

Brief Introduction to Two-Way Transponder Technique for Ranging and Time Transfer

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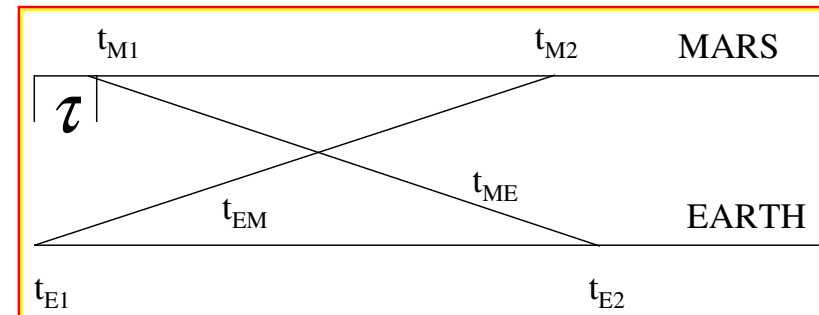
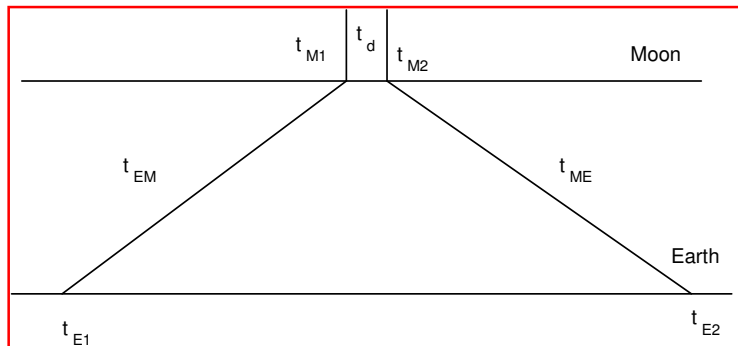
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Laser Transponders: Laser Ranging Beyond the Moon

- Given the current difficulty of laser ranging to passive reflectors on the Moon, conventional single-ended ranging to passive reflectors at the planets is unrealistic due to the R^{-4} signal loss.
- Since double-ended laser transponders have active transmitters on both ends of the link, the signal strength falls off only as R^{-2} and this makes interplanetary ranging and time transfer possible.

Types of Two-Way Transponders*



- **Echo Transponders ($R \ll 1 \text{ AU}$)**

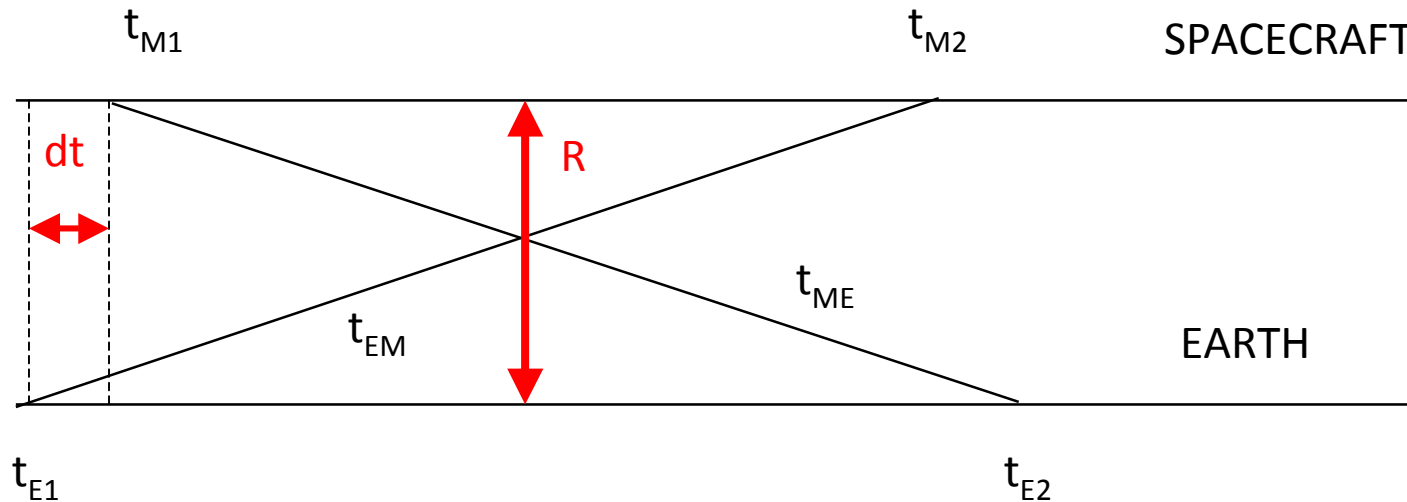
- Spacecraft transponder detects pulses from Earth and fires a reply pulse back to the Earth station.
- To determine range, the delay t_d must be known a priori (or measured onboard and communicated back to Earth) and subtracted from the measured round-trip time-of-flight at the Earth station.
- Works well on “short” links (e.g. to the Moon) where the single shot detection probability at both terminals is high.

