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*, *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*).

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.

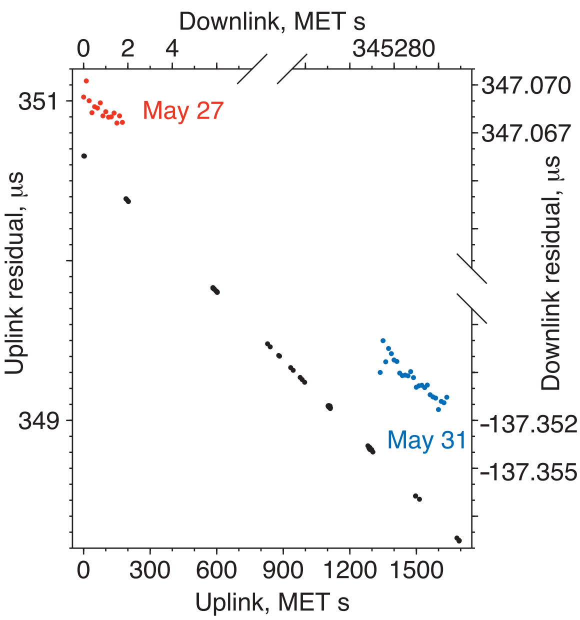

Fig. 1. Pulse-received times at MLA and GGAO. The graph shows that ground laser pulses (black symbols) were received by MLA ~0.35 ms earlier than predicted. Similarly, the ground-receive time of MLA pulses was ~0.34 ms earlier on 27 May (red symbols) but ~0.14 ms later on 31 May (blue symbols).

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

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6. Materials and methods are available as supporting material on *Science* Online.
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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.

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Supporting Online Material
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