Laser Ranging at Interplanetary Distances

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Abstract

In May 2005, timed observations of short laser pulses of light between the Mercury Laser Altimeter (MLA) instrument aboard the MESSENGER spacecraft, and the Goddard Geophysical Astronomical Observatory (GGAO) measured the two-way range time-of-flight with sub-nanosecond precision. A one-way optical experiment was conducted a few months later from GGAO to the Mars Orbiter Laser Altimeter (MOLA) aboard the Mars Global Surveyor (MGS) spacecraft at a distance of 81 Gm (0.54 AU). These experiments demonstrated the possibility of interplanetary communication and precise ranging using modest power.

Introduction

Laser ranging in space began with ranging to retroreflectors on the Moon placed by the Apollo [Faller et al., 1969] and Luna missions. Pulses fired by a powerful, earth-based laser are reflected back to the transmitting site, where time-of-flight measurements are made using standardized clocks. Such measurements routinely achieve decimeter precision using very short pulses and single-photon detectors. Laser ranges require only small corrections for atmospheric transmission, and provide precise constraints on the dynamics of the Earth-Moon system. With retroreflectors, the number of photons available for timing decreases with the fourth power of the distance, making distances much beyond the Moon's orbit impractical. A transponder, on the other hand, receives pulses and sends pulses back in a coherent fashion so that the photon count decreases only by the square of distance in both directions, making ranging possible at far greater distances. The Mercury Laser Altimeter (MLA) ranging experiment in May, 2005 demonstrated the concept of asynchronous transponders [Degnan, 2002] in which two laser terminals independently fire pulses at each other, with timing recorded for analysis at a common location. The times of the paired observations are then used to solve for two-way range as well as a spacecraft clock offset. Multiple transponder observations can additionally constrain the spacecraft clock drift, the range rate and the range acceleration.

The MLA experiment used the 1.2-m telescope facility of the Goddard Geophysical Astronomical Observatory (GGAO) to fire at and detect pulses from MLA at a distance of 24 Gm, or 0.16 AU. It served to calibrate the instrument transmitter and detector far field characteristics and alignment, as well as confirm the distance inferred from radio tracking. The results of this experiment were communicated in brief [Smith et al., 2006]. In September 2005, one-way laser transmission was achieved to the Mars Orbiter Laser Altimeter (MOLA) instrument at Mars [Abshire et al., 2006] from GGAO using a more powerful laser firing at 49 Hz. MOLA no longer had its laser or timing capability but could record the rate of detector triggers using the spacecraft 8-Hz timing signal. An encoded sequence was transmitted using a 1-Hz shutter. The number of pulses received was strongly correlated with the modulation of the outgoing pulses. This experiment demonstrated the feasibility of laser

communication at 81 Gm, and confirmed the spacecraft clock offset of Mars Global Surveyor to a precision of ~4 ms.

