# TRANSPONDERS SESSION SUMMARY

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Transponder applications are becoming a real option. Feasibility studies using the optical facility at Goddard and the MOLA on the Mars Explorer and MLA on the Messenger spacecraft have demonstrated successfully one-way and two-way optical ranging at interplanetary distances. These experiments became possible because of the lucky opportunity based on the availability of missions for the test of at least some mission aspects of transponders. A full transponder concept is in preparation for the Lunar Reconnaissance Orbiter (LRO) with the goal of improving the orbit determination for the altimeter application. This will be the first mission where ILRS support is required for a transponder application. Currently there are several simulation and evaluation efforts under way in order to improve the understanding of the potential of transponders, both in simulation and in a collocated ranging experiment.

# 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.

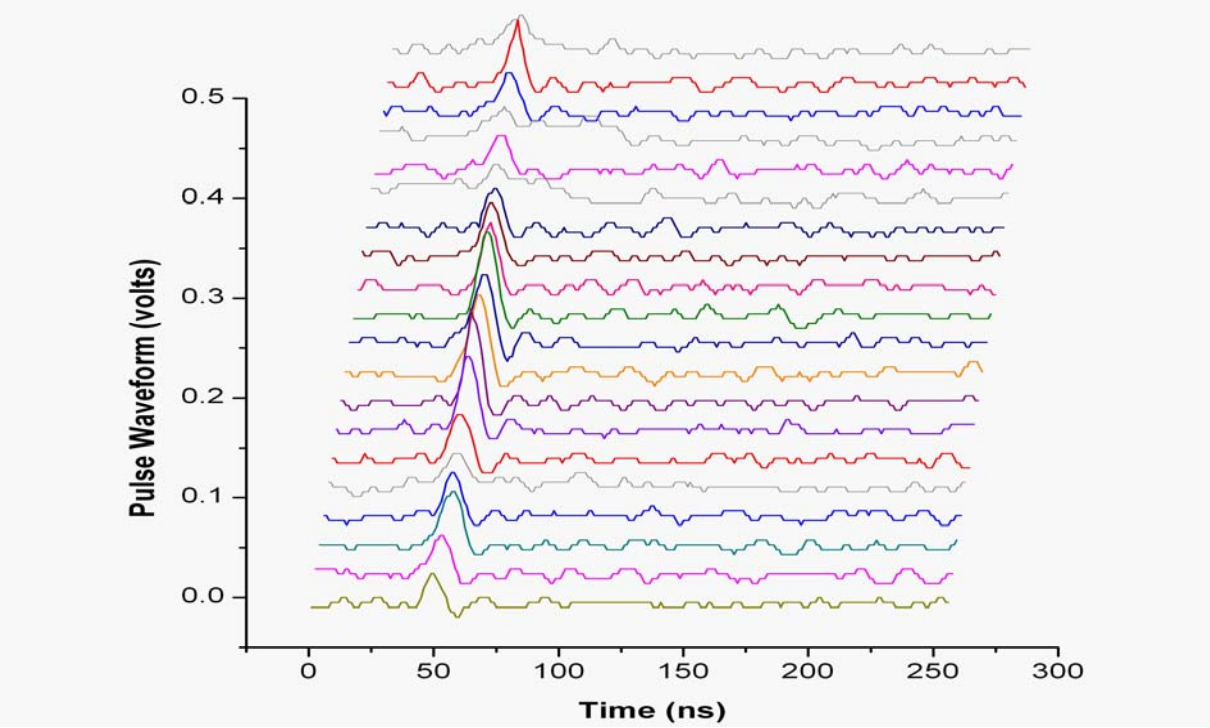

***Figure 1.*** *MLA Pulse waveforms recorded at GGAO on May 27, 2005, along with a few cloud echoes (gray curves) from the ground laser.*

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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# Simulating Interplanetary Transponder and Laser Communications Experiments Via Dual Station Ranging To SLR Satellites

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## Abstract

*Laser transponders open up new opportunities for SLR in solar system and planetary science and general relativity, and laser communications offers orders of magnitude more bandwidth in transferring sensor data from our planetary neighbors and their moons. As new missions are proposed by the spacefaring nations to take advantage of these technologies, there will undoubtedly be a need to simulate interplanetary links and test the Earth-based and spaceborne terminals under realistic operational scenarios prior to launch. Dual station ranging to the SLR satellite constellation, in which Station A provides the radiation source received by Station B and vice versa, can provide a realistic testbed for future interplanetary transponder and lasercom systems, simulating not only the high space loss at interplanetary distances (due to the more rapid* $R^{-4}$ *falloff in signal levels from passive satellites) but also the passage of the transmitted and received beams through the turbulent atmosphere. Satellites which induce minimal pulse spreading are best suited to this application, and the current SLR satellite constellation can simulate interplanetary links as far out as Saturn. The lunar reflectors can simulate distances of 93 AU or more, well beyond the Kuiper belt.*

## Introduction

In 2005, NASA/GSFC succeeded in performing a two-way asynchronous laser transponder experiment [Degnan 2002] with the Messenger spacecraft at a distance of 24 million km [Smith et al, 2006]. This achievement was followed just three months later by a one way transfer of pulses to the Mars Global Surveyor at a distance of 80 million km. Although these were experiments of opportunity rather than design, they clearly established the feasibility of precise interplanetary laser ranging and wide bandwidth communications. Laser transponders open up new opportunities for SLR in solar system and planetary science and general relativity, whereas laser communications offers orders of magnitude more bandwidth in communicating sensor data from our planetary neighbors and their moons back to Earth. As new missions are proposed by the spacefaring nations to take advantage of these technologies, there will undoubtedly be a need to simulate interplanetary links and test the Earth-based and spaceborne terminals under realistic operational scenarios prior to mission approval and launch. In addition to overcoming large $R^{-2}$ space-losses over interplanetary distances, the laser beams in these future systems must traverse Earth's turbulent atmosphere, which produces effects such as beam spreading, beam wander, and scintillation (fading) [Degnan, 1993]. These effects can become much more pronounced as we attempt to extend the range of transponder or lasercom operations by reducing the uplink beam divergence in order to concentrate more energy on the remote terminal.