- **Asynchronous Transponders ($R > 1 \text{ AU}$)**

- Transmitters at opposite terminals fire asynchronously (independently).
- Signal from the opposite terminal must be acquired autonomously via a search in both space and time (easier when terminals are on the surface or in orbit about the planet)
- The spacecraft transponder measures both the local transmitter time of fire and any receive “events” (signal plus noise) on its own time scale and transmits the information back to the Earth terminal via the spacecraft communications link. Range and clock offsets are then computed.
- This approach works well on “long” links (e.g., interplanetary) even when the single shot probability of detection is relatively small

*J. Degnan, *J. Geodynamics*, Nov. 2002.

Timing Diagram and Non-Relativistic Equations for Asynchronous Ranging and Time Transfer

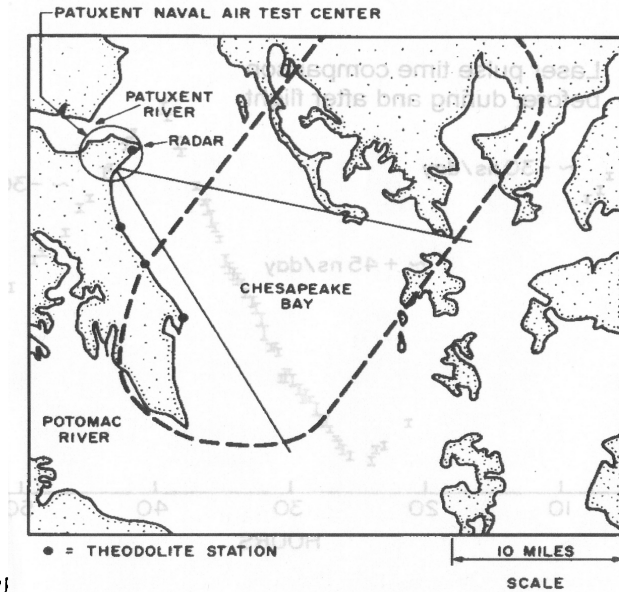
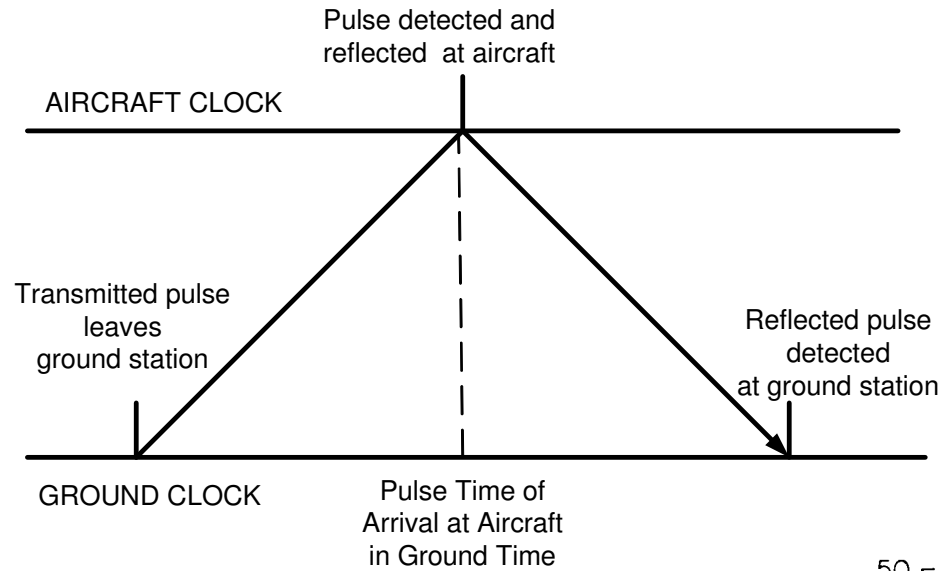


