The 24 Million Km Link with the Mercury Laser Altimeter

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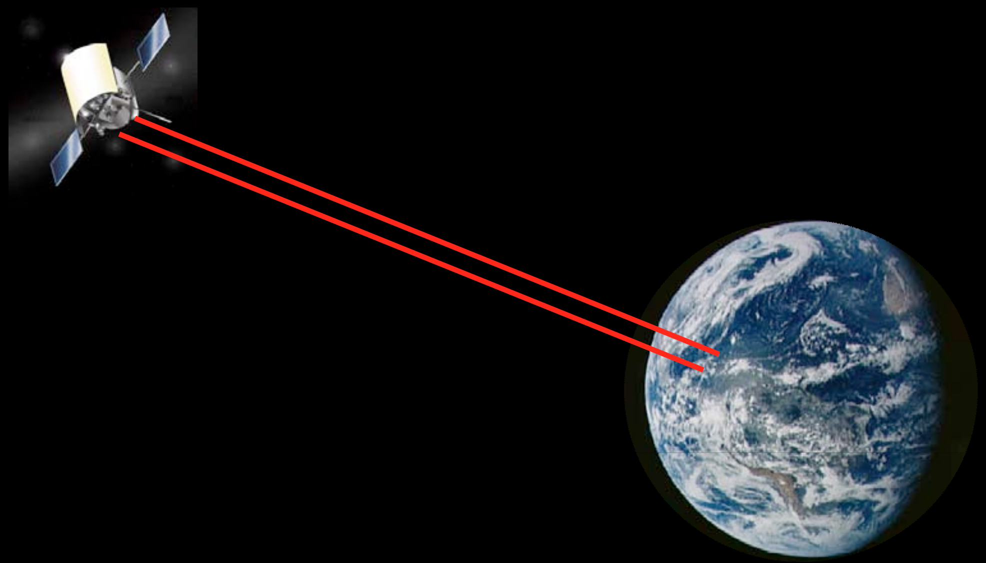

MOLA Science Team Meeting
Bishop’s Lodge, Santa Fe, NM
August 24-25, 2005

MESSENGER
Test Objectives

Messenger: MErcury Surface, Space ENvironment, GEochemistry and Ranging

6.6 year travel time to Mercury... There's not a whole lot to do during this time.

Dave Smith called a meeting and asked, "What about a transponder experiment?"

Official goals were:

- ➡ Verify laser performance; verify laser pointing and receiver boresight with respect to MESSENGER spacecraft coordinates.
- ➡ Verify MLA ranging function and performance using a ground laser to simulate backscattered pulses.
- ➡ Calibrate MLA boresight offset with Mercury Dual Image System (MDIS).

MESSENGER
Recent Publications

BREVIA

Two-Way Laser Link over Interplanetary Distance

David E. Smith,[1*] Maria T. Zuber,[1,2] Xiaoli Sun,[1] Gregory A. Neumann,[1,2] John F. Cavanaugh,[1] Jan F. McGarry,[1] Thomas W. Zagwodzki[1]

The detection and precise timing of low-energy laser pulses transmitted over interplanetary distances will enable advances in fundamental physics and solar system dynamics (*1*), as well as high-bandwidth deep-space communications (*2*, *3*). The MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) spacecraft (*4*), launched 3 August 2004, is carrying the Mercury Laser Altimeter (MLA) (*5*) as part of its instrument suite on its 6.6-year voyage to Mercury. In an experiment performed before an Earth flyby, the MLA successfully ranged to Earth and received laser pulses from the NASA Goddard Geophysical and Astronomical Observatory (GGAO) (*6*).

The only other deep-space laser ranging demonstration occurred before MLA in 1992, when two ground-based lasers were pointed toward the Galileo spacecraft and the signals were detected at a distance of 6 × 10⁶ km as streaks of light by the spacecraft's camera (*7*). In contrast, the MLA Earth-ranging experiment operated like an asynchronous transponder (*8*), in which space-based and Earth-based laser terminals independently fired timed pulses at each other, with the transmitted and received pulse times linked by means of a stable spacecraft clock. The times of the paired observations were used to solve for a common range and clock offset (*6*).

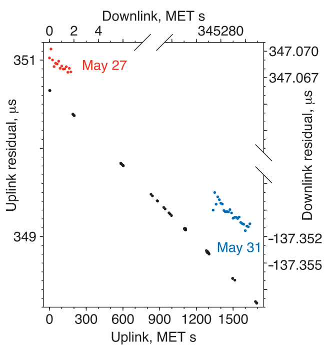

Fig. 1. Pulse-received times at MLA and GGAO. The graph shows that ground laser pulses (black symbols) were received by MLA ~0.35 ms earlier than predicted. Similarly, the ground-receive time of MLA pulses was ~0.34 ms earlier on 27 May (red symbols) but ~0.14 ms later on 31 May (blue symbols).

The MESSENGER spacecraft clock is an ovenized quartz oscillator (*4*) that measures mission elapsed time (MET) and is periodically synchronized to coordinated universal time (UTC) by the terrestrial reference system terrestrial dynamic time. Over the test period 26 to 31 May 2005, the spacecraft clock, to which the MLA is periodically calibrated, was stable to approximately one part per billion (ppb).

In three observing opportunities, the MLA laser was fired for 5-hour periods while the spacecraft scanned Earth at a rate of 16 μrad s^{-1} along lines spaced 32 μrad apart, for a total scan area of 3.2 by 3.2 mrad. Event timers logged pulse transmission and arrival times at GGAO, referenced to UTC within 100 ns absolute time. A digital oscilloscope at a frequency of 1 GHz also recorded the received pulse shapes. Sixteen consecutive pulses were recorded at 19:47:24 UTC on 27 and 24 May; more were recorded at 19:42:02 UTC on 31 May.

Simultaneously, a laser at GGAO was beamed upward toward MLA. The uplink pulses, along with noise triggers from the sunlit Earth, were received within a 15-ms range window during each 125-ms shot interval. Inspection of the stored instrument data revealed 90 pulses over a 30-min time frame, 17 on multiple channels, whose timing matched the GGAO fire times.

The interpretation of these events as downlink and uplink ranges required a joint solution (*6*) for spacecraft clock and state parameters (Fig. 1). The solution yielded a clock offset and drift rate at the origin time and the range as a function of time at the spacecraft (Table 1) (*9*). Downlink observations were fit with a root mean square residual of 0.39 ns, whereas uplink observations suffered from marginal signal link and were fit with an rms residual of 2.9 ns. Formal standard deviations indicate that the range was determined with an accuracy of ±20 cm. Our range agrees with that derived from the reconstructed ephemeris from X-band Doppler tracking (7.2 GHz uplink; 8.4 GHz downlink) to within 52 m. This experiment has demonstrated subnanosecond laser pulse timing and accomplished a two-way laser link at interplanetary distance. In addition, it established a distance record for laser transmission and detection.

Table 1. Solution parameters.

Parameter	Laser link solution	Spacecraft ephemeris	Difference
Range (m)	23,964,675,433.9 ± 0.2	23,964,675,381.3	52.6
Range rate (m s^{-1})	4,154.663 ± 0.144	4,154.601	0.062
Acceleration (mm s^{-2})	–0.0102 ± 0.0004	–0.0087	–0.0015
Time (s)	71,163.729670967 ± 6.6 × 10^{-10}	71,163.730019659	0.000348692
Clock drift rate (ppb)	1.00000001559 ± 4.8 × 10^{-10}	1.00000001564	–3.2 × 10^{-10}

References and Notes

1. D. E. Smith, M. T. Zuber, J. J. Degnan, J. B. Abshire, paper presented at Marcel Grossman 8, Jerusalem, 1997.
2. J. Bland-Hawthorn, A. Harwit, M. Harwit, *Science* **523**, 293 (2002).
3. B. L. Edwards *et al.*, paper presented at *AIAA* (2003).
4. A. G. Santo *et al.*, *Planet. Space Sci.* **49**, 1481 (2001).
5. J. F. Cavanaugh *et al.*, in preparation.
6. Materials and methods are available as supporting material on *Science* Online.
7. K. E. Wilson, J. R. Lesh, T.-Y. Yan, *Proc. SPIE* **1866**, 138 (1993).
8. J. J. Degnan, *J. Geodynam.* **34**, 551 (2002).
9. The range is not a true geometric time of flight because both terminals are accelerating, but the round-trip time is adequately constrained in this fashion.
10. We gratefully acknowledge the efforts of the MESSENGER spacecraft team, the MLA instrument team, and the staff of NASA's GGAO. The MESSENGER Project is supported by NASA's Discovery Program.

Supporting Online Material
www.sciencemag.org/cgi/content/full/311/5757/53/DC1
Materials and Methods
Table S1
References and Notes

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10.1126/science.1120091

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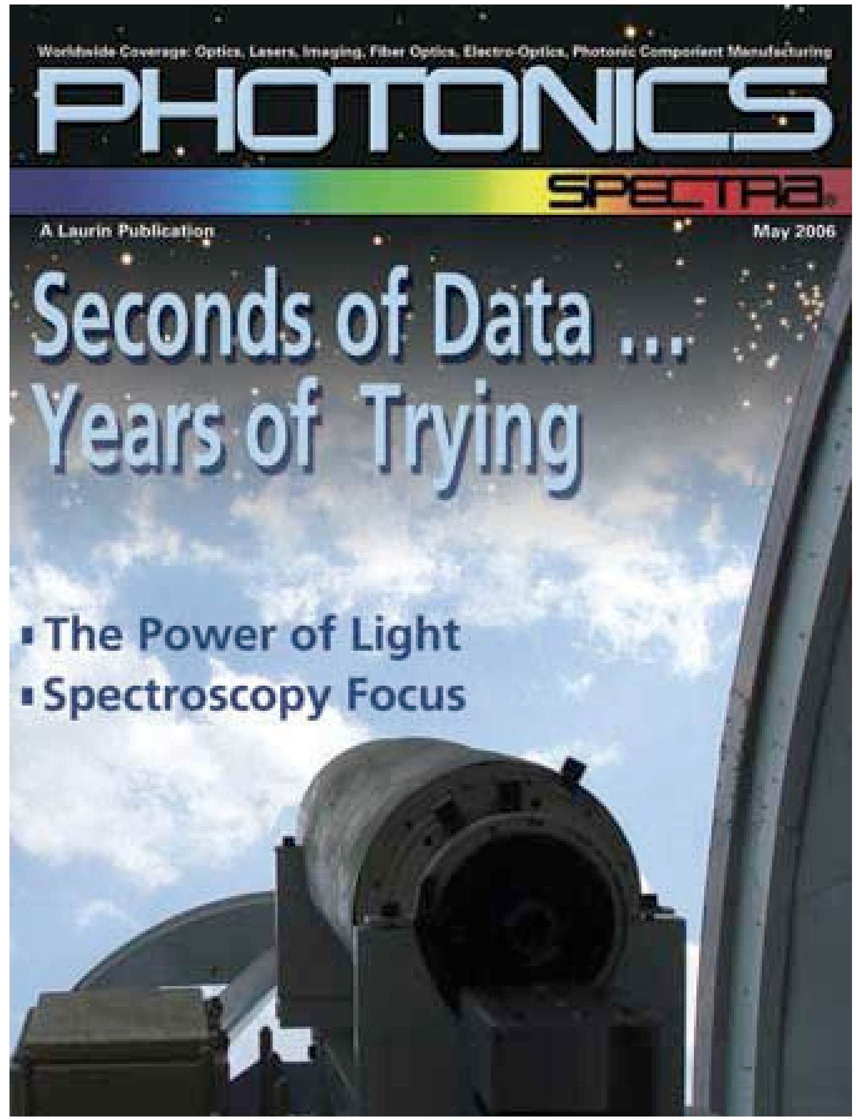
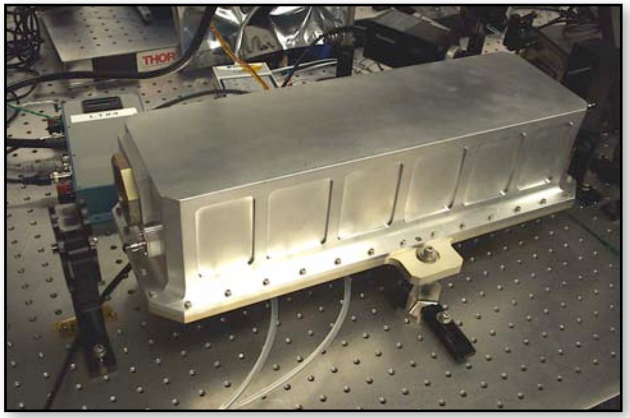