End-to-end ground based experiments which can convincingly simulate all aspects of these complex systems are both difficult to envision and expensive to implement. Fortunately, atmospheric transmission and turbulence effects on the uplink and

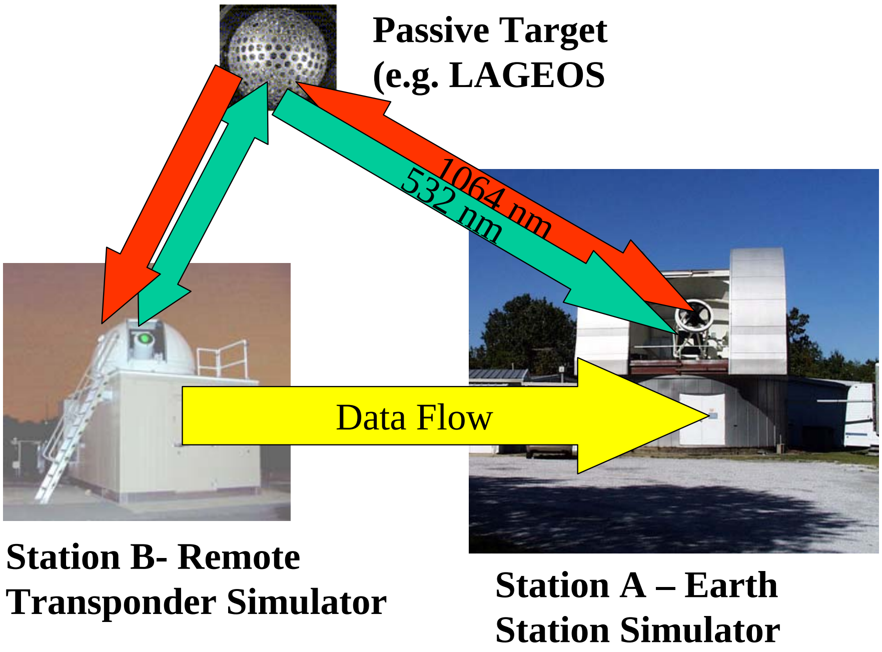

***Figure 1:*** *Dual station laser ranging to LAGEOS with, for example, the GSFC 1.2 meter telescope facility simulating the Earth station and NASA's 40 cm aperture SLR2000 system simulating the remote terminal.*

downlink beams are the same whether the uplink beam is being reflected from a passive high altitude satellite in Earth orbit as in SLR/LLR or transmitted from a distant transponder or lasercom terminal in Deep Space. Dual station ranging to the SLR satellite constellation, in which Station A provides the radiation source received by a nearby Station B and vice versa as in Figure 1, can provide a realistic and inexpensive testbed for future interplanetary transponder and lasercom systems by duplicating not only the high space loss at interplanetary distances (due to the more rapid $R^{-4}$ falloff in signal levels from passive satellites) but also the passage of the transmitted and received beams through the turbulent atmosphere. Each station must be located within the reflected return spot of the other station, and this requirement typically restricts the inter-station separation to within a few hundred meters. The larger terminal, simulating the Earth station, would exchange reflected pulses from the satellite with a smaller station, simulating the remote transponder or lasercom terminal. Figure 1 illustrates GSFC's 1.2 meter telescope facility ranging to LAGEOS in the infrared (1064 nm) while NASA's 40 cm aperture photon-counting SLR2000 system ranges to the same satellite in the green (532 nm). In order to simulate a dual wavelength transponder or lasercom experiment Each station is equipped with a receiver channel at a second wavelength to detect reflected pulses from the sister station. The experiment is self-calibrating since the transponder measures the dogleg defined by Station A – satellite – Station B while the individual ranging systems measure the Station A – satellite and Station B – satellite distances, albeit at slightly different epoch times. Ground surveys typically define the interstation vector, or third leg of the triangle, to better than 2 mm. This provides an accurate way to test the ranging and time transfer algorithms. Similarly, the Bit Error Rate (BER) of an "interplanetary" laser communication system can be obtained by directly comparing the incoming and outgoing bits at the adjacent sites. Such experiments are currently being pursued at NASA [McGarry et al, 2006].

Automated acquisition of the Earth station by the remote terminal can be demonstrated by either turning off or ignoring the closed ranging loop at 532 nm while it searches for the reflected light at 1064 nm. The ability to lock Station A onto the satellite via a closed single ended ranging loop at 1064 nm ensures a steady source of photons from the Earth station for the remote terminal to find and lock onto.

**Link Equations**

The link equations define the received signal strength at either station. For the infrared link from the Earth station A to the remote terminal B via a passive satellite, the link equation is given by [Degnan, 2001]

$$n_R^{AB} = \frac{4\eta_q^B \eta_t^A \sigma_s \eta_r^B T_A^{2\sec\theta_A}}{h\nu_A \left(\theta_t^A\right)^2 (4\pi)^2} \frac{E_t^A A_r^B}{R_R^4} \tag{1}$$

which depends on the transmitted energy $E_t$, the receive aperture $A_r$, detector quantum efficiency $\eta_q$, the photon energy $h\nu$, the one-way zenith atmospheric transmission $T_a$, the satellite zenith angle $\theta_A$, the divergence half-angle of the laser beam $\theta_t$, the target optical cross-section $\sigma_t$, measured in square meters, and the optical throughput efficiencies of the transmitter ($\eta_t$) and receiver ($\eta_r$) optics respectively. The *A* and *B* superscripts and subscripts signify the terminal for which the value applies, and are reversed for the opposite link from terminal *B* to *A*. The quantity $R_R$.is the slant range to the target satellite. For the nominally circular orbits of typical SLR targets, $R_R$.can be expressed as a function of the satellite height above sea level *h*, and the satellite zenith angle

$$R_R(h,\theta_A) = -R_E\cos\theta_A + \sqrt{(R_E\cos\theta_A)^2 + h(h+2R_E)} \tag{2}$$

where $R_E$ = 6378 km is the mean volumetric radius of the Earth and (2) reduces to *h* when $\theta_A = 0$.

