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

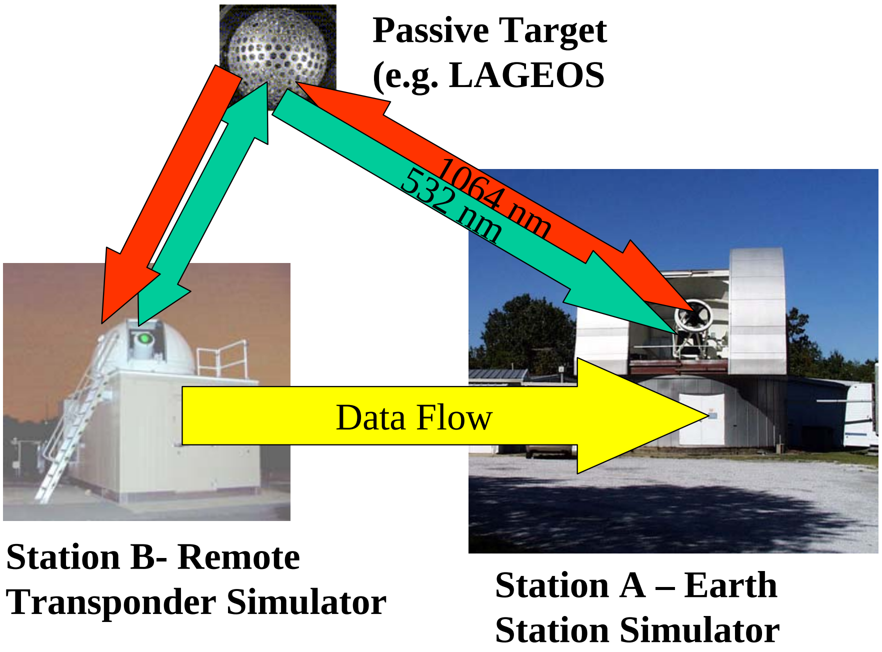

Figure 1: *Dual station laser ranging to LAGEOS with, for example, the GSFC 1.2 meter telescope facility simulating the Earth station and NASA's 40 cm aperture SLR2000 system simulating the remote terminal.*

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 η_q, the photon energy $h\nu$, the one-way zenith atmospheric transmission T_a, the satellite zenith angle θ_A, the divergence half-angle of the laser beam θ_t, the target optical cross-section σ_t, measured in square meters, and the optical throughput efficiencies of the transmitter (η_t) and receiver (η_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 $0^o \leq \theta_A \leq 70^o$, 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 0.79×10^{-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.

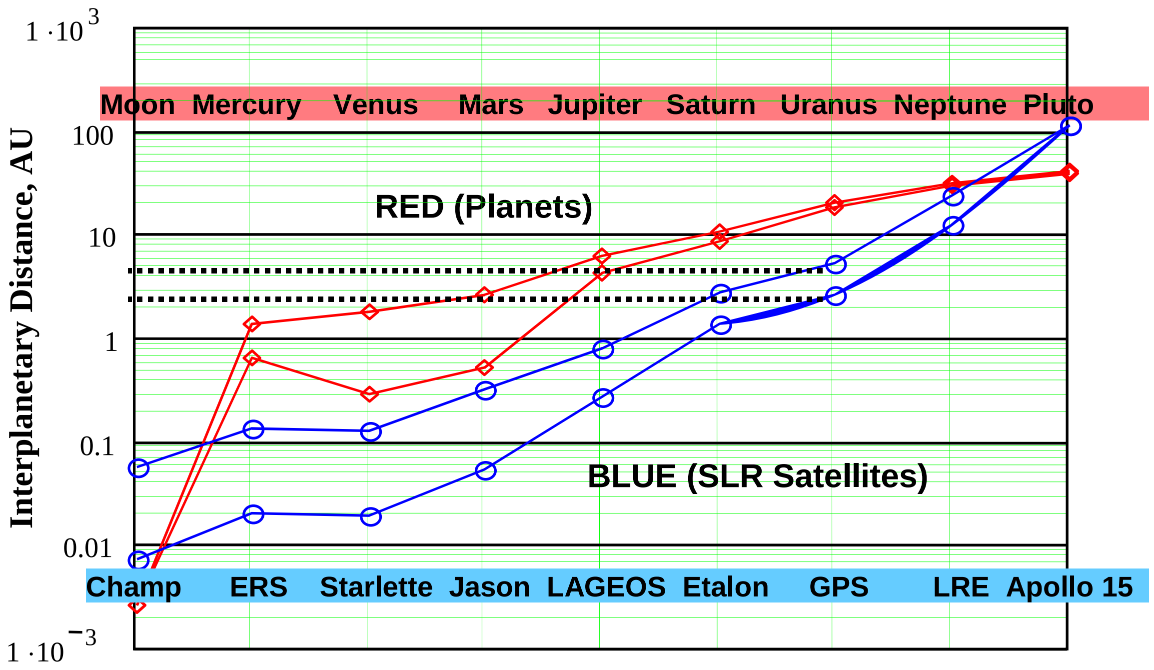

***Figure 2:** The minimum and maximum distances from the Earth to the Moon and the 8 planets listed at the top of the graph is illustrated by the two red curves in the figure. The minimum and maximum transponder ranges simulated by the various SLR satellites listed at the bottom of the figure is indicated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

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References

[1] Degnan, J.J., "Millimeter Accuracy Satellite Laser Ranging: A Review", in Contributions of Space Geodesy to Geodynamics: Technology, D. E. Smith and D. L. Turcotte (Eds.), AGU Geodynamics Series, Volume 25, pp. 133-162, 1993

[2] Degnan, J. J., "Asynchronous Laser Transponders for Precise Interplanetary Ranging and Time Transfer", Journal of Geodynamics (Special Issue on Laser Altimetry, pp. 551-594, November, 2002.

[3] Degnan, J. J., "Photon Counting Microlaser Rangers, Transponders, and Altimeters", Surveys in Geophysics, Special Issue on Evolving Geodesy, Vol 22, Nos. 5-6, pp. 431-447, 2001.

[4] McGarry, J., T. Zagwodzki, P. Dabney, P. Dunn, J. Cheek, "Laser Ranging at Planetary Distances from SLR2000", these proceedings, 2006.

[5] Smith, D.E., M. T. Zuber, X. Sun, G. A. Neumann, J. F. Cavanaugh, J. F. McGarry, and T. W. Zagwodzki, *Science*, **311**, p. 53, 2006.