MESSENGER
Ground Station and Spacecraft Parameters

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

MESSENGER/ MLA

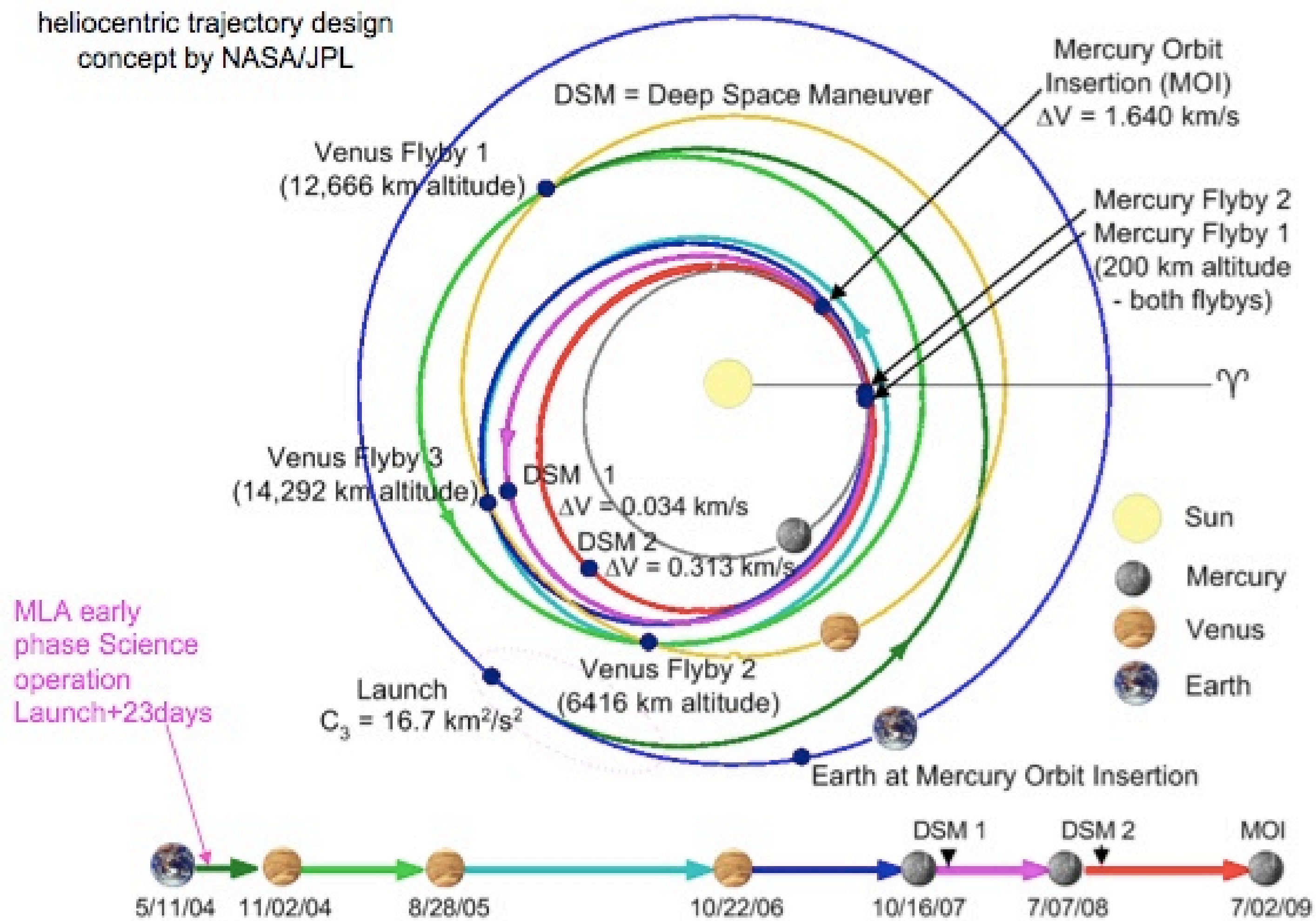


GGAO/ Homer-1

HOMER ran at 17 mJ/pulse

MESSENGER

Spacecraft Transit to Mercury



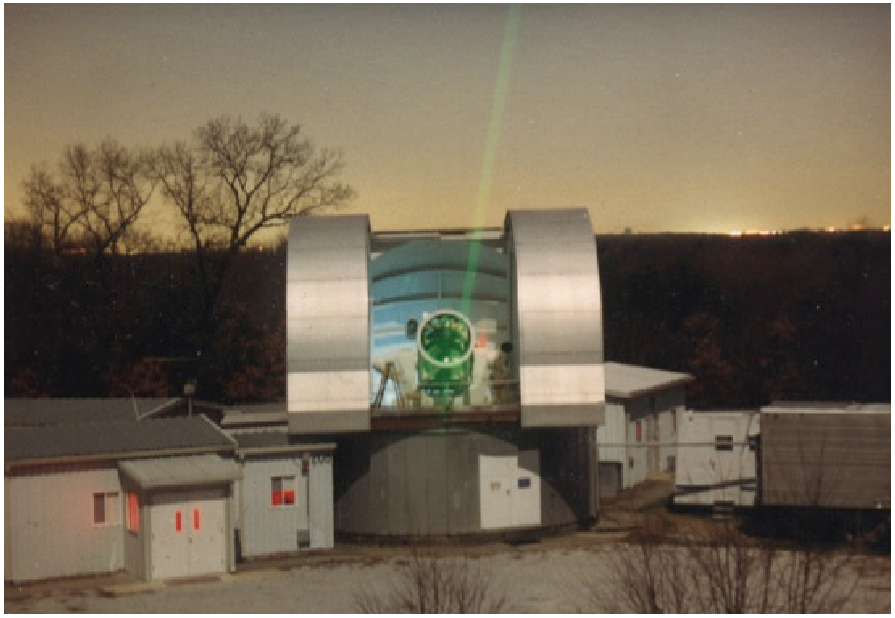
GGAO/
Homer-1

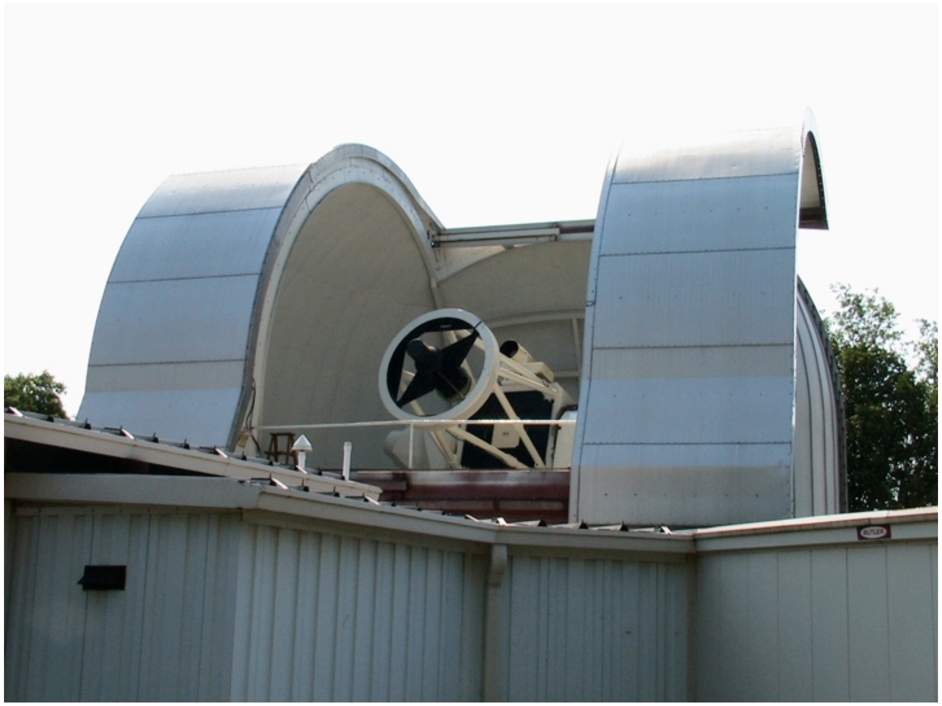
MESSENGER

Ground Station Hardware

Goddard Geophysics and Astronomical Observatory (GGAO)1.2 meter telescope for satellite laser ranging (SLR).

Part of the original SLR global network for monitoring continental drift and technology development.