We provide here further details regarding these experiments and prospects for future laser ranging and communication in deep space.
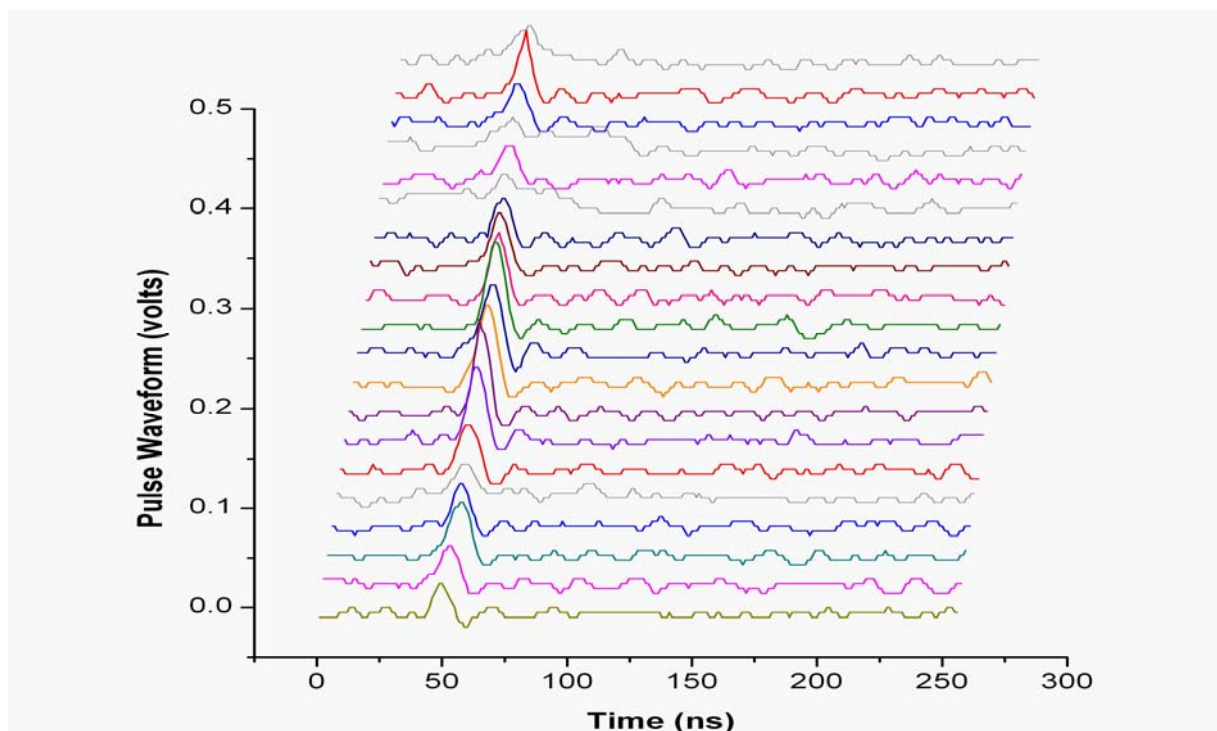
Ground Transmitter and Receiver

The HOMER life-test laser [Coyle and Stysley, 2005] employed in the MLA-Earth experiment produced 16 mJ per shot at 240 Hz. MLA received pulses at 8 Hz, the electronics allowing about 14 ms in each shot interval for returns. Thus it was anticipated that the laser would place three or more pulses inside the timing window. A 10X beam expander collimated the outgoing beam divergence to approximately 50 microradians (90% energy) after transmission through a portion of the 1.2-m telescope of the Goddard Geophysical Astronomical Observatory (GGAO). The energy per shot at the entrance to the 0.0417-m^2 MLA telescope would be 0.6 fJ, neglecting losses in transmission and atmospheric attenuation. The energy at the telescope measured from shots detected at low and high thresholds by the MLA was 0.083 ± 0.04 fJ. After the experiment, it was found that coatings on six folding mirrors in the GGAO optical path had been optimized for 532 nm operation and transmitted only 70% of 1064 nm light, reducing total transmission to about 12%. The effective transmitted energy of the ground system was reduced accordingly, amounting to about 2 mJ per shot. Since the MLA experiment and the Earth-MOLA experiment performed soon thereafter, the mirrors have been recoated and total transmission at 1064 nm is about 70%.

Ground and spacecraft timing

Absolute time and range measurements using a transponder requires tying local event timers to terrestrial time standards. Timing at GGAO was provided by GPS-steered rubidium clocks. A Honeywell precision event time digital counter (TDC) logged the leading-edge times of outgoing and incoming laser pulse triggers with respect to UTC at 10-ps resolution [Kalisz, 2004]. The waveform of each pulse was also digitized by means of a 1-GHz oscilloscope. The centroid time resulting from fitting a Gaussian envelope to the waveforms provided the most precise timing, owing to the extended nature and variable height of the detected pulses (Figure 1). These centroid times were also corrected to UTC seconds of day as recorded by the GPS-steered clock. GPS time errors result in absolute ground clock uncertainty of ~40 ns. Slowly-varying GPS errors do not affect relative times between transmit and receive pulses, which were fit with a root-mean-square residual of 0.39 ns.

Timing was corrected for a 44.2 ns path delay between the transmit laser start detector and the TDC, an optical path delay of 43.8 ns between the transmit detector and the telescope mount reference point, and a 110.2 ns delay from the GPS receiver antenna to the TDC. The latter delay is also applied to the time of the received pulses. The optical path from the telescope mount to the detector assembly and the electronic delay between the detector and the TDC was ~20 ns. Significant forward scattering through clouds likely caused pulse broadening and some delay. Atmospheric refraction delays of tens of ns should also be considered when determining the absolute times of flight, in view of the relatively low 30-35° elevation of the spacecraft above the horizon, but these were not applied. An independent calibration of all timing delays using an earth satellite retroreflector could not obtained during the allotted time owing to cloudy conditions.

