Interplanetary Spacecraft Laser Ranging: The Quest for 1 AU.

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Introduction: Since the first successful laser ranges to Earth-orbiting satellites 50 years ago, tracking spacecraft using laser beams throughout the solar system has been pursued as a practical tool for fundamental physics, planetary dynamics, and high-bandwidth communication. The establishment of a 2-way link between a pair of active terminals can provide time transfer and ranges with a precision of a few parts in 10^{12} [1]. We review the science and practical lessons of a successful 2-way link achieved between the Mercury Laser Altimeter (MLA) and the 1.2-m telescope at the NASA Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt, a 1-way link to the Mars Orbiter Laser Altimeter (MOLA) instrument at Mars, some successful lunar experiments (LOLA, LLCD), and several unsuccessful attempts.

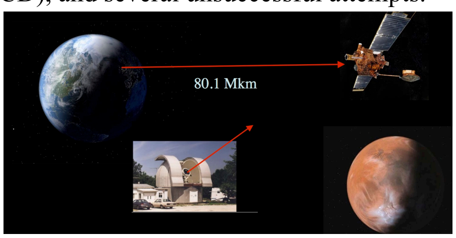

Figure 1: 1064-nm wavelength laser link to Mars from the Greenbelt GGAO facility (not to scale).

Interplanetary Experiments: As a planned calibration of the MLA instrument during cruise, the receiver boresight vector, only known to an accuracy of a few milliradians post-launch, was precisely determined in the spacecraft inertial navigation frame by a series of passive scans in March 2005 across the sunlit Earth. In an active experiment at the end of May, a 15-mJ laser was fired continuously at 240 Hz, and 90 pulses from GGAO were received by MLA as it swept across Earth. This was followed by detection of laser waveforms on the ground. These were timed to a precision of 400 ps after accounting for fire time jitter, clock offset, and the 4.2 km/s relative velocity. Analysis of the combined uplink and downlink data resulted in a range measurement of 24 million km, precise to 0.2 m, and in good agreement with predictions of distance from radio tracking, after accounting for relativistic time delay [2, 3].

In September 2005, a one-way experiment was conducted at a distance of 80 million km, firing a series of 49-Hz, ~0.1-J laser pulses toward the Mars Global Surveyor orbiter as it scanned the MOLA instrument slowly across the Earth [4]. The first of three scheduled days was cloudy, but telemetry verified the instrument alignment. Although the MOLA precision timing hardware no longer was operating, the receiver could count the number of noise triggers within each of 8 time bins per second. An intermittent (50% duty cycle) train of pulses was fired, and the total of 170 trigger counts arriving in a matching pattern. This pattern was sufficient to constrain the overall spacecraft-to-instrument time bias to within a few milliseconds. On the final day, the laser duty cycle was set to 100%, the pulse energy was increased by 10%, and a total of 414 pulses were recorded. The MOLA experiment succeeded with the help of an experienced flight operations team, nearly ten years post-launch.

Lunar Experiments: The Lunar Orbiter Laser Altimeter (LOLA) was designed for nadir operation simultaneously with an earth-pointed receiver for one-way laser ranging [5] and a communication demonstration [6]. In 2009 and 2014, the LOLA laser was scanned across the GGAO field of view to measure changes in transmit energy, beam quality, and alignment. A high-rate Lunar Laser Communication Demonstration experiment was flown on board the LADEE spacecraft in 2013, where a multiscale range encoding was built into the two-way LLCD system [7].

Unsuccessful Attempts: Attempts to range to the NEAR-Shoemaker spacecraft in 1999 were blocked by bad weather. Ranging to MLA in Mercury orbit at 1 AU in 2014 has so far been unsuccessful. An attempt in 2010 to use the Geoscience Laser Altimeter System orbiting outside Earth's atmosphere to see pulses from MLA during interplanetary cruise at 0.7 AU failed owing to inability to control pointing of an Earth-orbiting satellite in modes of operation other than Earth nadir.

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