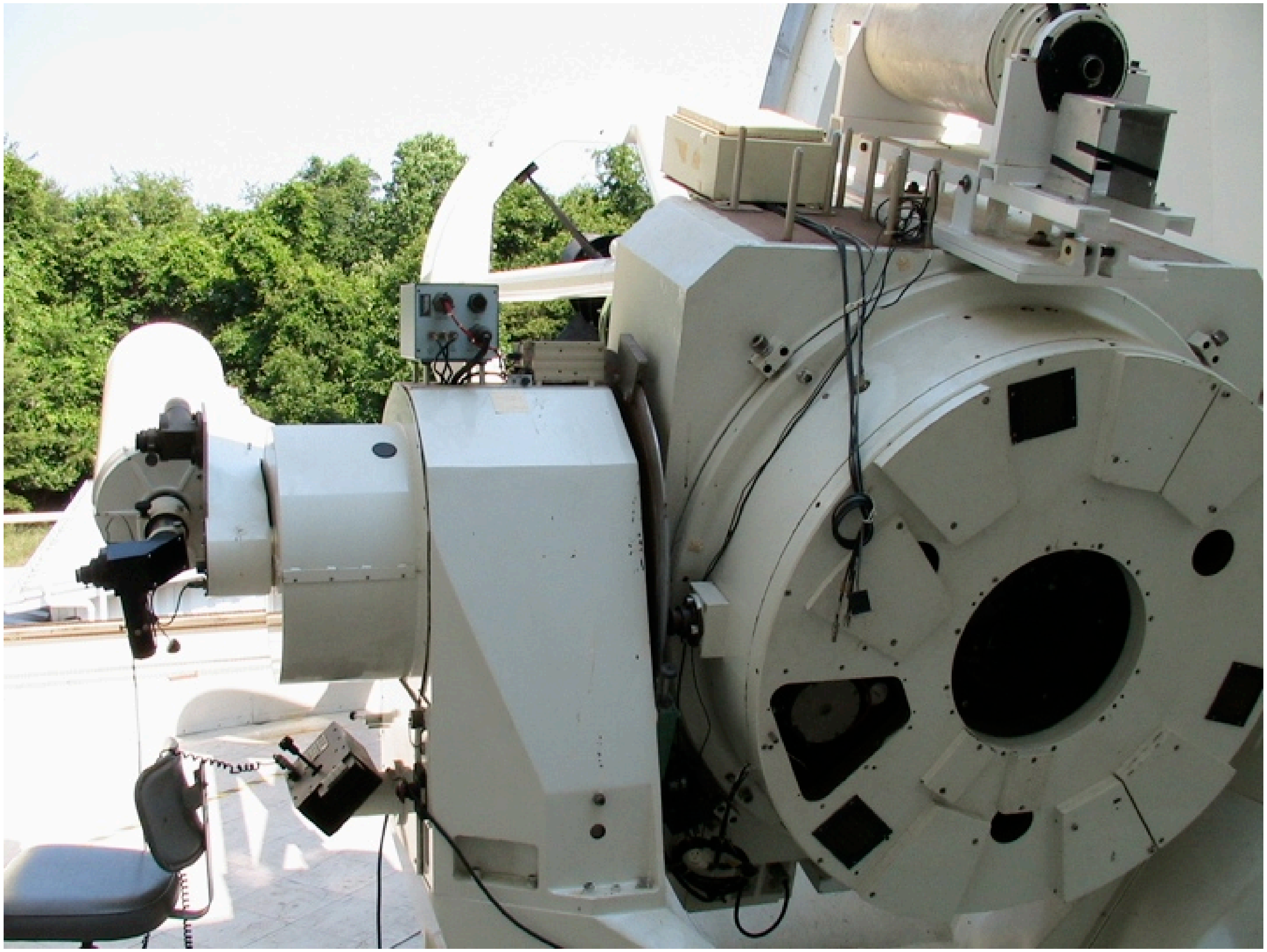


MESSENGER

Ground Station

MESSENGER

Ground Station



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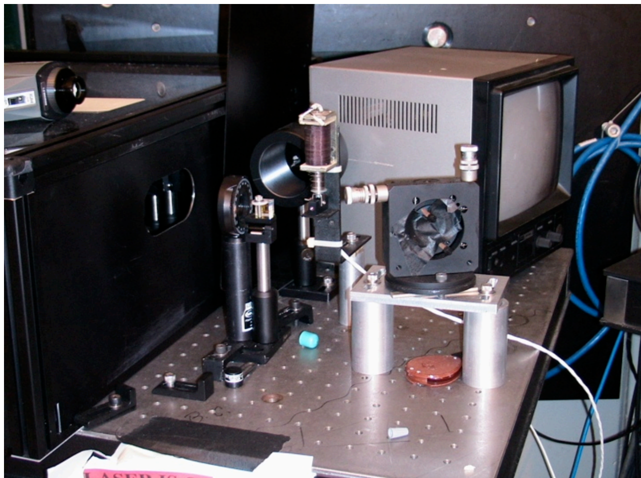
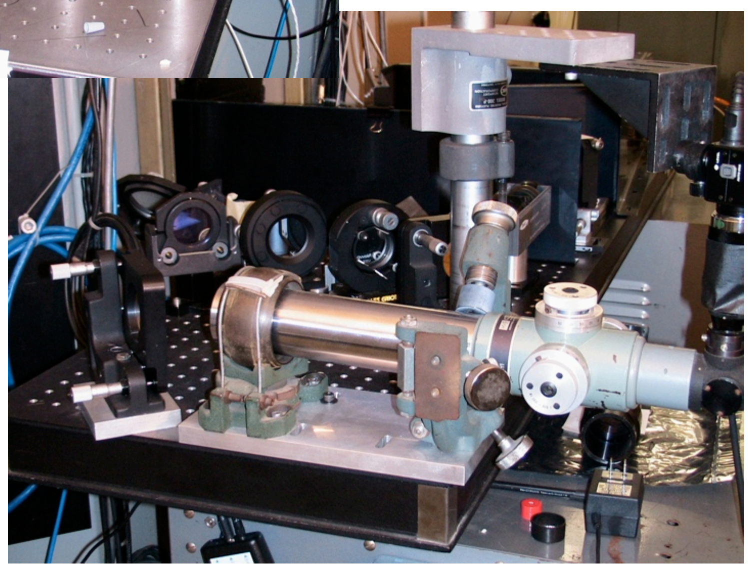
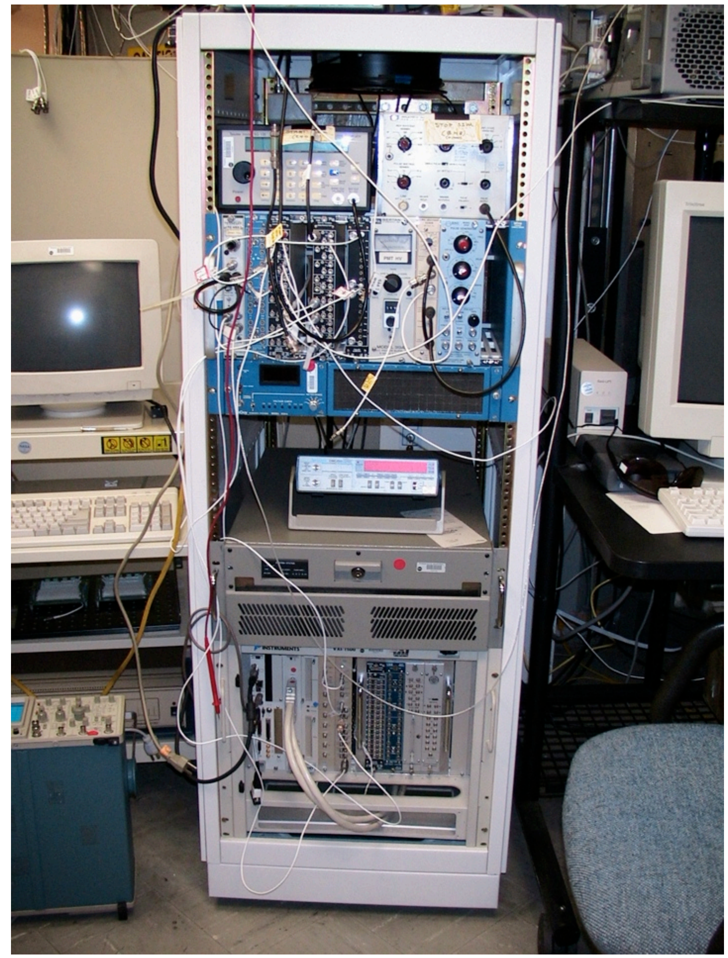
Ground Station



Ground Station
Laser Transmitter
HOMER



Transmit & beam shaping optics



TOF Receiptver Electronics

MESSENGER

Ground Station Laser

- MLA Link Experiment provided unique opportunity to gather long term data on next generation flight quality laser design.
- Long term runs can be expensive and tie up equipment and lab space. We were able to gather ~ 2 Billion shots on this design over 3 months.
- Automated installation allowed no impact to MLA Link experiment. Employed a digital flip mirror with no effect on pointing and provided in situ laser performance data during for link calculations.

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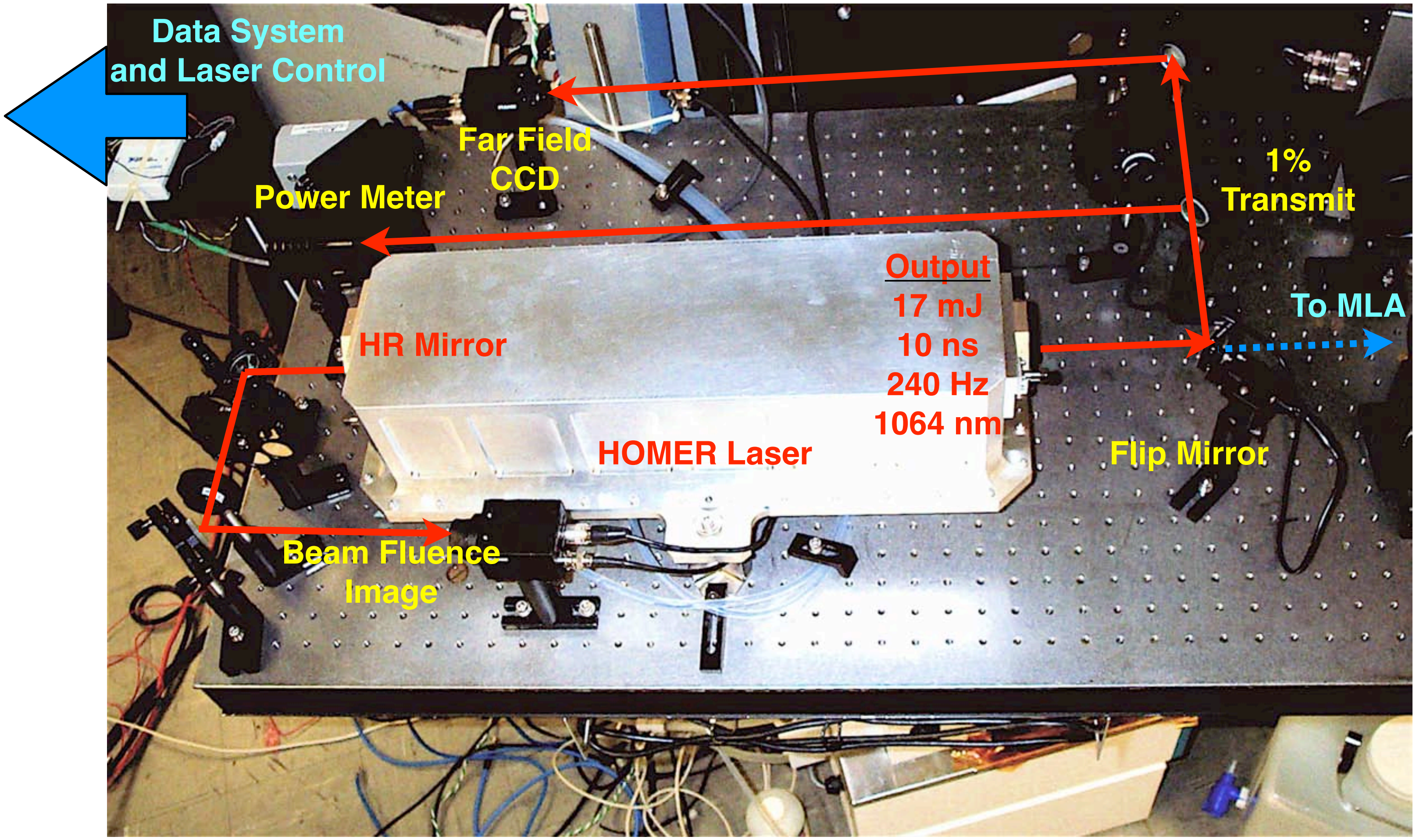
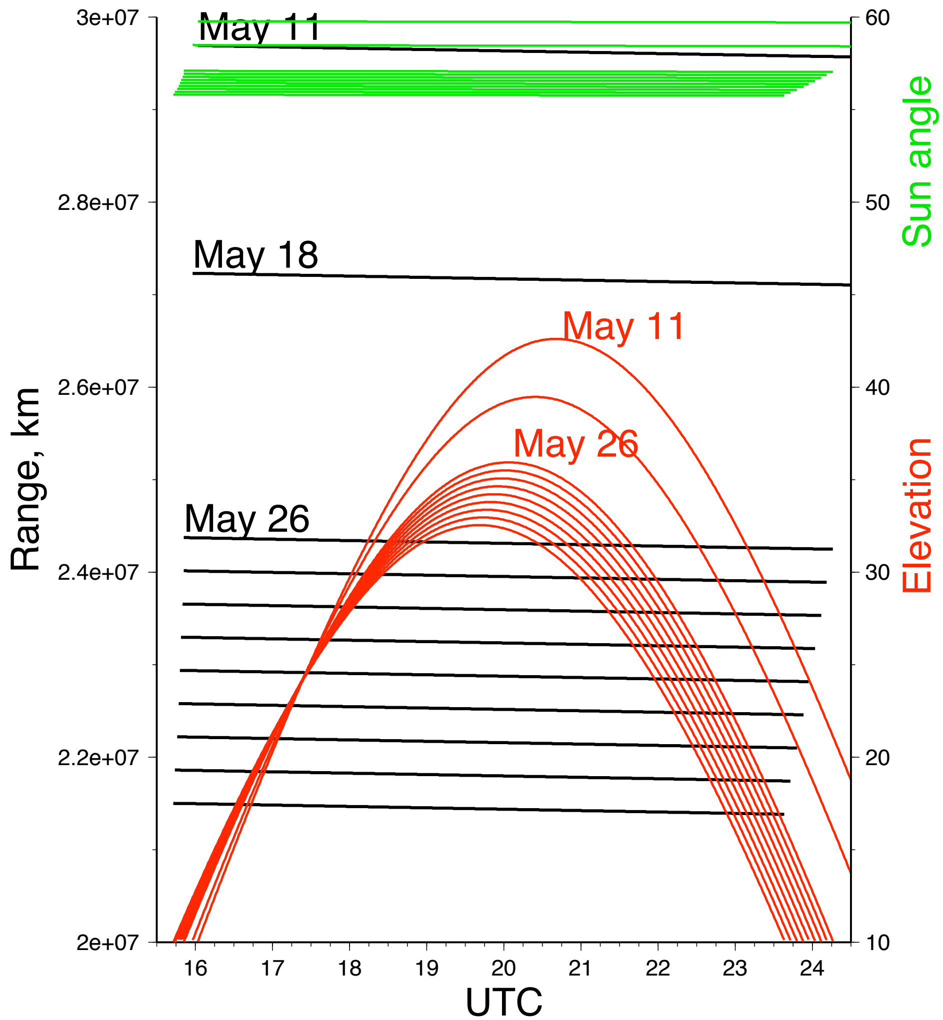
Ground Station Laser: Extended Run Experiment



MESSENGER
Spacecraft Trajectory & Viewing from GGAO



Scan start time (UTC)

Passive Scans:

5/11/2005 18:40:28
5/18/2005 18:24:00
(scan duration: 4hr 0’ 10”

Laser Scans:

5/26/2005 17:14:00
5/27/2005 17:11:00
5/31/2005 16:59:00
(scan duration: 5 hr 41’ 40”

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Scan Pattern

- Passive raster scan over 7x7 mrad area, 70 rows, 100 μrad spacing between rows (8000 km detector diameter area on Earth).
- Active raster scan over 3.2 x 3.2 mrad area, 100 rows, 32 μrad spacing between rows, with pause in the middle pointing at GSFC.
- Scan rate 16 μrad s^{-1} on each row (1800 km diameter, maximum of 5 sec laser illumination on any spot on Earth).
- 200 sec/row; 100 sec pause at center of scan for a total of 5 hr 41 min 40 sec. ??? check these numbers
- Starting time for scans programmed so that middle of scan occurs at max elevation angle from GSFC to MESSENGER.
- MDIS images sunlit Earth at start, middle and end of scan to provide cross calibration between MLA and MDIS.

