will allow pointing within 5° of Sun

1-way Laser Ranging Experiments

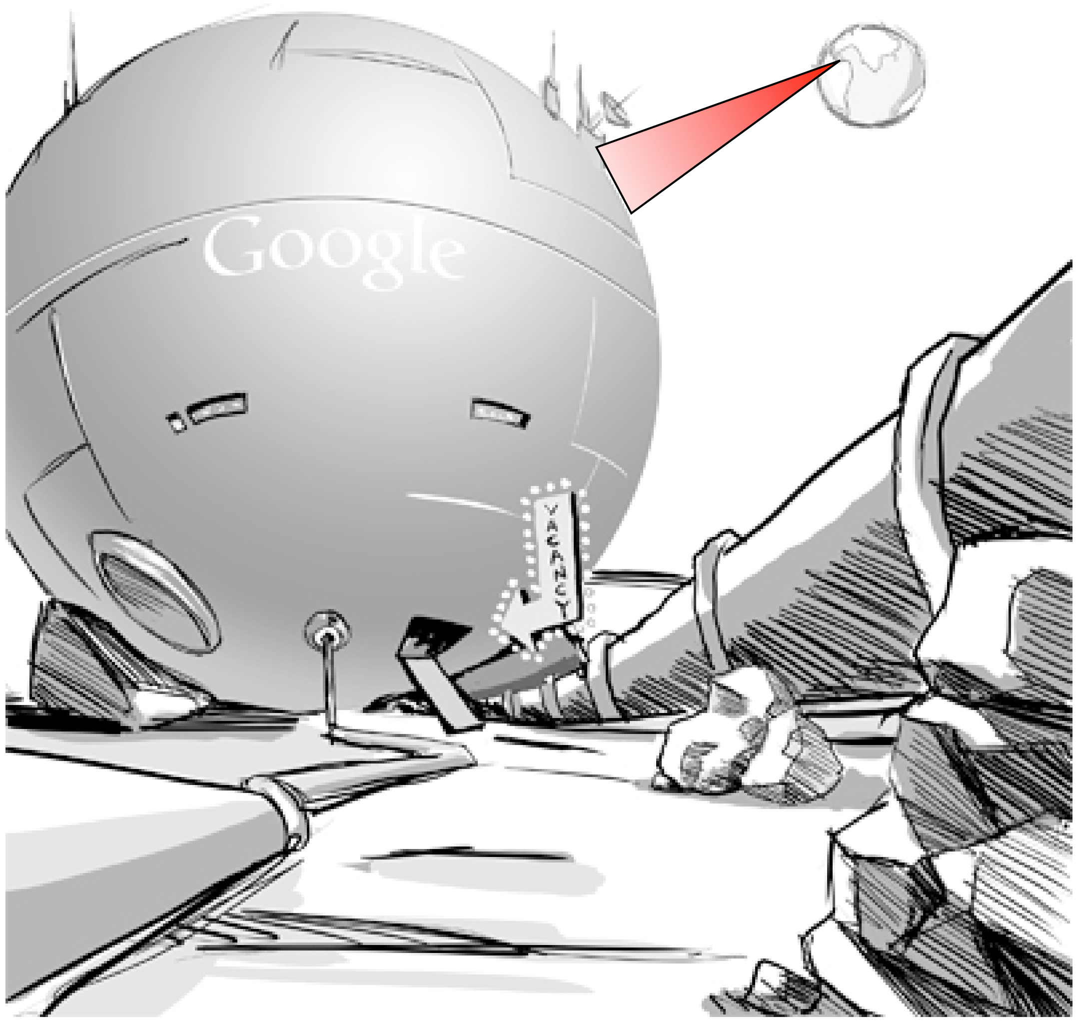
- MOLA recorded ~500 pulses fired from GGAO in Sept. 2005 at a distance of 80 Gm. Timing was relatively crude, but sufficient to characterize instrument time offset to ~10 ms.



- Lunar Reconnaissance Orbiter will use its precision oscillator and a small 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 will be used for tracking and gravity model improvement.



Summary and Conclusions



- Interplanetary laser ranging is enabled by accurate timing and narrow beam divergence. 24 Gm has been demonstrated, 80 Gm was shown to be possible, with modest facilities.
- Tracking, communication, and measurement of gravitational effects are feasible.
- Vacancy signs are on in the solar system.