For interplanetary transponder or lasercom links, the link equation is given by [Degnan, 2001]

$$n_T^{AB} = \frac{4\eta_q^B \eta_t^A \eta_r^B T_A^{\sec\theta_A} T_B^{\sec\theta_B}}{h\nu_A \left(\theta_t^A\right)^2 (4\pi)} \frac{E_t^A A_r^B}{R_T^2} \tag{3}$$

Setting the mean signal counts equal in (1) and (3), we can derive an expression for the equivalent transponder distance, $R_T$, in terms of the actual slant range to the satellite, $R_R$, i.e.

$$R_T(h,\theta_A,\sigma_s) = R_R^2(h,\theta_A)\sqrt{\frac{4\pi}{\sigma_s}\left(\frac{T_B^{\sec\theta_B}}{T_A^{\sec\theta_A}}\right)} \cong R_R^2(h,\theta_A)\sqrt{\frac{4\pi}{\sigma_s}\frac{1}{T_A^{\sec\theta_A}}} \tag{4}$$

where the approximation holds if the remote terminal is in interplanetary cruise phase, in orbit, or sitting on the surface of a planet or moon with little or no atmosphere ($T_B$ ~1).

Since the SLR satellites are normally tracked over the range $0^o \le \theta_A \le 70^o$, Eq. (4) defines a maximum and minimum simulated transponder range for each satellite. These are indicated by the blue curves in Figure 2 for selected satellites where we have assumed a value $T_A$ = 0.7 corresponding to the one-way zenith transmission for a standard clear atmosphere at 532 nm. The red curves are plots of the minimum and maximum interplanetary distances of the Moon and other planets from Earth.

It is worthwhile to note that atmospheric turbulence can influence the effective transmitter beam divergence on the uplink, but this cancels out in our derivation of (4). Furthermore, the fading statistics for the dual station ranging experiment to the passive satellite should be comparable to that of an interplanetary transponder or lasercom experiment, at least to the extent that the satellite adequately mimics a coherent point source of radiation.

Figure 2 demonstrates that a dual station ranging experiment to the lowest of the SLR satellites, Champ, provides a weaker return than a two way lunar transponder. Low elevation angle experiments to Jason are comparable to a Venus or Mars link when they are closest to Earth. Experiments to the LAGEOS and Etalon satellites would simulate ranging to Mercury, Venus, and Mars throughout their synodic cycles while experiments to GPS and LRE (at 25000 km) would simulate links up to and beyond Jupiter and Saturn. Dual station experiments to the Apollo 15 reflector on the lunar surface would simulate transponder links to over 100 AU, well beyond the orbit of Pluto and the Kuiper Belt. These results are summarized in Table 1.

The nine SLR satellites represented in Figure 2 were chosen based on the following criteria:

- The satellite array should not significantly spread nanosecond pulses (important to both transponder and lasercom experiments)
- The satellites should simulate a wide range of equivalent interplanetary distances for experimentation and allow a step-wise demonstration of distance capabilities from the Moon to the inner and outer solar system.
- The satellite suite should permit measurements at a variety of elevation angles to fully explore atmospheric effects which typically worsen at low elevations.

The primary characteristics of these satellites, taken from the ILRS Web Site and used in the computation of equivalent transponder ranges, are also summarized in Table 1.

Another way to interpret Figure 2 is to say that any single SLR station that can track the aforementioned satellites has demonstrated an adequate Energy-Aperture (EA) product for the corresponding transponder link under the same noise background and atmospheric conditions. Since all of the ILRS stations are required to track LAGEOS for membership, they all have adequate EA-product to track out to about 1 AU. About a third of ILRS stations regularly track GPS, which from Figure 2 or Table 1 implies an equivalent transponder range out to 5 AU. The NASA MOBLAS system, with an *EA*-Product of 0.045 $Jm^2$ and a Power-Aperture (*PA*) Product of 0.23 $Wm^2$ , falls into this category as does the photon-counting Graz station in Austria with *EA* and *PA* products of only $0.79 \times 10^{-5}$ $Jm^2$ and 0.157 $Wm^2$ respectively. As mentioned previously, three stations have routinely tracked the Apollo reflectors but only at night with low noise background and single photon returns. Nevertheless, the same *EA*-product, which is only about 70% larger than a MOBLAS, should permit transponder links beyond 100 AU under equivalent operating conditions.

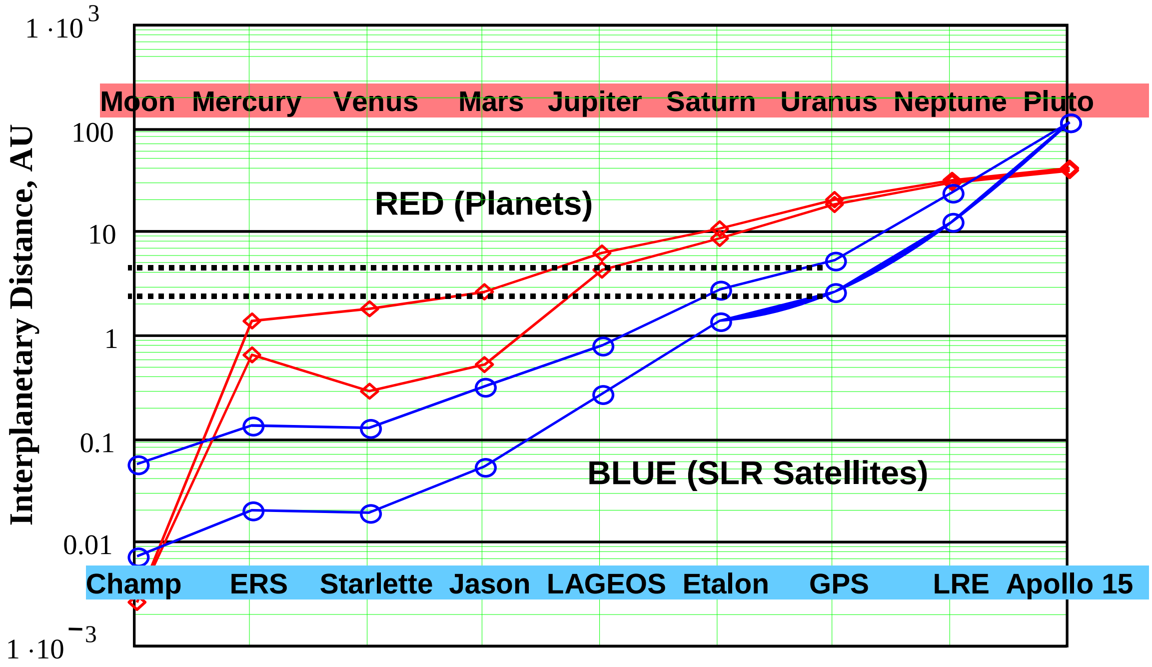

***Figure 2:*** *The minimum and maximum distances from the Earth to the Moon and the 8 planets listed at the top of the graph is illustrated by the two red curves in the figure. The minimum and maximum transponder ranges simulated by the various SLR satellites listed at the bottom of the figure is indicated by the two blue curves.*