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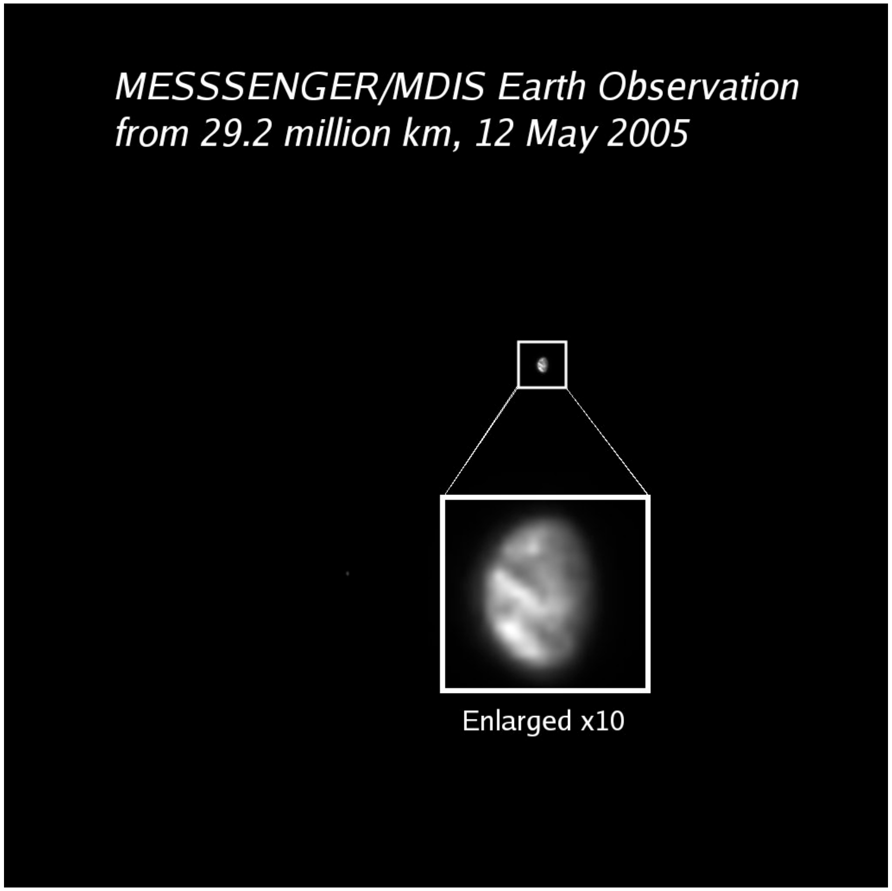
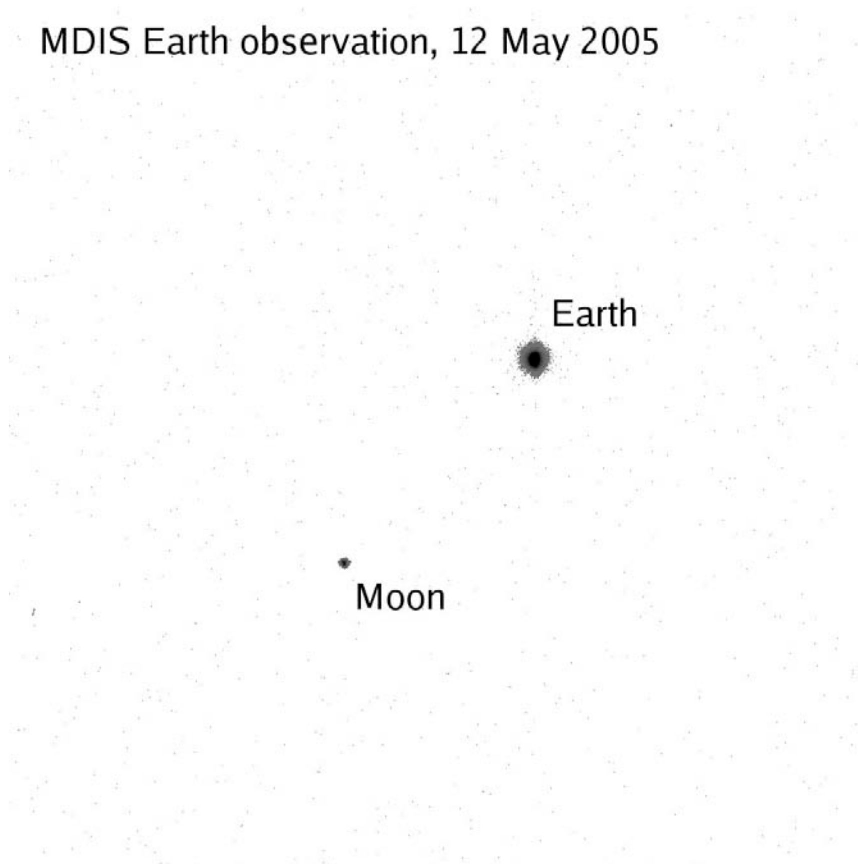
Earth from MDIS





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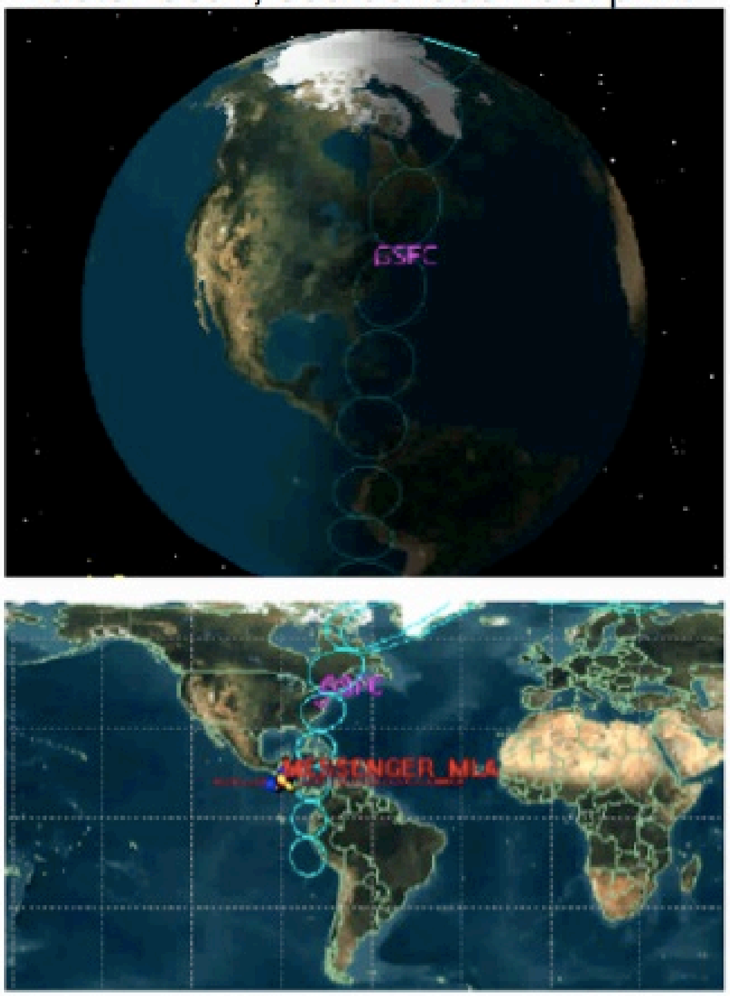
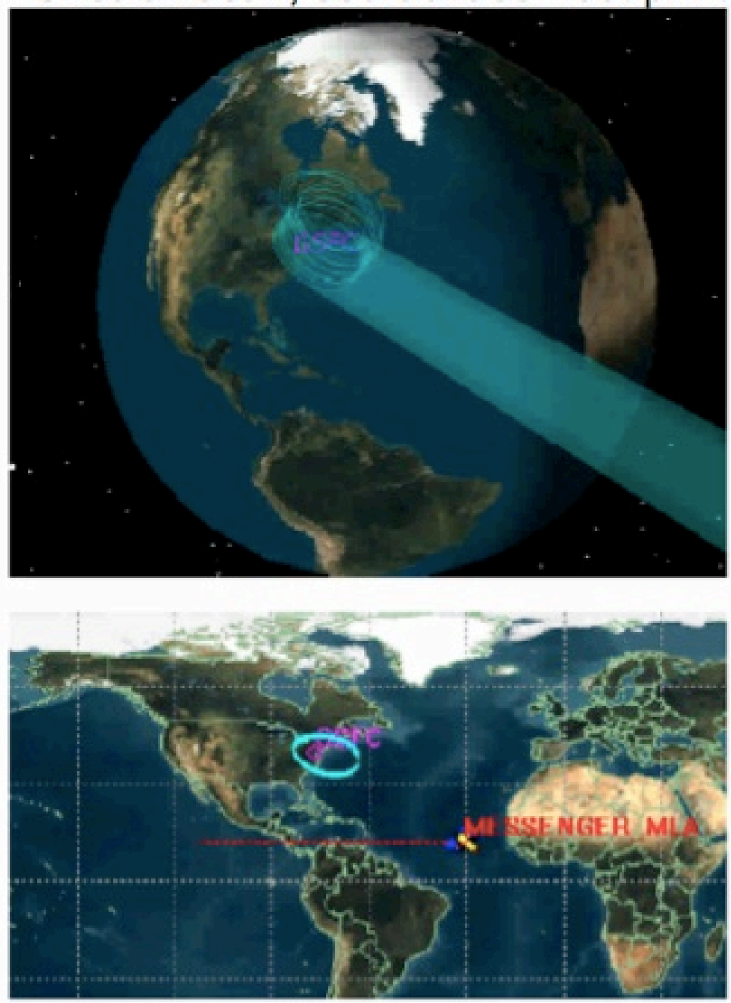
Sample Earth Scan Patterns