The MESSENGER spacecraft [Solomon et al., 2001] employs an ovenized quartz-crystal-based oscillator whose frequency is stable to a few parts in 10^{12} over the course of an hour [Cooper, 2004]. The Mercury Laser Altimeter (MLA) acquires its time base from the spacecraft via a one-pulse-per-second (PPS) tick along with the corresponding mission elapsed time (MET) message over the data bus. The hardware PPS signal provided to MLA was benchmarked at 21 μs uncertainty during ground testing [Cavanaugh et al., 2007]. The PPS offset, and the offset between the MLA event time reference T0 and the PPS tick, are very stable over short intervals of time. The latter is monitored by the instrument at 125-ns resolution. Thus the spacecraft clock can be related to the MLA timing only to tens of microseconds in an absolute sense, but are precisely coupled over intervals of an hour.

Figure 1. *MLA Pulse waveforms recorded at GGAO on May 27, 2005, along with a few cloud echoes (gray curves) from the ground laser.*

The MLA obtains a 5 MHz clock signal from the spacecraft which drives a coarse event timer. The transmit and receive event timers consist of a set of time-to-digital converters (TDC) based on the tapped delay line technique [Paschalidis et al., 1998]. The tapped lines consist of a series of logic gates that count from an event to the next 5-MHz clock edge. An on-chip delay-lock-loop calibrates the overall delay time against an external reference clock signal, and the delay of each gate is measured on the ground. The combined circuits can time the leading and trailing edges of the transmitted laser pulses and the received echo-pulses to ~400 ps resolution. Coarse and fine clock counts are downlinked via telemetry. A zero-range offset bias of 23.8 ns for high threshold returns and 30.9 ns for low threshold returns is subtracted to account for electronic delays in the receiver relative to the start pulse.

The spacecraft radio telemetry system is used to calibrate MET against time standards at the Deep Space Network (DSN). Spacecraft time must be correlated to a dynamical

time to millisecond accuracy for geodetic purposes, in order to position MESSENGER in space and derive altitude from ranges. The MESSENGER project maintains a clock file giving corresponding MET and Terrestrial Dynamic Times (TDT). An event on the spacecraft at a given MET tick is considered simultaneous with an event at the corresponding terrestrial time, as viewed from the Solar System Barycenter. Owing to special relativity, corresponding times may not appear simultaneous to a terrestrial observer. The Navigation and Ancillary Information Facility (NAIF) toolkit models the travel of light between Earth and MESSENGER in a barycentric inertial frame and was used herein.

MESSENGER Range and Time Transfer Results

During the MLA-Earth experiment, the MESSENGER clock correlation file was updated twice over the course of a week, with coefficients given in Table 1. The clock rate typically varied by <1 part in 10^9 over the period of four days, however, telemetry time coding errors at the DSN on the day before the experiment resulted larger-than-usual variation. Independent verification of the spacecraft timing system integrity was an important goal of the ranging experiment. The downlink time residual was found to be 347 microseconds, while the uplink residual was 351 microseconds. The average residual offset of the spacecraft clock was therefore 349 microseconds. However, post-processing of the spacecraft timing (Stanley B. Cooper, email communication, November 8, 2006) suggests that this clock offset was ~49 microseconds. For reference, the mission requirement is to maintain time correlation to 1 ms.

Table 1. Spacecraft clock correspondences used during experiment.

MET	TDT	Rate of MET
25632557	26-MAY-2005T22:11:17.912822	1.00000001564
25963200	30-MAY-2005T18:02:00.917993	1.00000001704
MLA-Earth result, uncorrected for relativistic time delay		
25710307	27-MAY-2005T19:46:03.729662	1.00000001559

Range residuals were calculated via least squares, resulting in a solution from two-way light time of 23,964,675,433.9 m at the 25710307 MET tick, with range decreasing at a rate of 4,154.663 m/s. A spacecraft ephemeris solution using radio tracking data (msgr_20040920_20050823_od032.bsp) predicted a range of 23,964,674,906.35 m. However, the relativistic (Shapiro) delay in the speed of light and bending of light path due to the solar gravitational potential amounted to an equivalent of 486.60 m in each direction, so that the effective range was 23,964,675,392.95 m, or 41 m less than measured by the MLA experiment. There are several sources of error that could account for this discrepancy: the spacecraft ephemeris, errors in the measurement model used for comparison, errors in ground timing and path correction, or combinations of these errors. Such close agreement, to a part per billion in range, is truly remarkable. The formal error in the laser range solution was 0.2 m, or one part in 10^{11}.