***Table 1:*** *Characteristics of selected SLR satellites which can be used to simulate Deep Space transponder or lasercom links (altitudes and cross-sections from ILRS web site).*

| **Satellite** | **Altitude (km)** | **Cross-section ($10^6$ m$^2$)** | **Transponder Range (AU)** | **Simulation** |
|---|---|---|---|---|
| **Champ** | 500 | 1.0 | 0.007-0.057 | Beyond Lunar (0.0026 AU) |
| **ERS 1 & 2** | 800 | 0.85 | 0.02-0.135 | |
| **Starlette/Stella** | 950 | 1.8 | 0.019–0.123 | |
| **Jason** | 1,300 | 0.8 | 0.054-0.306 | |
| **LAGEOS** | 6,000 | 15 | 0.263-0.771 | Mercury, Venus, Mars (0.28 to 2.52 AU) |
| **ETALON** | 19,000 | 55 | 1.38-2.72 | |
| **GPS** | 20,000 | 19 | 2.60-5.06 | Jupiter near PCA (4.2 AU) |
| **LRE (elliptical)** | 25, 000 (max) | 2 | 12.52-23.12 | Beyond Jupiter, Saturn (4.2 to 10 AU) |
| **Apollo 15** | 384,000 | 1,400 | 111.6 | Beyond Outer Planets & Kuiper Belt (40 to 50 AU) |

## Summary

Based on the recent successful GSFC experiments to the Messenger and MGS spacecraft, the space-qualified technology for decimeter accuracy interplanetary laser transponders is clearly available now. More compact sub-centimeter accuracy photon-counting systems can be made available within 2 to 3 years with very modest technology investments, and interest in fundamental physics experiments using transponders at NASA is high. Furthermore, detailed exploration of remote planets and moons with modern high data rate sensors previously developed for near-Earth applications will require high bandwidth lasercom systems to transmit the data back to Earth.

The link equations for laser transponders and communications are identical. We have demonstrated that retroreflector arrays on international SLR spacecraft are capable of simulating interplanetary transponder and lasercom links through the turbulent atmosphere. This provides a means for testing potential ground and spacecraft hardware, acquisition procedures, and ranging and time transfer algorithms prior to mission approval. New SLR targets on future HEO/GEO missions could provide an improved testbed with long experiment times and temporally uniform signal strengths. They could also provide better simulations of future missions to the outer planets (e.g. Jupiter and Saturn). In fact, the Jovian moon, Europa, and the Saturnian moons, Titan and Enceladus, have been identified as the top three priorities for exploration by NASA's Outer Planets Advisory Group (OPAG) in their July 2006 report.

The one drawback of using the current SLR target arrays for dual station experiments is that they are composed of large, "spoiled" [Degnan, 1993] retroreflectors. The angularly tight but complex far field patterns produced by these arrays force the stations to lie within a few hundred meters of each other and result in a signal strength which varies with both time and spacecraft-station geometry. Large panels of unspoiled small diameter retroreflectors (~7 mm) placed on future high altitude satellites (GPS/GLONASS altitudes or higher), on the other hand, would relax the proximity requirements for the dual stations to a few km, extend experiment times to several hours or more, and eliminate retroreflector-induced temporal non-uniformities in the return signal strength.

## Acknowledgement

This work was initiated following a lively technical discussion on potential ways to demonstrate transponder technologies with Dr. Ulrich Schreiber at the October 2005 ILRS Workshop in Eastbourne, UK.

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# Laser Ranging At Planetary Distances from SLR 2000

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## Abstract

*The SLR2000 prototype system will be participating in two separate planetary transponder laser ranging experiments: (1) as one end of the Goddard in-house asynchronous transponder experiment in 2007, and (2) as the primary ground station for one-way ranging to the Lunar Reconnaissance Orbiter (LRO) in late 2008 and 2009.*

*The modifications to SLR2000 to participate in these projects are relatively few and are very synergistic with the SLR completion effort. This paper describes the transponder experiments and the changes required at SLR2000.*

## Introduction

SLR2000 is the prototype for NASA's Next Generation of Satellite Laser Ranging (SLR) Systems. It was originally designed to be a completely automated, eye-safe Satellite Laser Ranging System, with a lower cost of operation, a high reliability, and an accuracy comparable to the existing NASA MOBLAS systems [McGarry]. Because of its arcsecond level pointing capability, its timing accuracy (both absolute and relative) and its ability to independently measure fire and return times, this system is an excellent candidate for transponder work.

The 1.2 metre telescope (aka 48 inch telescope) was developed by Goddard in 1974 as a research and development facility. It has hosted many laser ranging and other experiments over the years including the first successful 2-way asynchronous transponder experiment at 24 million kilometres with the Mercury Laser Altimeter (MLA) on the MESSENGER spacecraft in 2005, and the first successful 1-way laser ranging experiment at ~80 million kilometres with the Mars Obiter Laser Altimeter (MOLA) on the MGS spacecraft orbiting Mars, also in 2005. The 1.2 metre telescope is owned and operated by the Laser Remote Sensing Branch (code 694) at the Goddard Space Flight Center.

Both systems are located at Goddard's Geophysical and Astronomical Observatory (GGAO) which has been the site of most of NASA's ground breaking work in laser ranging, including the some of the first laser ranging returns ever recorded, the development and checkout of the MOBLAS and TLRS systems in the late 1970s and early 1980s, and the MLA and MOLA Earthlink experiments described above. It is also home to MOBLAS-7 which is the NASA SLR Network standard for performance.

