The 24 Million Km Link with the Mercury Laser Altimeter

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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).
Two-Way Laser Link over Interplanetary Distance

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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). The MESSENGER (Military/Spacecraft, Space Environment, Geosciences, Chemistry, and Range) spacecraft, launched 3 August 2004, is carrying the Mercury Laser Altimeter (MLA) (3) as part of its instrument suite on its 6.8-year voyage to Mercury. In an experiment performed before Earth (Fig. 1), the MLA successfully ranged to Earth and received laser pulses from the NASA Goddard Space Flight Center. Geophysical and Astronomical Observatory (GSAM) (4). The only other deep-space laser ranging demonstration occurred before MLA in 1992, when two ground-based laser stations were pointed toward the Galileo spacecraft and the signals were detected at a distance of \(6.5 \times 10^8\) km as streaks of light by the spacecraft's camera (5). In contrast, the MLA Earth-ranging experiment operated like an astronomical transponder (6), 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 pulse observations were used to solve for a common range and clock offset (6). The MESSENGER spacecraft clock is an optical quartz oscillator (7) that measures mean sidereal time (MST) and is periodically synchronized to coordinated universal time (UTC) by the terrestrial reference system (7). Over the test period 26 to 31 May 2005, the spacecraft clock, to which the MLA is periodically calibrated, was able to approximate one part per billion (ppb) to within 5 ppb.

In these observing opportunities, the MLA laser was fired for 6-hour periods while the spacecraft scanned Earth at a rate of 10 to 15 long times spaced 32 s apart, for a total scan area of 3.2 by 3.2 rad. Event times logged pulse transmission and received times at GSAM, referenced to UTC within 100 ns absolute time. A digital oscilloscope at a frequency of 1 Gb/s also recorded the received pulse shapes. Sixteen consecutive pulses were recorded at 19:47:24 UTC on 27 and 28 May, more were recorded at 19:42:02 UTC on 31 May.

Simultaneously, a laser at GSAM was targeted upward toward MLA. The optical pulse, along with noise triggers from the sunlit Earth, was received within a 15-nanosecond window during each 125-ms shot interval. Inspection of the recorded instrument data revealed 56 pulses over a 30-nanosecond frame, 17 on multiple channels, whose timing matched the GSAM pulse times. The interpretation of these events as downlink and uplink ranges required a joint solution (8) for spacecraft clock and station parameters (Fig. 2). The solution yielded a clock offset and drift rate at the origin time and the range as a function of time at the spacecraft (Tables 1 and 2). Downlink observations were fit with a root-mean-square residual of 0.39 m, whereas uplink observations suffered from random signal loss and were fit with an rms residual of 2.9 m. Formal standard deviations indicate that the range was determined with an accuracy of 0.20 m. Our range agrees with that derived from the reconstructed Ephemeris from X-band Doppler tracking 12.7 Gb/s (8.6 Gb/s downlink) 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.

References and Notes


Supporting Online Material

www.sciencemag.org/cgi/content/full/311/5763/531/DC1

Materials and Methods

References and Notes

13 September 2005; accepted 7 November 2005


3. B. B. B. B. K. K. K. B.


5. B. B. B. B. K. K. K. B.


7. B. B. B. B. K. K. K. B.


9. B. B. B. B. K. K. K. B.


11. B. B. B. B. K. K. K. B.


13. B. B. B. B. K. K. K. B.


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### MESSENGER Ground Station and Spacecraft Parameters

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

HOMER ran at 17 mJ/pulse
MESSENGER
Spacecraft Transit to Mercury
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

Ground Station
Laser Transmitter
HOMER

Transmit & beam shaping optics

TOF Receiver Electronics
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.
Ground Station Laser: Extended Run Experiment

HOMER Laser
- Output: 17 mJ
- Pulse Duration: 10 ns
- Repetition Rate: 240 Hz
- Wavelength: 1064 nm

HR Mirror
Power Meter
Far Field CCD
Beam Fluence Image
Flip Mirror

Data System and Laser Control
1% Transmit
To MLA
Scan start time (UTC)

Passive Scans:
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”)

Range, km
16 17 18 19 20 21 22 23 24
UTC
May 11
May 18
May 26

Elevation
0 - 60
Sun angle

May 11
May 26
Passive raster scan over 7x7 mrad area, 70 rows, 100 $\mu$rad spacing between rows (8000 km detector diameter area on Earth).

Active raster scan over 3.2 x 3.2 mrad area, 100 rows, 32 $\mu$rad spacing between rows, with pause in the middle pointing at GSFC.

Scan rate 16 $\mu$rad 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.
MESSENGER/MDIS Earth Observation from 29.2 million km, 12 May 2005

MDIS Earth observation, 12 May 2005

Enlarged x10

Earth

Moon
Sample Earth Scan Patterns

Raster Scan, 80urad laser foot print

Circular Scan, 80urad laser foot print

Gene Heyler/APL Nov. 2003
Preliminary passive scans to test pointing and alignment.

3 mrad offset -> corrected
(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
Pulse Arrival Times: 05/27/05

Pulse Arrival Time Modulo 0.125s (8Hz),
May 27, 2005

Random Noise

Cloud echoes from the ground laser (240Hz laser pulses but the oscilloscope could only record <80 waveforms/s)

More cloud echoes 47.5 sec later

Potential MLA laser pulses

Noise or Cloud Echoes

Potential MLA laser pulses

Coarse Time (EST, Daylight Saving Time)
45 minutes earlier

6 minutes later
Yellow dots show reconstructed laser spots at 1 s intervals.
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.
Individual (black) and averaged (red) waveforms match laser characteristics convolved with detector/preamp response.
The change in TOF data shows the relative MLA velocity as it approaches Earth.

Event time minus last 48" laser fire time

MLA returns

Time past 48" laser fire (msec)

Seconds of Day (UTC)
Pulse Arrival Time and Residual of Linear Fit

Event time modulo 8Hz

\[ y = 1.0274 - 1.3924 \times 10^{-5}x \]

\[ R = 0.99999 \]

Time_Mod(0.125) (sec)

Measured Time - Linear Fit (sec)

Time(UTC, May 27, 2005)

05/27/05 scan.
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.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Laser Link Solution</th>
<th>Predicted Spacecraft Ephemeris</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range, m</td>
<td>23,964,675,433.9±0.2</td>
<td>23,964,675,381.3</td>
<td>52.6</td>
</tr>
<tr>
<td>Range rate, m s⁻¹</td>
<td>4154.663±0.144</td>
<td>4154.601</td>
<td>0.062</td>
</tr>
<tr>
<td>Acceleration, mm s⁻²</td>
<td>-0.0102± 0.0004</td>
<td>-0.0087</td>
<td>-0.0015</td>
</tr>
<tr>
<td>Time, s</td>
<td>71163.729670967±6.6x10⁻¹⁰</td>
<td>71163.730019659</td>
<td>0.000348692</td>
</tr>
<tr>
<td>Clock drift rate, ppb</td>
<td>1.00000001533±4.8x10⁻¹⁰</td>
<td>1.00000001564</td>
<td>-3.1x10⁻¹⁰</td>
</tr>
</tbody>
</table>
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).