Gene Heyler/APL Nov. 2003

Raster Scan, 80urad laser foot print



Circular Scan, 80urad laser foot print

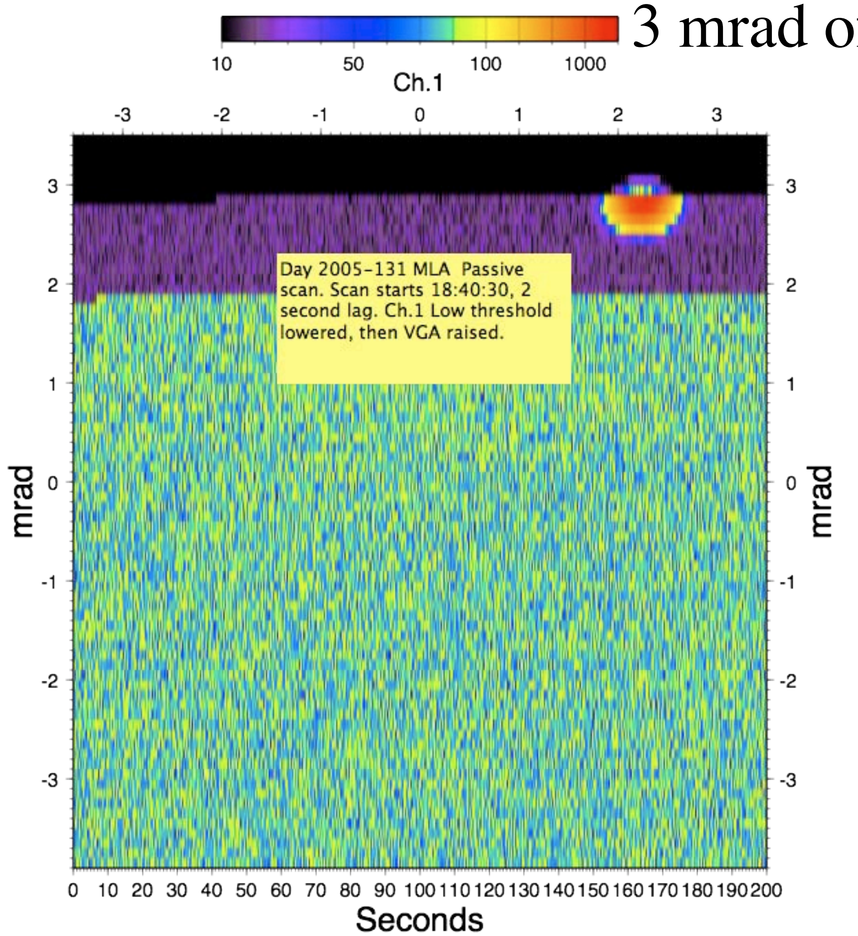


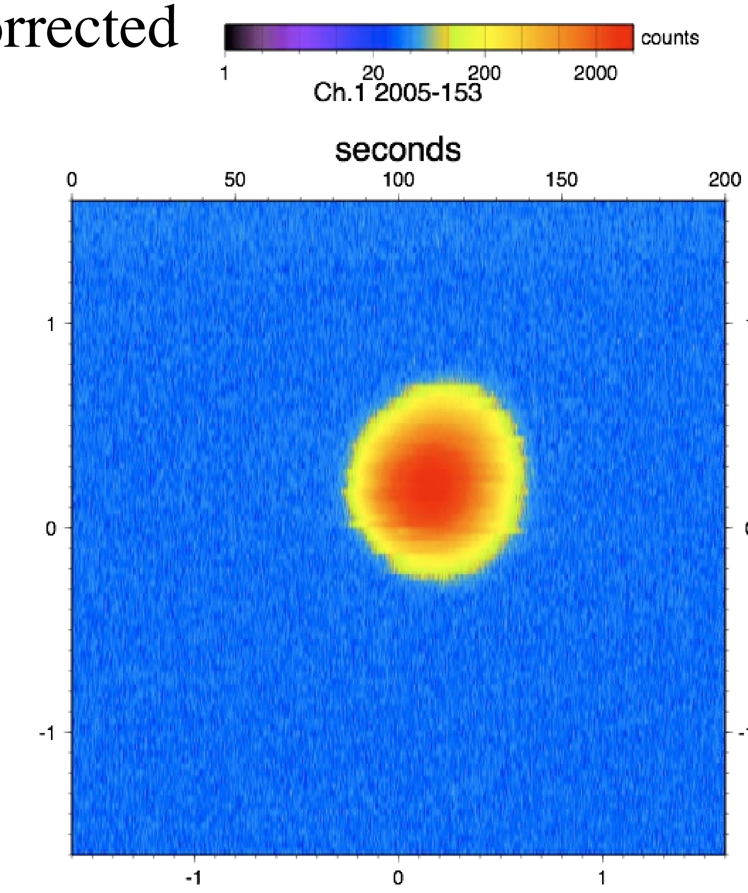
MESSENGER

Earth at 1064 nm

- Preliminary passive scans to test pointing and alignment.

3 mrad offset -> corrected





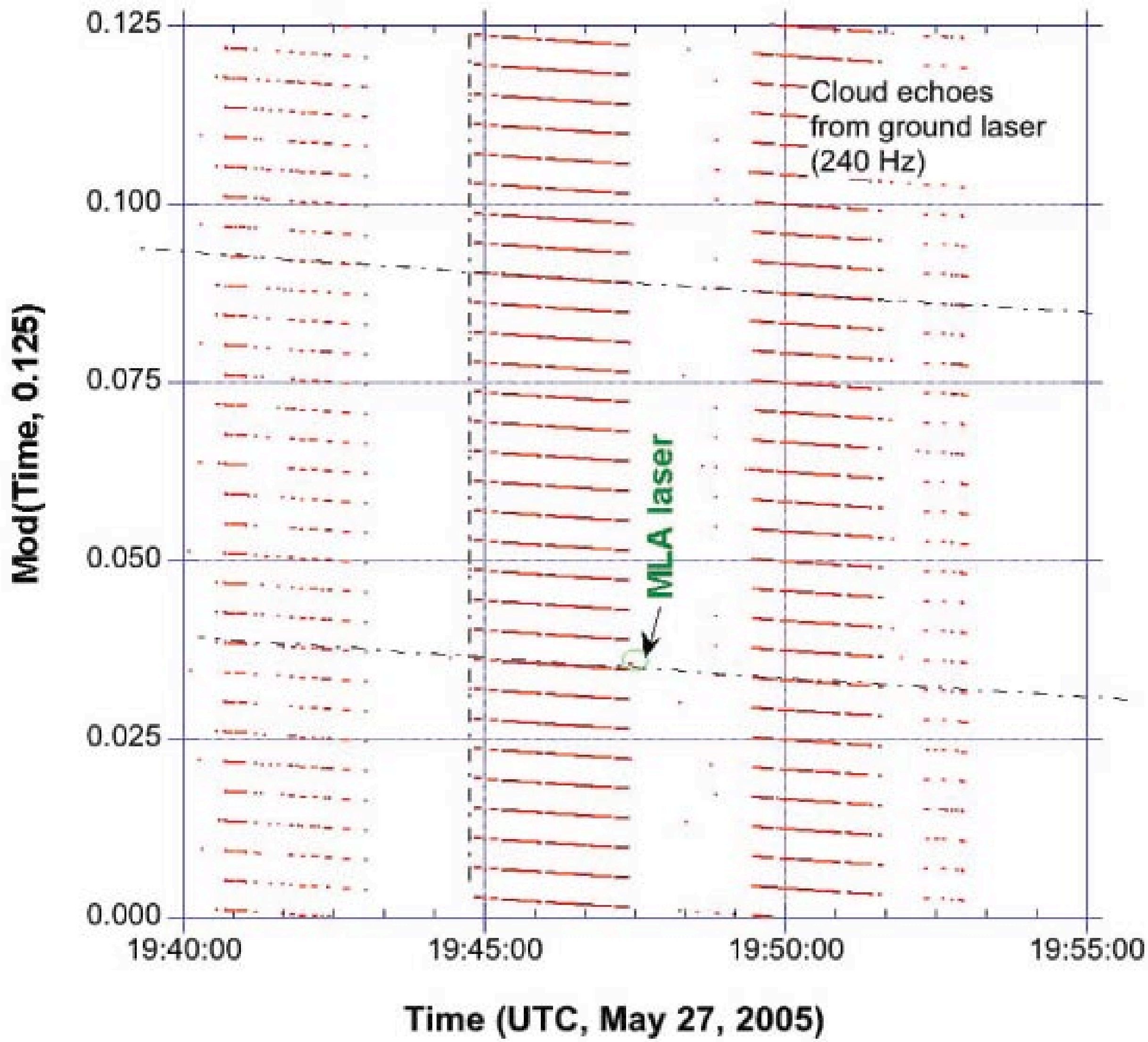
MESSENGER

Pulse Arrival Times: 05/27/05

(Red data)
Ground station TOF data from HOMER laser striking clouds

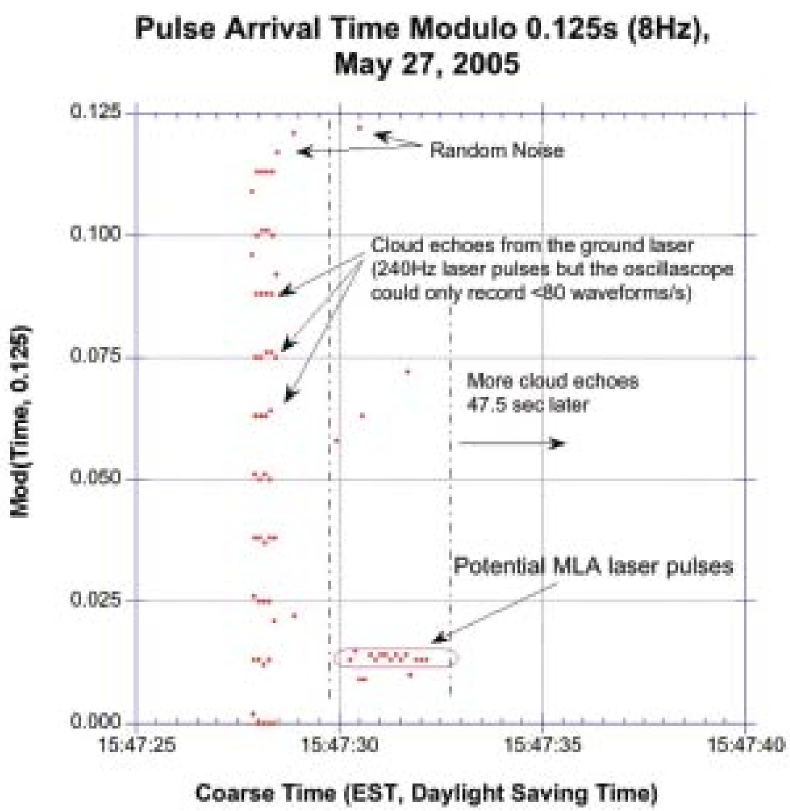
The MLA laser's (default operation @ 8 Hz) received pulses at GGOA are seen in lower 3rd of plot overlapping the cloud data.

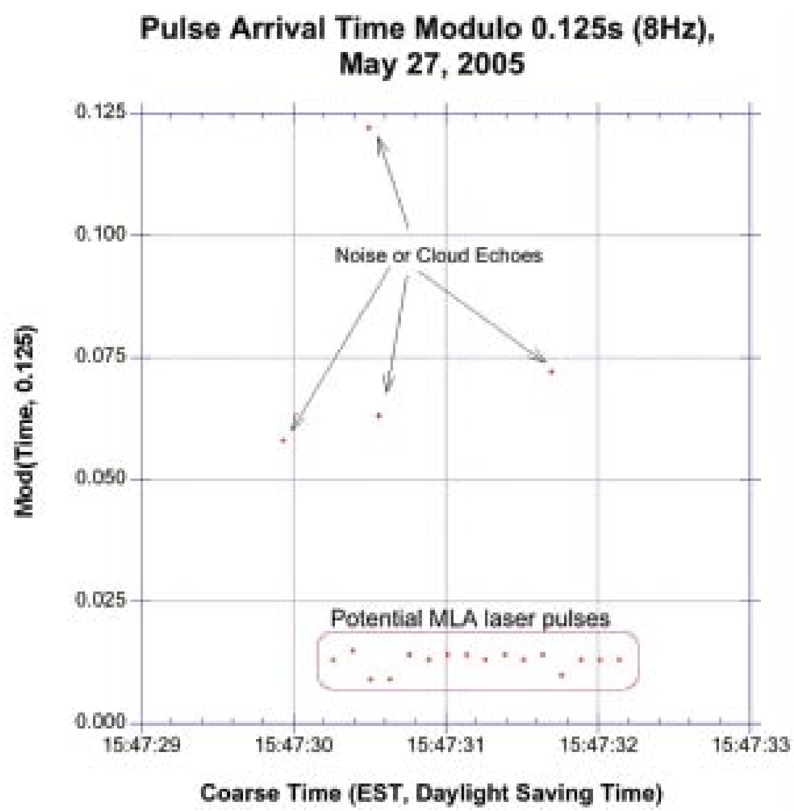
3 attempts made to "see" MLA: May 24, 27, 31