## Two-way asynchronous transponder demonstration

The goal of this in-house Goddard project is to demonstrate two-way asynchronous acquisition and ranging between two ground systems at Goddard's Geophysical and Astronomical Observatory (GGAO). The 1.2 metre telescope will function as the planetary spacecraft and will transmit at 50Hz in the IR (1064nm) and receive SLR2000's green (532nm) returns. SLR2000 will function as the ground station,

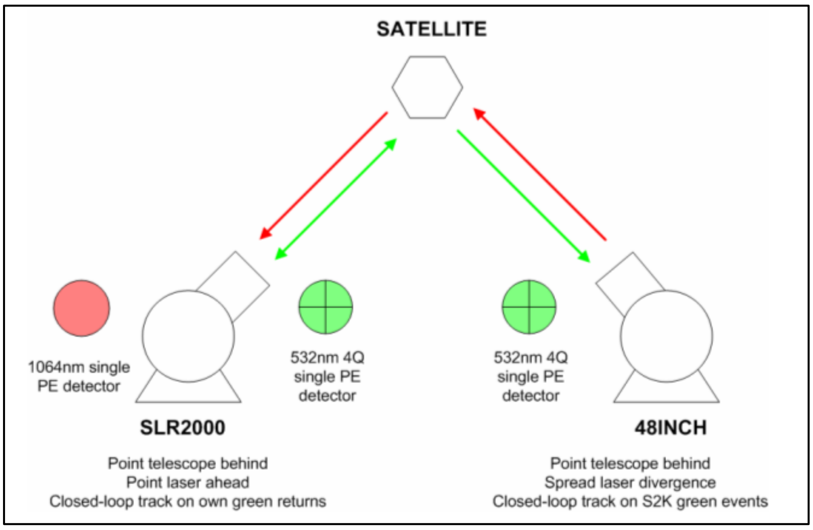

***Figure 1:*** *Two-way asynchronous transponder experiment concept*

firing at 2 khz in the green and receiving the 1.2 metre telescope's IR returns. The laser pulses will be bounced off of retro-reflector equipped satellites to provide the simulation of planetary distances (Figure 1). The stations are sufficiently close that both are within the return footprint from the satellites. SLR2000 will closed-loop track on its own green returns and the 1.2 metre will closed-loop track on the green SLR2000 returns. Fire and return times will be collected by each station. A clock will be used at the 1.2 metre telescope that will simulate the frequency drift of a spacecraft clock. The event information from both stations will be used as input to analysis software that will determine the ranges, clock offset and frequency drift between stations.

Optical breadboard space has been added to SLR2000 to support this experiment along with a dichroic beam splitter (532nm / 1064nm) for the receive channel, beam reduction optics, a narrow band pass filter, and a fiber optic delivery to the 1064nm photodetector (Figure 2). The candidate detector is a Perkin Elmer model SPCM-AQC(4) photodetector with a quantum efficiency of ~2% and better than 500 picosecond jitter. An additional discriminator will be added and one additional event time channel will be used (for the 1064nm returns). There are minimal software changes required to the operational software at SLR2000 to perform this experiment.

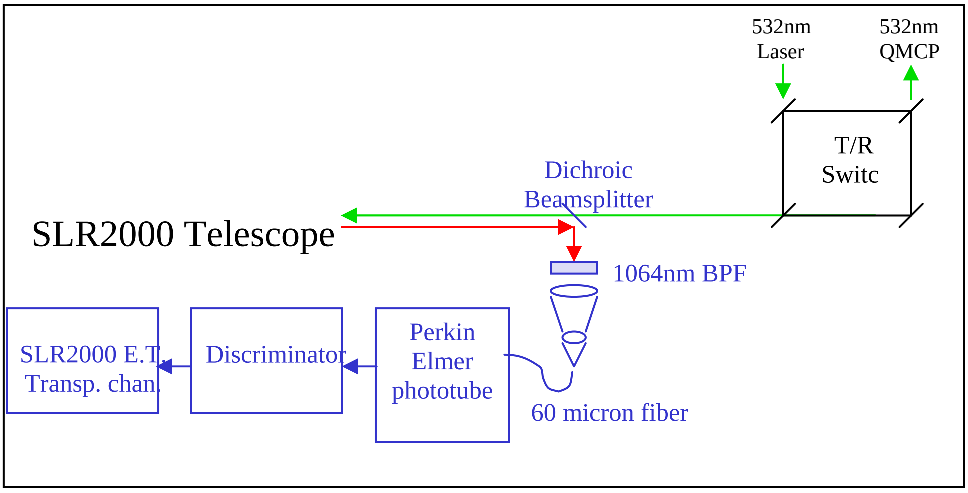

***Figure 2:*** *Additions for 1064nm transponder returns at SLR2000*

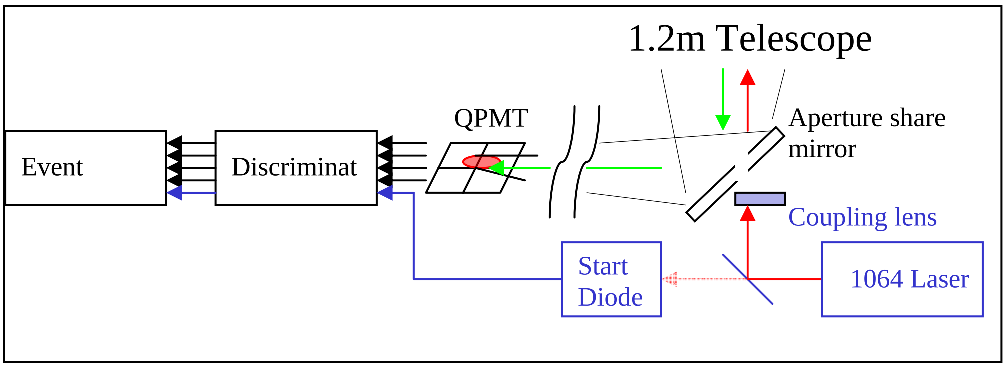

*Figure 3: 1.2 meter telescope configuration for transponder experiment*

Modifications to the 1.2 metre telescope configuration include the addition of a 532nm ungated single photon quadrant detector (Hamamatsu metal channel dynode PMT) and four discriminators, along with a band pass filter for the 532nm events from SLR2000 and a 1064nm blocking filter to prevent backscatter from local laser (Figure 3). Much of the configuration used for the MLA-Earthlink and MOLA-Earthlink experiments will be used for this project including the computer, the Time-to-Digital Converter (TDC), the Continuum Inlite II-50 laser (up to 50 Hz at 1064nm with a 6 nanosecond pulse width), and aperture sharing of the transmit-receive. Software modifications include handling of the four quadrant channels for closed-loop tracking.