MOLA Time Transfer Results

Distances to Mars are well-constrained by years of tracking of spacecraft and landers, and the clock drift on Mars Global Surveyor (MGS) has been very small, so that the

clock correlation file is updated only a few times a year to maintain the specified 10-ms accuracy. The primary purpose of this test was to determine the clock offset between the MOLA data stream and spacecraft time. MGS was commanded to scan twice across a 0.2x0.2° (3.5x3.5 mrad) region of the sky centered on the apparent position of Earth, during each of three nights in September 2005. The 1-3 mrad uncertainty in pointing control of the 9-yr-old spacecraft, as well as the 0.8 mrad detector field of view, made scanning necessary. Passive radiance confirmed that the detector was aimed correctly. MOLA detector threshold was set to produce 1-2 noise counts per second from Earth background light. In each 8-Hz interval, the number of triggers is recorded. A maximum of 6 or 7 shots from the 49-Hz ground laser could have been detected in each interval. In fact, at most 7 triggers above threshold occurred in any single interval, consistent with the expected probability of detection. Roughly 500 such pulses were counted during one successful evening, and from the pattern of counts, it was clear that the pulses were being recorded somewhat later than expected, consistent with a 114-ms skew between the spacecraft time signal and Earth time. Such a bias had earlier been estimated using the altimetry in an eccentric orbit [Rowlands et al., 1999].

Prospects for future experiments

Opportunities to repeat the MLA-Earth experiments occur at several intervals beginning in May 2007, at distances of 100 Gm or more (0.66 to 1 AU). The MESSENGER spacecraft must maintain its sunshade Y-axis within ~12 degrees of the Sun while pointing the instrument Z-axis toward earth, a geometry which also maximizes the elongation of the MLA with respect to the Sun as seen from Earth. The first MLA experiment required several days to complete, even with moderately good visibility. It was severely constrained by the pointing knowledge of the spacecraft, such that no more than 24 shots were received on the ground from MLA during a single observing session. As a result of the experiment, the repeatability of the MLA boresight was determined from passive scans to be within 50 microradians from day to day, and within each scan, the control of each scan line was within its 16-microradian spacing. During several windows through the clouds, the MLA receiver was able to detect ~90 shots from the ground, but never with a probability of detection greater than 1-2%. In 15 events, both a high and a low threshold trigger occurred, with leading and trailing edge times. Such timing allows for estimation of the pulse width and energy, assuming a Gaussian waveform, as detailed in Cavanaugh et al. [2007]. The energy received at the telescope entrance from these events averaged 0.083 fJ, or 0.064 fJ at the detector after transmission losses.

From June 18 to 24, 2007, attempts were made to repeat the MLA experiment at a distance of 104 million km shortly after MESSENGER's second Venus flyby, when the instrument could be safely pointed at Earth. With the improvement in telescope optics, using a single-photon-counting detector, there was sufficient link even with the relatively low ~18 mJ energy of MLA's 1064-nm pulses to range to GGAO at this distance. A 250-mJ laser firing at 48 Hz was employed to improve the probability that a shot would be received within each 14-ms window occurring at 8 Hz, after proper phasing. Communication of a message to the MLA was attempted by modulating the position of each pulse by a variable number of microseconds. However, a myriad of problems with the optical and mechanical ground systems as well as unfavorable weather prevented communication in either direction.

An opportunity for MLA at a similar distance will occur in March 2008, where the elongation of MESSENGER from the Sun will be at a maximum of 44°, with two opportunities in 2009 at elongations of 39° and 36°. It will also be possible to perform the experiment twice per year in Mercury orbit, although solar rejection at the Earth station will require a very narrow field of view. The continued MLA experiments will further demonstrate the ability of lasers to perform precise range measurements, time transfer, and communications throughout the solar system. At these distances the Shapiro delay reaches 10-20 μs. The ability of MLA to see more dramatic effects during solar conjunction is precluded by spacecraft sun avoidance constraints, but the solar avoidance requirements of the MLA optical design itself are minimal. Such experiments could be considered in future interplanetary deployments.

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