MESSENGER

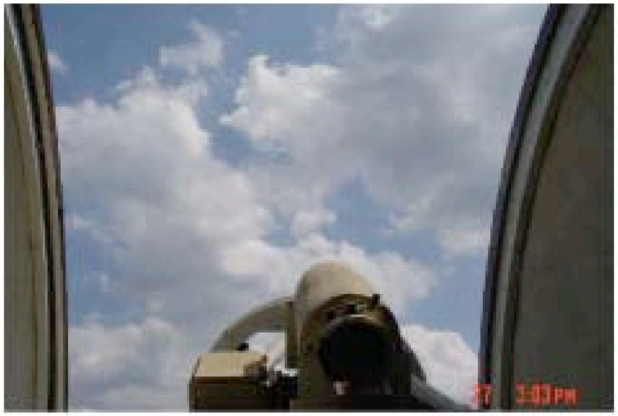
Pulse Arrival Times: 05/27/05



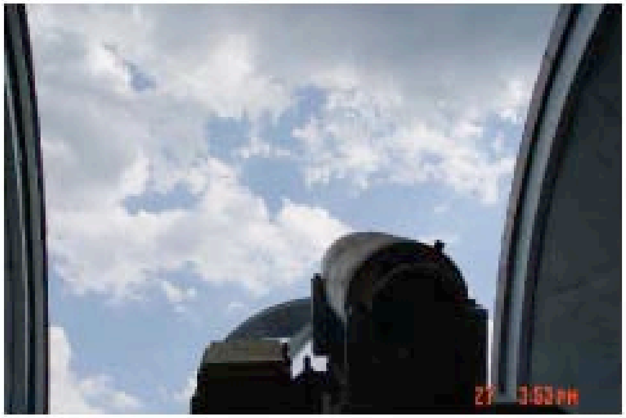


MESSENGER
Weather -- 05/27/05

45 minutes earlier



6 minutes later



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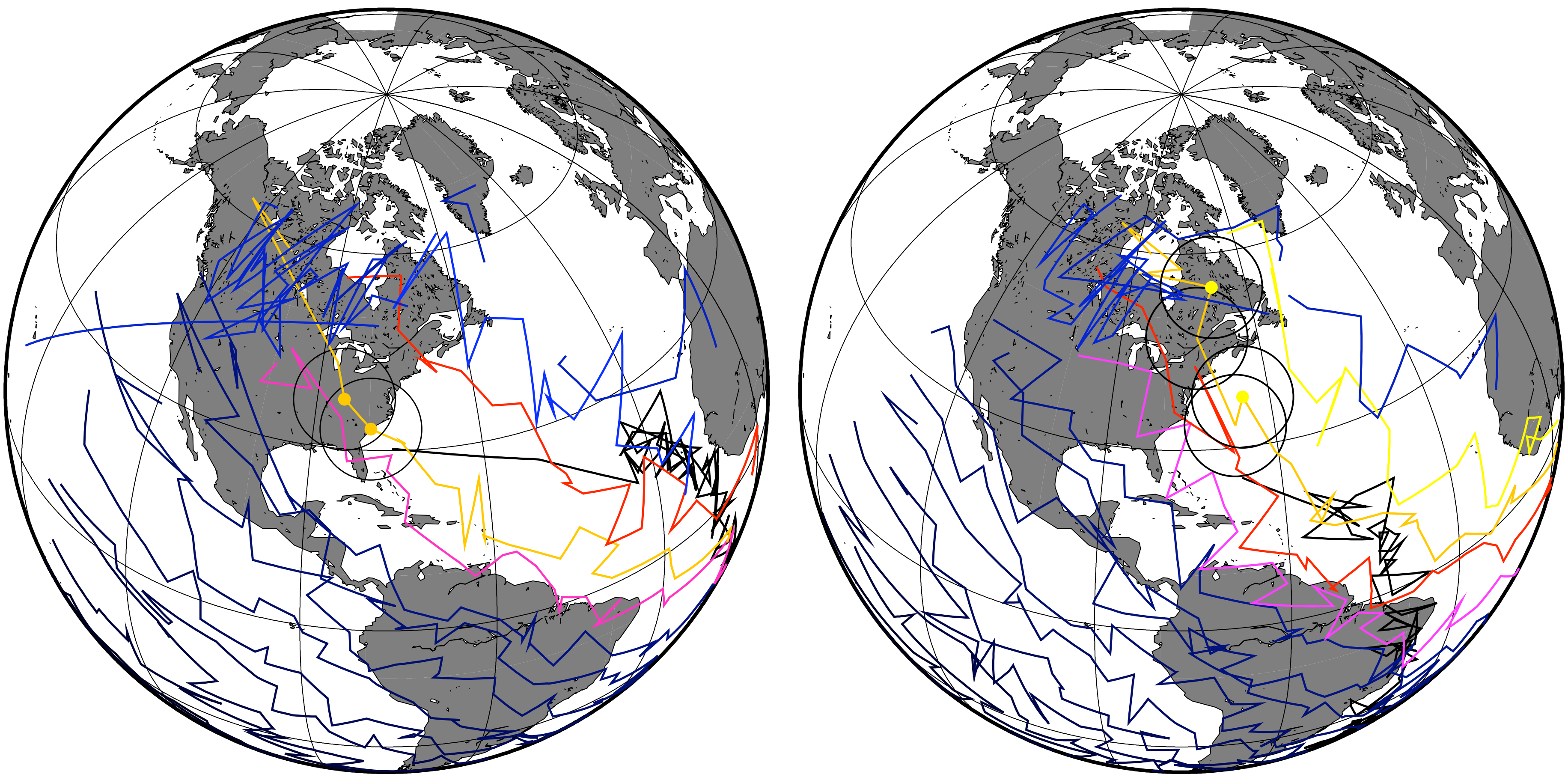
Reconstructed MLA Tracks

Yellow dots show reconstructed laser spots at 1 s intervals.



05/27/05 05/31/05

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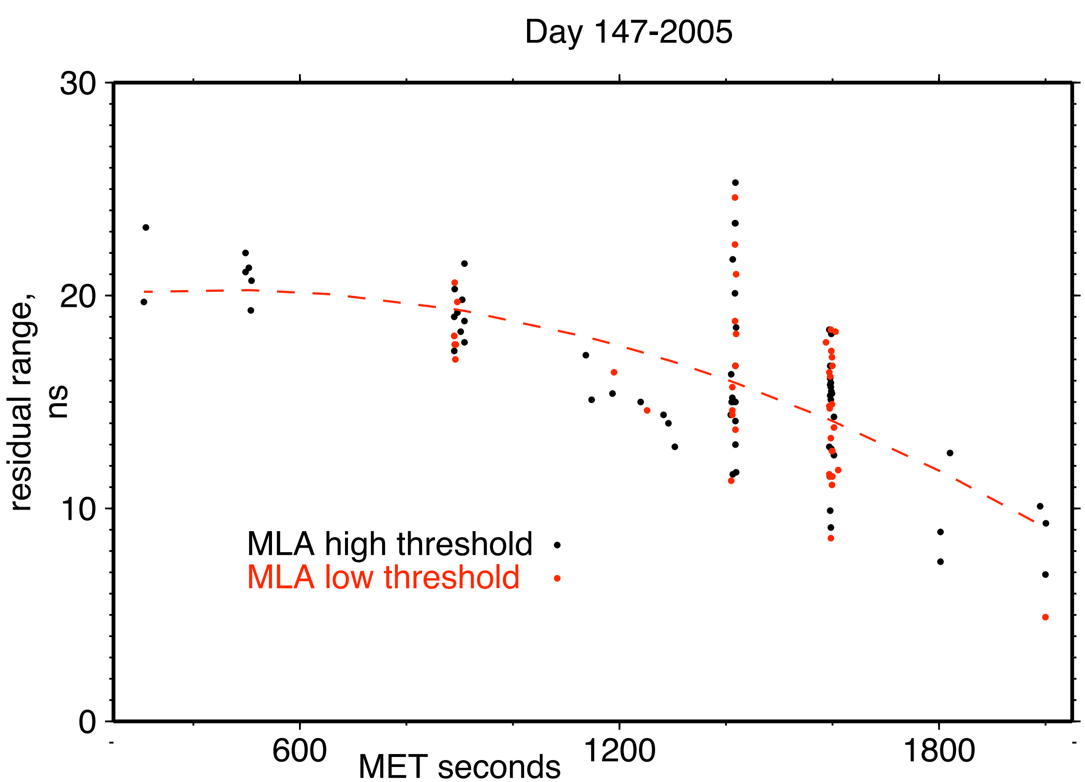
Uplink data

Residual from linear fit



HOMER output 17 mJ pulses at 240 Hz. Detector scanned across beam at ~200 s intervals.

Link margin at MLA much lower than downlink, owing to smaller aperture and low transmission of ground telescope (~12%). At best alignment, only 4% of HOMER shots detected, but thousands of noise returns.

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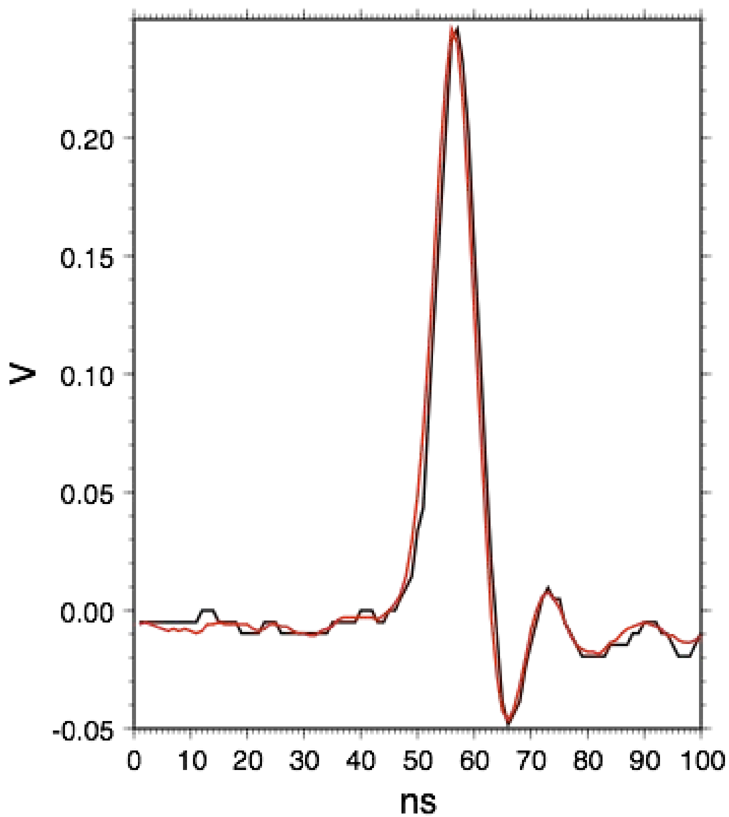
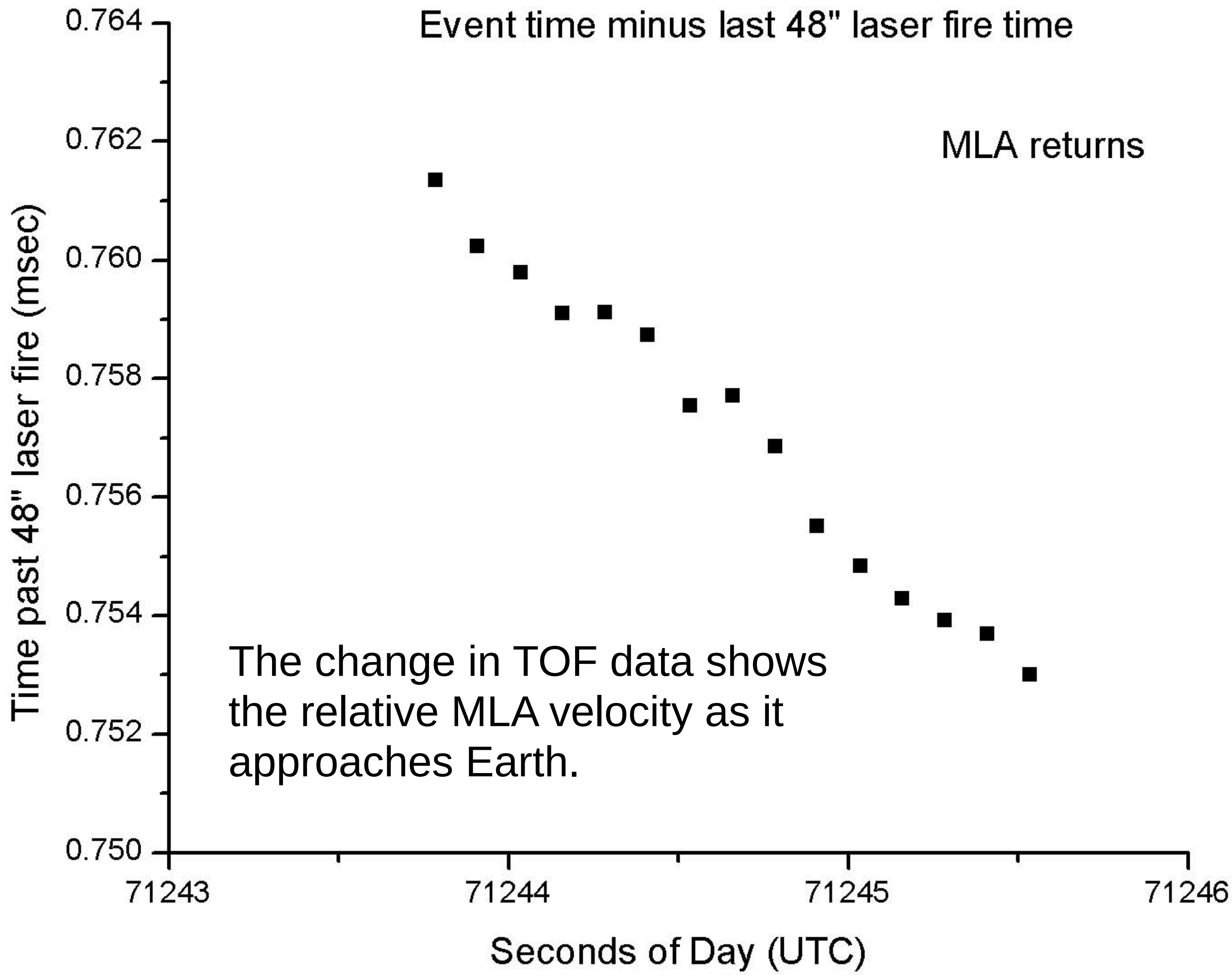
Downlink Waveform



Individual (black) and averaged (red) waveforms match laser characteristics convolved with detector/preamp response

MESSENGER
MLA Earthlink: 05/27/05



The change in TOF data shows the relative MLA velocity as it approaches Earth.