The transmit and receive times from both SLR2000 and the 1.2m telescope will be processed to remove the noise. The clock bias and drift can be modeled as a linear function of the 1.2 metre telescope's time. The range error can be modeled as a quadratic equation in time. A least squares fit of the fire and receive event data to the resulting equations (shown below in Figure 4) would then provide the ranges as well as the relative clock offset and drift.

Both systems are nearing completion of the required modifications and both have tracked green returns from MOBLAS-7's fires. The 1.2 metre telescope's mirrors are in the process of being recoated in preparation for an upcoming laser communications experiment. When the recoating is complete in the spring of 2007 the two-way asynchronous transponder data collections will begin.

## One-way laser ranging to the Lunar Reconnaissance Orbiter

The function of the Earth to LRO laser link is to achieve the mission's precision orbit determination requirement. The requirements on the SLR2000 ground station to accomplish this are:

1. Between 1 and 10 femtoJoules per square centimetre of signal must be delivered to the LRO-LR receiver aperture. For the SLR2000 laser with a 55 microradian laser divergence, this implies 30 milliJoules per pulse.

2. The wavelength must be 532 nm and the 3 Angstrom LRO-LR filter will be tuned to the actual SLR2000 laser in the lab.

3. The laser pulse width must be less than or equal to 8 nanoseconds FWHM.

4. Laser pulses must be delivered into the LOLA earth window at 28Hz.

5. The transmitted pulse time stamp accuracy must be maintained within 100 ns of UTC.

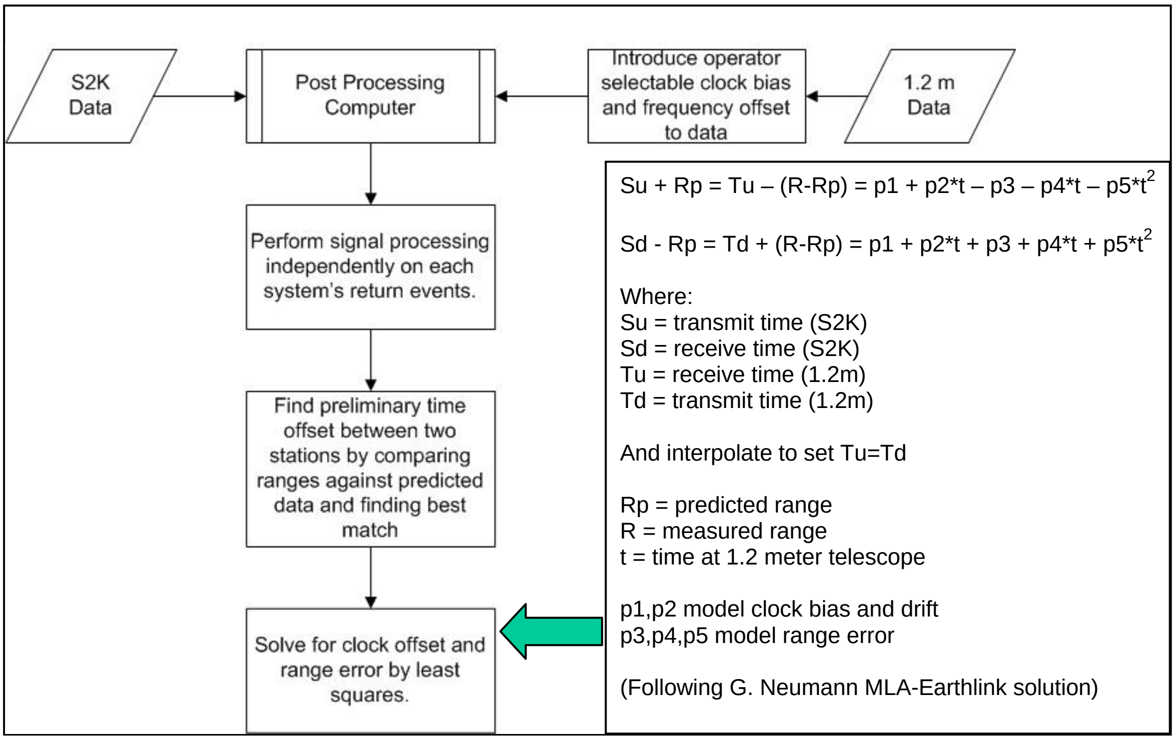

***Figure 4:*** *Post processing of fire and receive event times at two stations*

6. The relative laser time of fire must be measured to better than 200 picoseconds (1 sigma) shot-to-shot over a 10 second period. The laser fire time must be recorded to better than 100 picosecond resolution.

7. The frequency stability of the station's clock must be equal or better than 1.e-12.

8. The system must provide better than 407 hours of ranging data to LRO during year after launch. This number is achievable and takes into account the LRO visibility from the station, the outages due to weather, system failures, as well as aircraft avoidance outages.

To accomplish these requirements SLR2000 is purchasing a 28 Hz diode pumped Nd:YAG master oscillator power amplifier (MOPA) laser that can deliver up to 50 milliJoule per pulse at 532 nm in a 6-8 nanosecond pulse. It is a turn-key system with a projected lifetime of greater than 1 year of continuous use. Additional optical table space has been added for the laser and a removable kinematic mirror mount will be inserted to launch the LRO transmit beam and ensure an easy transition between SLR and LRO lasers. Because this laser is not eye-safe, an aircraft avoidance radar is also being added to the system.

The software for SLR2000 is being modified to handle the new laser parameters, to control the laser fire to hit the earth window on the spacecraft, to take new operator commands for control of the new laser, and to handle predictions for non-earth-orbiting satellites.

LRO-LR will be launched in late 2008. SLR2000 will be staffed to support the mission 10 hours a day, 7 days a week to cover those times when the moon is above 20 degrees elevation. LRO is visible to earth about one hour out of every two.

During the hour that the spacecraft is behind the moon SLR2000 will range to earth orbiting satellites with the eye-safe 2 khz SLR laser.

## Summary

Transponder experiments will extend capabilities of SLR2000 and demonstrate the system's ability to do planetary ranging which is the future of laser ranging. Earth orbiting satellite laser ranging and planetary transponder ranging can co-exist in SLR2000 and transitioning between the two will be seamless. The in-house Transponder experiment will complete in late 2007. The LRO mission will run from Fall 2008 through January 2010.

## Acknowledgements

The authors would like to thank John Degnan for the original concept of bouncing laser pulses off of earth orbiting satellites to simulate planetary transponder ranging [Degnan].