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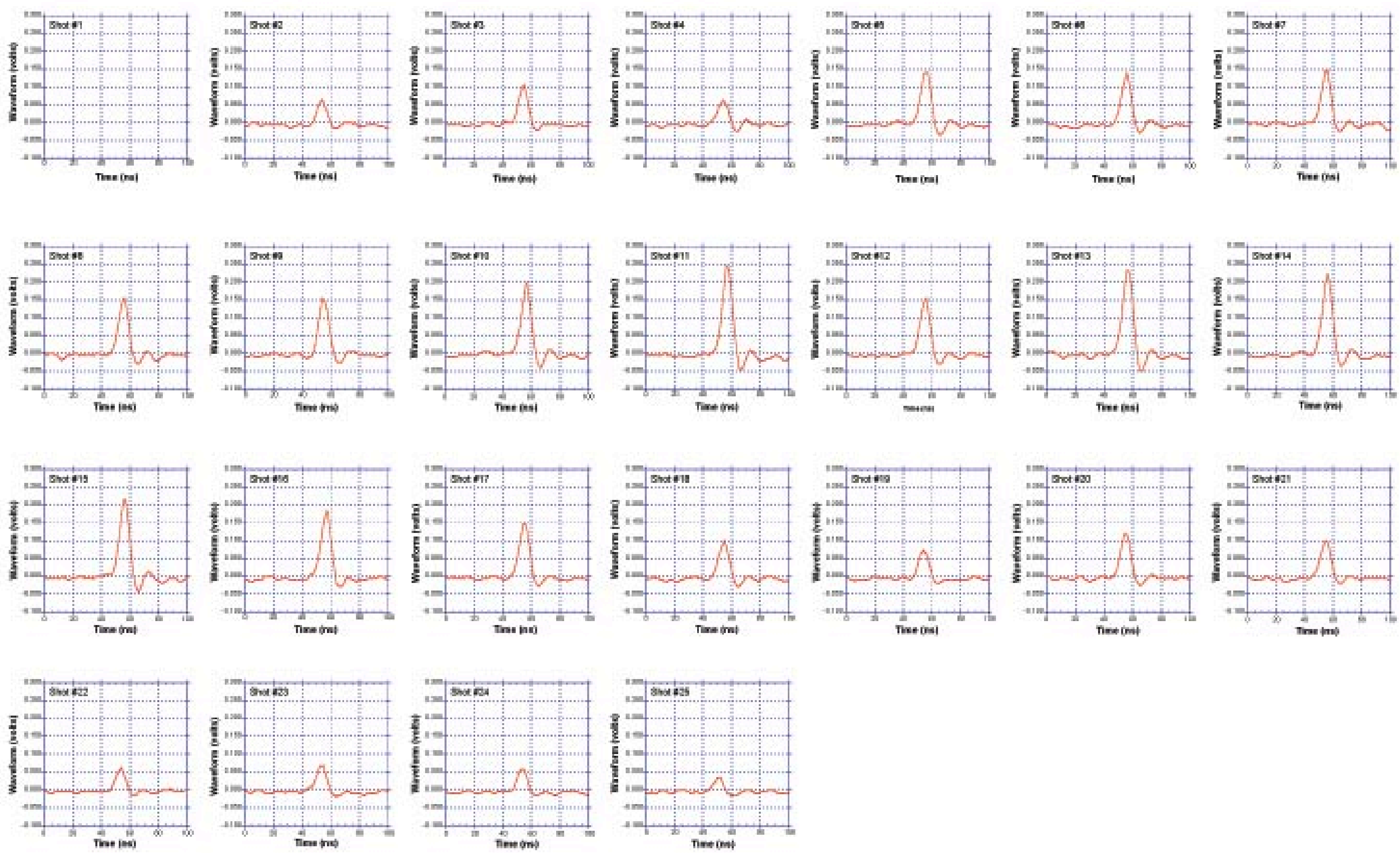
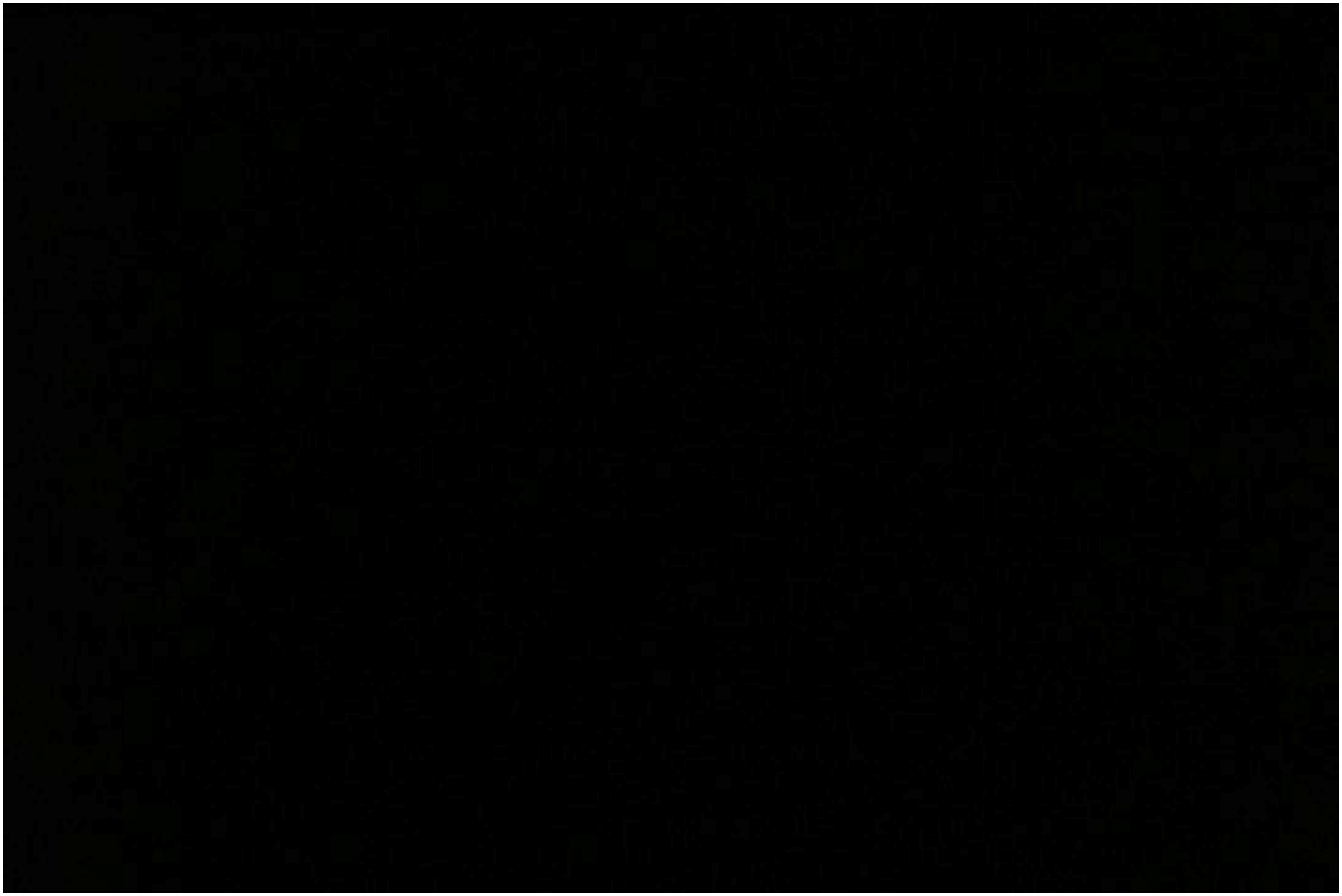
MLA Waveforms 05/31/05

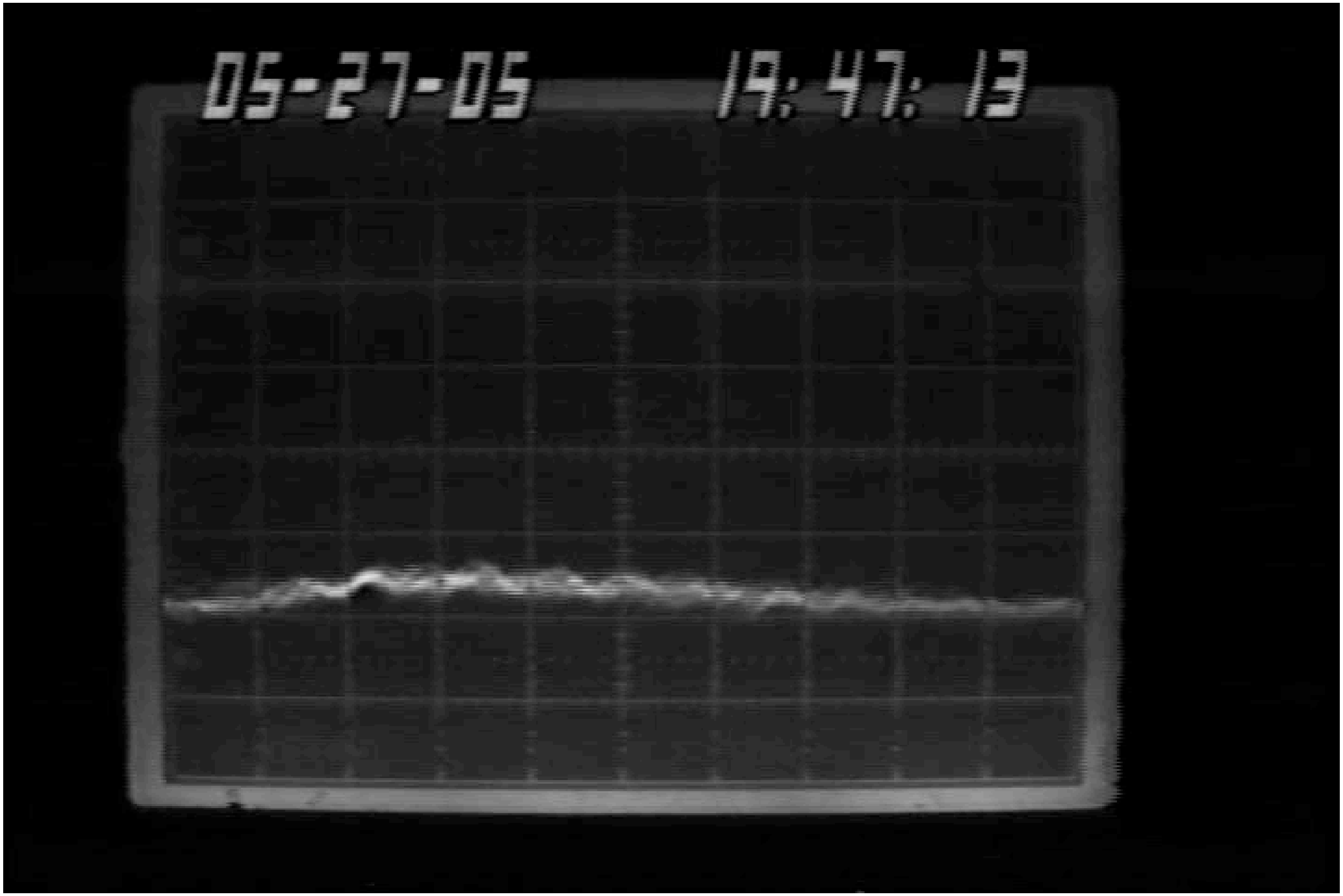


MESSENGER

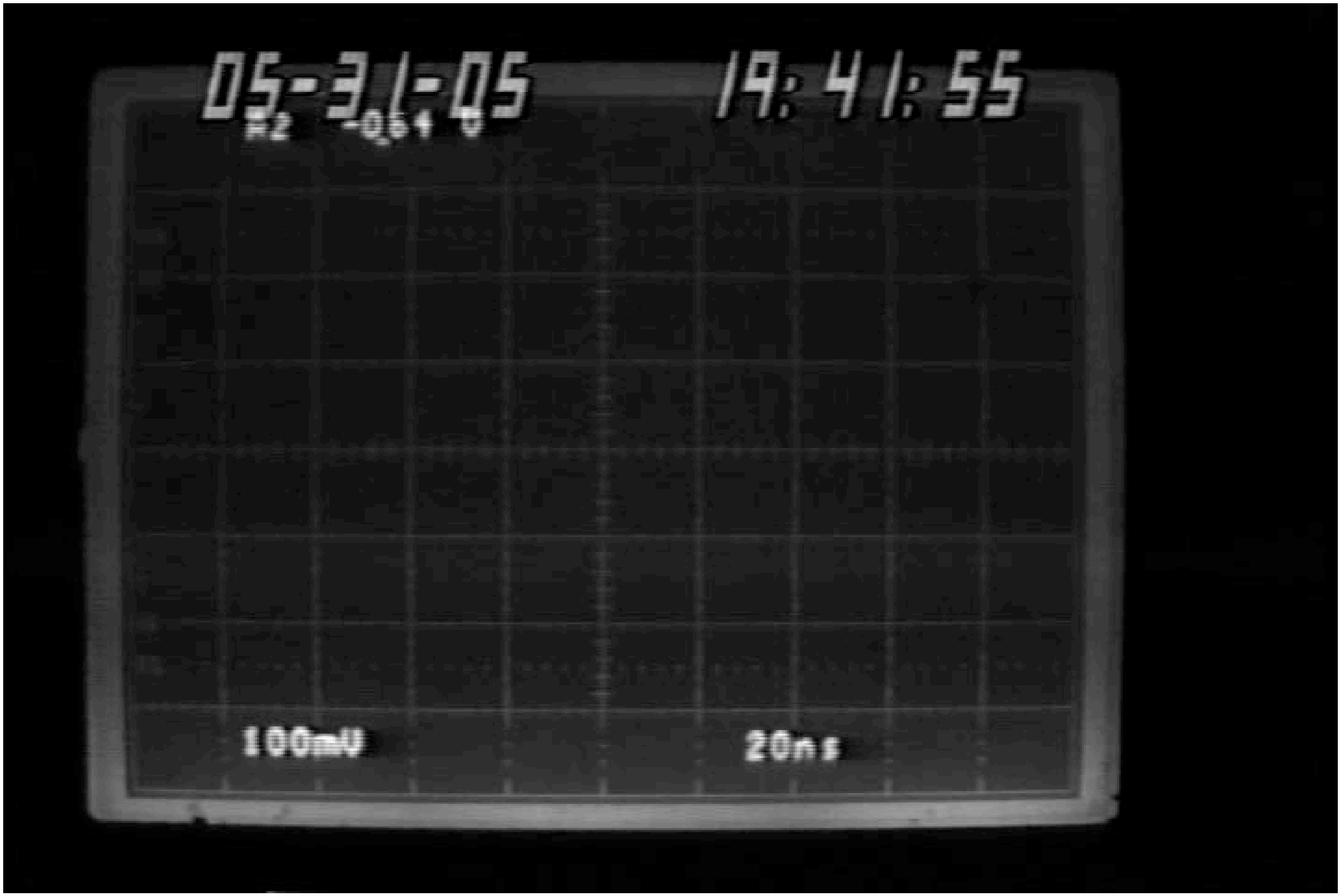
MLA Waveforms 05/27/05



MESSENGER
MLA Waveforms 05/31/05



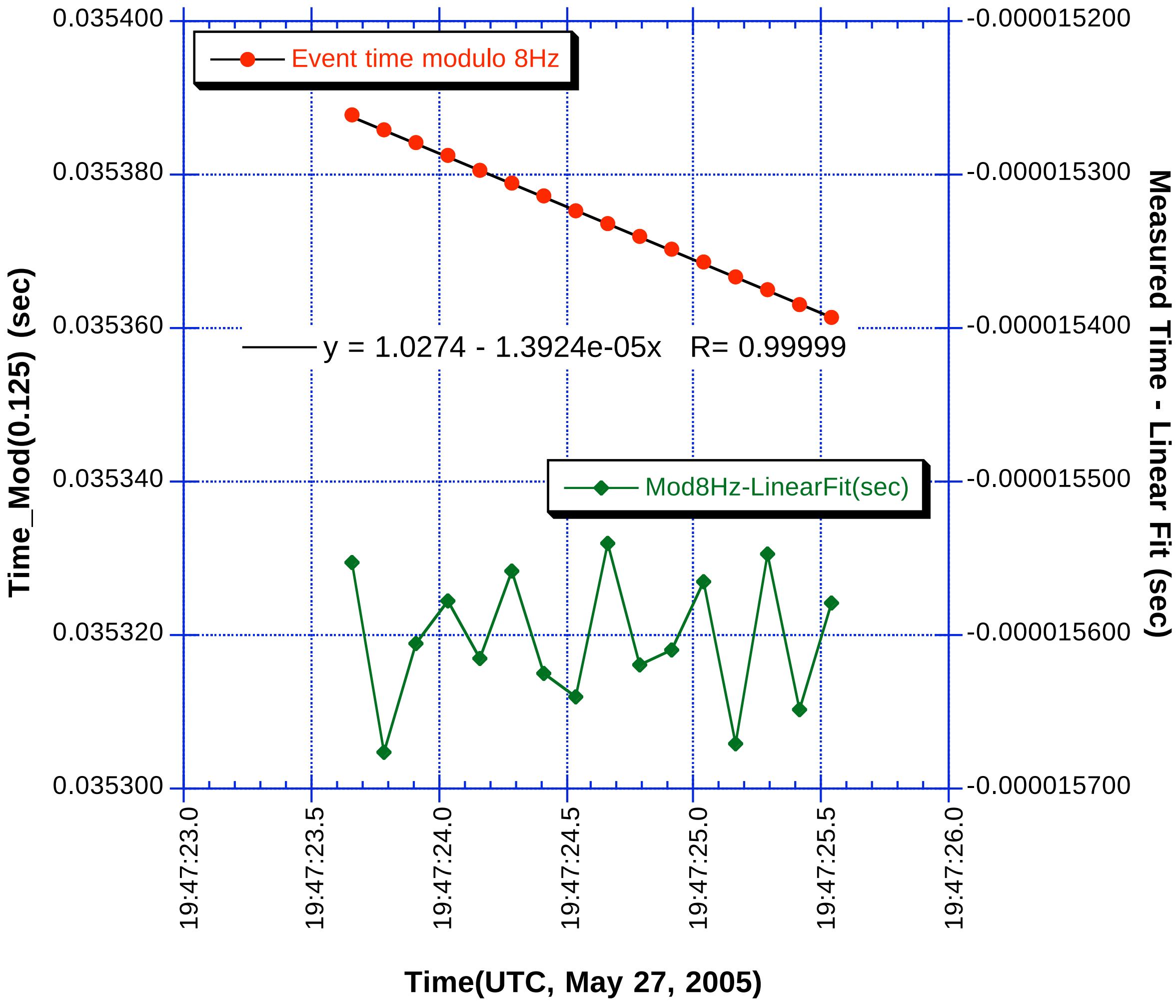
MESSENGER
MLA Waveforms 05/31/05



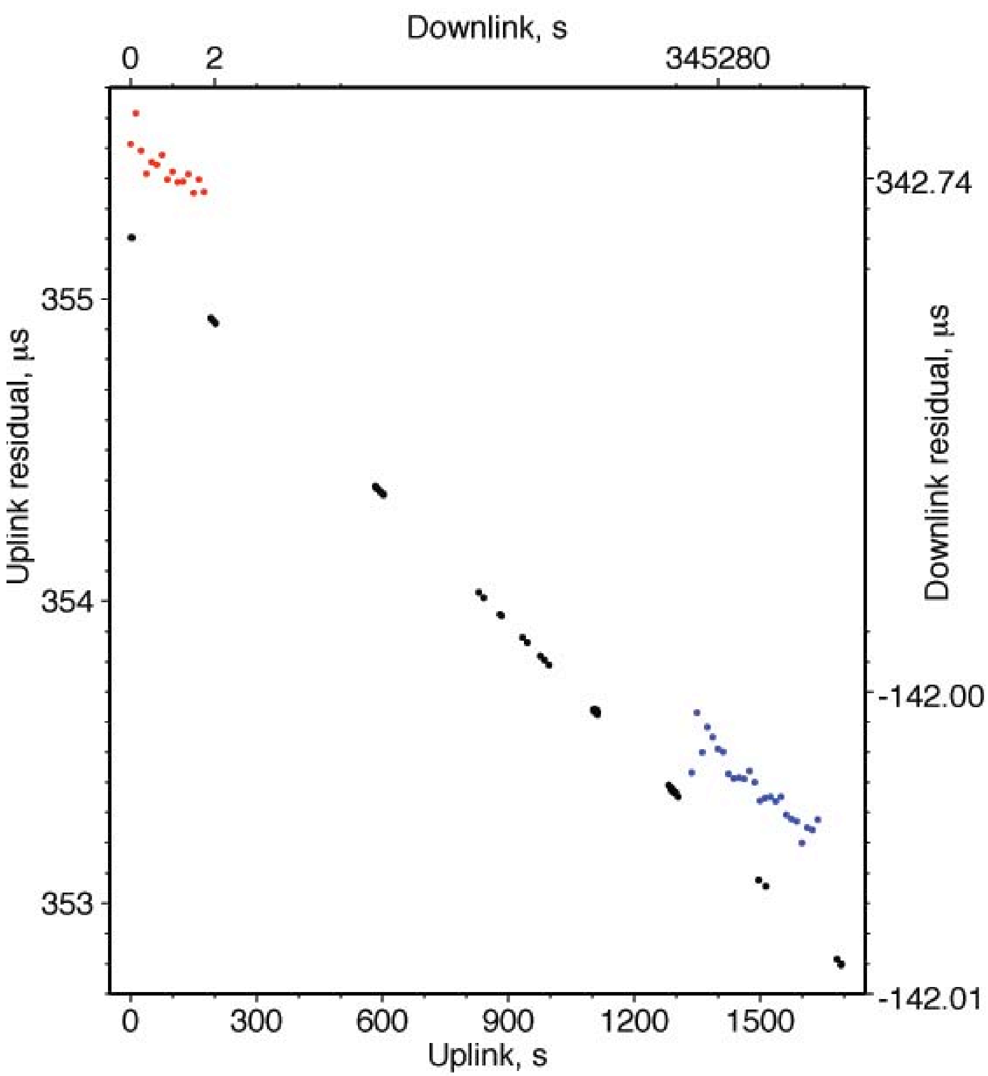
MESSENGER

Pulse Arrival Time and Residual of Linear Fit

● 05/27/05 scan.



MESSENGER
Received Pulses



- Black: ground pulses received at MLA; 0.35 ms later than predicted.
- Red: Ground received time of MLA pulses on May 27; 0.34 ms later than predicted
- Blue: Ground received time of MLA pulses on May 31; ~0.14 ms earlier than predicted.

➔ Use to two-way range, range rate, and acceleration at the reference epoch (2005-05-27T19:46:03 UTC), as well as the spacecraft clock offset and drift rate.

MESSENGER
Solution Parameters

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	71163.729670967±6.6×10^{-10}	71163.730019659	0.000348692
Clock drift rate, ppb	1.00000001533±4.8×10^{-10}	1.00000001564	-3.1×10^{-10}

MESSENGER

Passive Earth Calibration and 2-way Ranging Experiment: May 11, 18, 26, 27, and 31, 2005

- Detector performance verified and alignment calibrated wrt S/C inertial reference system. Star tracker to MLA detector alignment shifted ~3 mrad from preflight boresight, but was consistent day-to-day within 25 μrad.
- S/C pointing control was excellent during 5-hour slow scans.
- Laser function and thermal behavior is in good agreement with preflight data and predictions.
- Laser boresight was directly observed at GSFC, within 50 μrad of preflight alignment. Alignment is well within detector error budget.
- Two-way ranging to GSFC successful, allowing measurement of range, time transfer, S/C clock verification at 23,950,000 km distance.
- Accuracy of MESSENGER clock verified (<1 ms error).