We would like to thank the LOLA Instrument Principal Investigators David Smith and Maria Zuber for their efforts in getting laser ranging selected for LRO, as well as Xiaoli Sun, Greg Neumann, Ron Zellar, and David Carter for their continued support in the development of the LRO-LR ground system.

We would also like to thank our colleagues who have worked on the transponder experiment and on LRO-LR, including Christopher Clarke, Ray DiSilvestre, Howard Donovan, Julie Horvath, Anthony Mallama, Anthony Mann, Carey Noll, Donald Patterson, Randall Ricklefs, David Rowlands, Mark Torrence, and Susan Valett.

The 2-way asynchronous transponder work is being performed with Goddard in-house IRAD funding. The LRO-LR work is being performed with funding from the Lunar Reconnaissance Orbiter Mission.

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# Laser Ranging to the Lunar Reconnaissance Orbiter (LRO)

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## Abstract

*LRO will be launched in late 2008 carrying, amongst other payloads, the Lunar Orbiter Laser Altimeter (LOLA) which is a 1064nm laser altimeter for mapping the lunar surface, and the Laser Ranging (LR) receiver which is mounted on the earth-pointed High Gain Antenna (HGA). Laser Ranging with LRO (LRO-LR) is one-way from earth to spacecraft and will be used along with S-band tracking data and the LOLA altimeter data to develop an improved gravity model for both the near and far sides of the moon. SLR2000 will be the primary laser ranging station, but the project would like to extend an invitation to ILRS stations for their participation. The requirements for ranging include satisfying the laser wavelength (to match the onboard filter at 532nm), repetition rate (to hit the range window but minimize impact to the onboard threshold algorithm), transmit energy (to cross the detector threshold), and station timing (to ensure precise transmit time recording). The requirements are very similar to those for earth orbiting satellite laser ranging. We hope that many of you will consider participating in this exciting transponder experiment.*

## Introduction

LRO is a robotic component of the Moon to Mars vision proposed in January, 2004. LRO will be launched in October 2008 into a polar orbit around the Moon with an average altitude of 50 km. Lunar gravity necessitates orbital maintenance every 30 days (30-70 km altitude range) to maintain the polar orbit for the one-year nominal mapping mission. The LRO spacecraft has a suite of seven instruments: LOLA, a laser altimeter; LROC, a camera; LAMP, a Lyman alpha telescope; LEND, a neutron detector; DIVINER, a thermal radiometer; CRATER, a cosmic ray detector; and the mini-RF, radar technology demonstration. The LOLA altimeter addresses the geodetic measurement objectives of NASA’s robotic lunar exploration program, in particular – “Determine the topography of the Moon to geodetic quality from global to landing-site relevant scales.” and “Assess metre and smaller-scale features to facilitate safety analysis of potential future lunar landing sites”.

The precise determination of the Lunar topography from LOLA data, and positioning of the measurements made by other LRO instrument suite on the lunar surface requires accurate LRO orbits. The LRO orbits will be determined by high quality tracking of LRO and improvement in the knowledge of the Lunar gravity field. To enhance the orbit determination, the LRO mission includes a one-way laser ranging (LR) capability. The LR data will provide a 10 cm precision measurement of the position of LRO. In conjunction with the LOLA data, LRO positional accuracies will be 50 to 100 m along track and 1 metre radially from the Lunar center of mass after improvement of the lunar gravity field. One SLR station (Greenbelt, MD) is presently planned to track LRO; we are hoping for a second US station and help from the international SLR network.

### Measurement technique

The LRO-LR measurement is a one way range from earth to spacecraft with the ground station recording the time of the laser fire and the LOLA instrument onboard LRO recording the pulse arrival time. The 2 cm aperture LR receive telescope will be mounted on the spacecraft's High Gain Antenna (HGA). The optical signal will be routed via fiber optic cable to the LOLA instrument (see Figure 1). One of LOLA's five lunar detectors will receive the earth pulses as well as the lunar surface events.

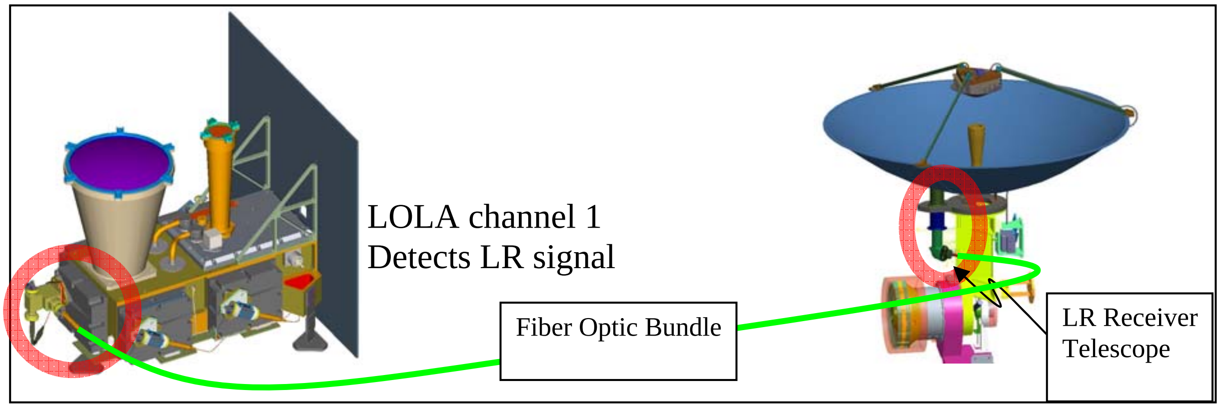

***Figure 1:*** *Optical signal path from HGA to LOLA instrument.*

SLR2000 is the primary ground station for LRO-LR and is required to transmit at 28Hz (the LOLA instrument's fire rate), and to control its laser fire times to ensure that all pulses arrive in the LOLA earth windows as shown in Figure 2 [McGarry]. There is no corresponding requirement for other participating stations to control their laser fire times, however, to ensure a minimum of one pulse per second arrival in the earth window, fire rates of 5 Hz and 10 Hz should be used when the laser fire time is not controlled.

No ground station should fire at LRO faster than 28Hz. Events that occur outside LOLA's range windows (earth or lunar) are interpreted as noise and will affect the threshold level which is controlled by a feedback loop based upon the noise counts outside the windows.

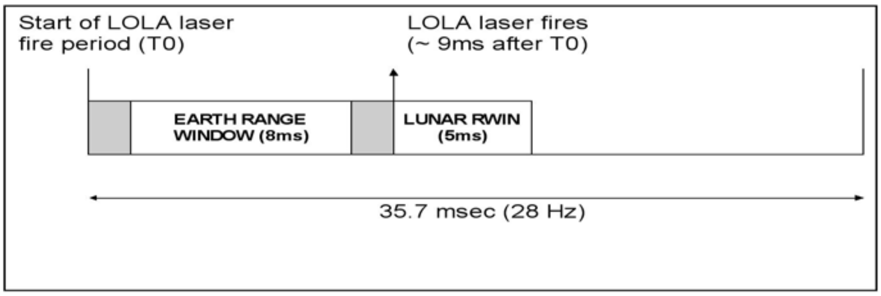

***Figure 2:*** *Timing of LOLA earth window relative to lunar window within the 28Hz laser fire period*

## Ground System Requirements

Stations participating in the LRO-LR experiment must satisfy the following requirements:

1. Deliver between 1 and 10 femtoJoules per square centimetre of signal to the receiver aperture. For SLR2000 with its 55 microradian laser divergence this translates into a transmit energy of 30 milliJoules per pulse.
2. The transmitting wavelength must be 532 nm. The exact wavelength will be determined in Spring 2007. The spacecraft filter is 3 Angstroms in width. A filter assembly will be sent to all interested stations later in 2007 to allow each station to determine if its laser meets the requirements.
3. The laser pulsewidth must be less than 8 nanoseconds.
4. The transmitted pulse time stamp accuracy must be maintained within 100 nanoseconds of UTC.
5. The system must measure the relative laser time of fire to better than 200 picoseconds (1 sigma) shot-to-shot over a 10 second period. Laser fire times must be recorded to better than 100 picosecond resolution.
6. The system should deliver at least one laser pulse to the LOLA earth window per second. The laser fire rate cannot exceed 28 Hz.
7. A shot to shot measurement of the output laser energy is desirable.
8. Data should be delivered to CDDIS in new ITDF (simple ASCII format) no slower than daily.

Most ILRS systems should have no problem meeting these requirements.

Other requirements will include coordination with the mission so that coverage can be limited to a single station at a time (at least initially), and reporting so that the mission knows ahead of time which stations will be participating each day.

## Operational Considerations

The period of the LRO orbit is approximately 2 hours. The orbit is polar and precesses so that at times the entire 2 hour orbit will be visible from earth. Due to the constraints on the HGA pointing, however, only ~1 hour out of each 2 hour orbit will be available for earth ranging, no matter what the orbital orientation is.

Predictions for LRO will be generated in CPF format. Code for non-earth orbiting satellites will be made available to all ILRS stations by Randy Ricklefs later this year [Ricklefs].

Feedback will be provided from LOLA in its housekeeping telemetry which will be delivered in semi-real-time from the spacecraft, through the LOLA Science Operations Center (SOC), to CDDIS. LOLA will be performing signal processing on the data in the earth window and should be able to recognize earth laser pulses that are fired synchronously to LOLA at 14 or 28Hz. Laser fire rates of 5 and 10 Hz will not be recognized by LOLA, however, the website, http://lrolr.gsfc.nasa.gov ,will contain other information as well (possibly a Go-NoGo flag), so participating stations should check it when ranging to LRO.

The flow of all of the data for LRO-LR is shown in Figure 3.

Stations interested in participating as a ground station for LRO-LR are invited to contact the authors or Michael Pearlman (mpearlman@cfa.harvard.edu).

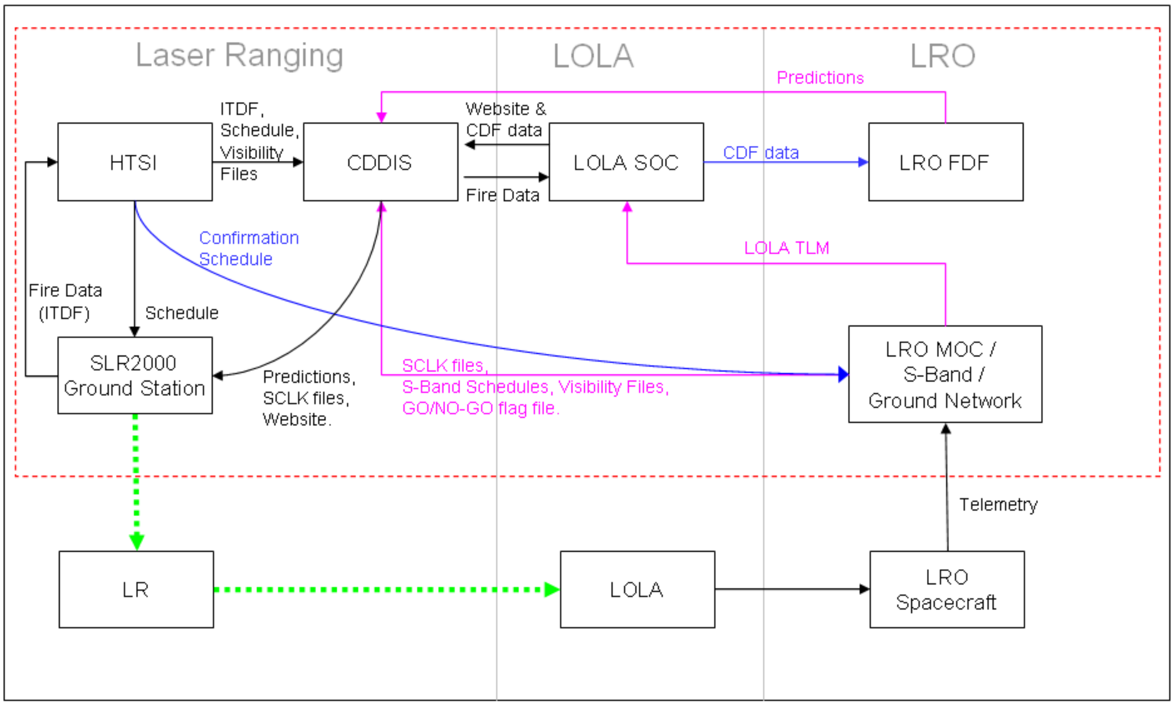

***Figure 3:*** *LRO-LR data flow block diagram.*

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