Range $R = c(t_{ME} + t_{EM})/2 = c [(t_{E2} - t_{E1}) + (t_{M2} - t_{M1})]/2$

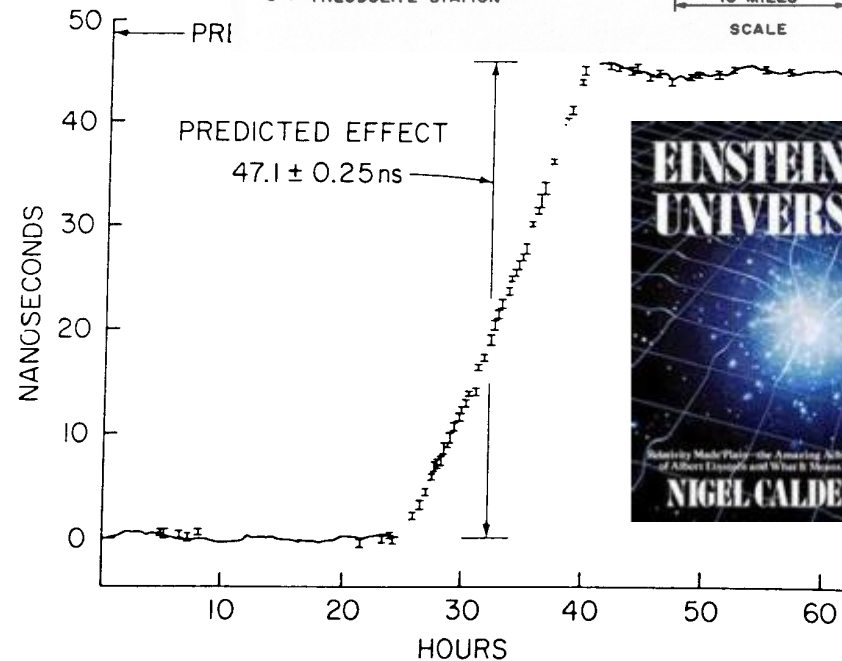
Clock Offset $dt = [(t_{E2} - t_{E1}) - (t_{M2} - t_{M1})]/[2(1 + R/c)]$

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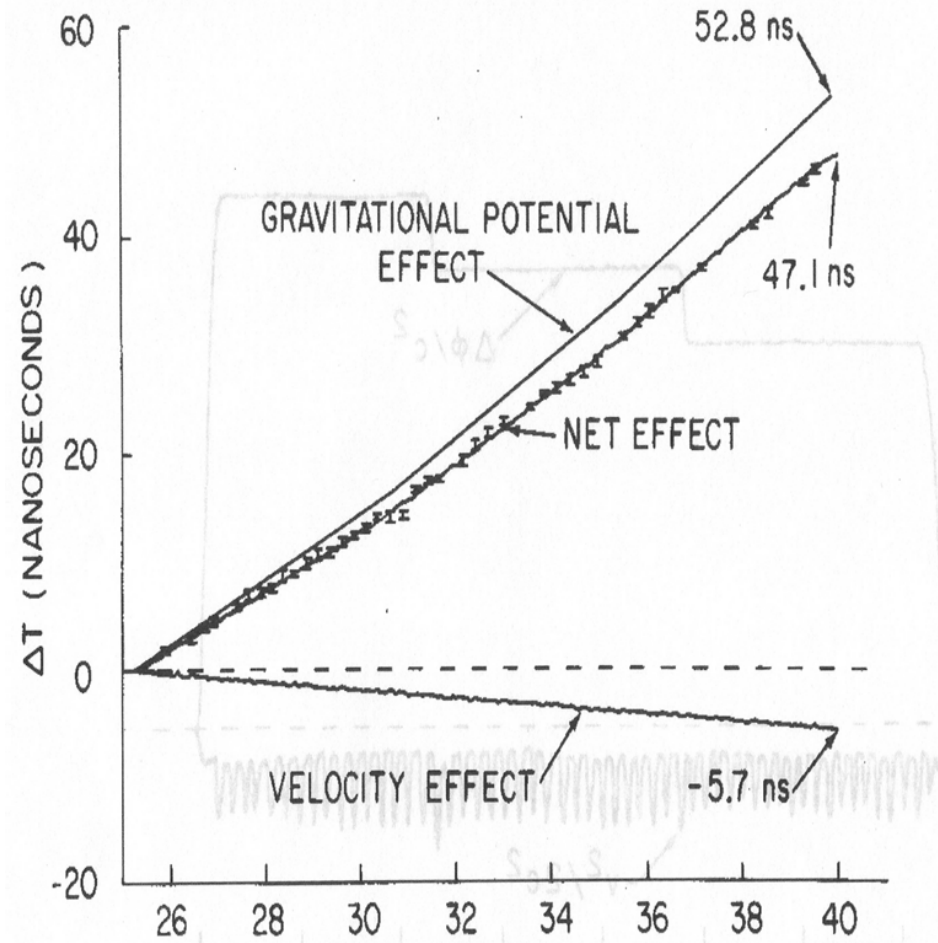
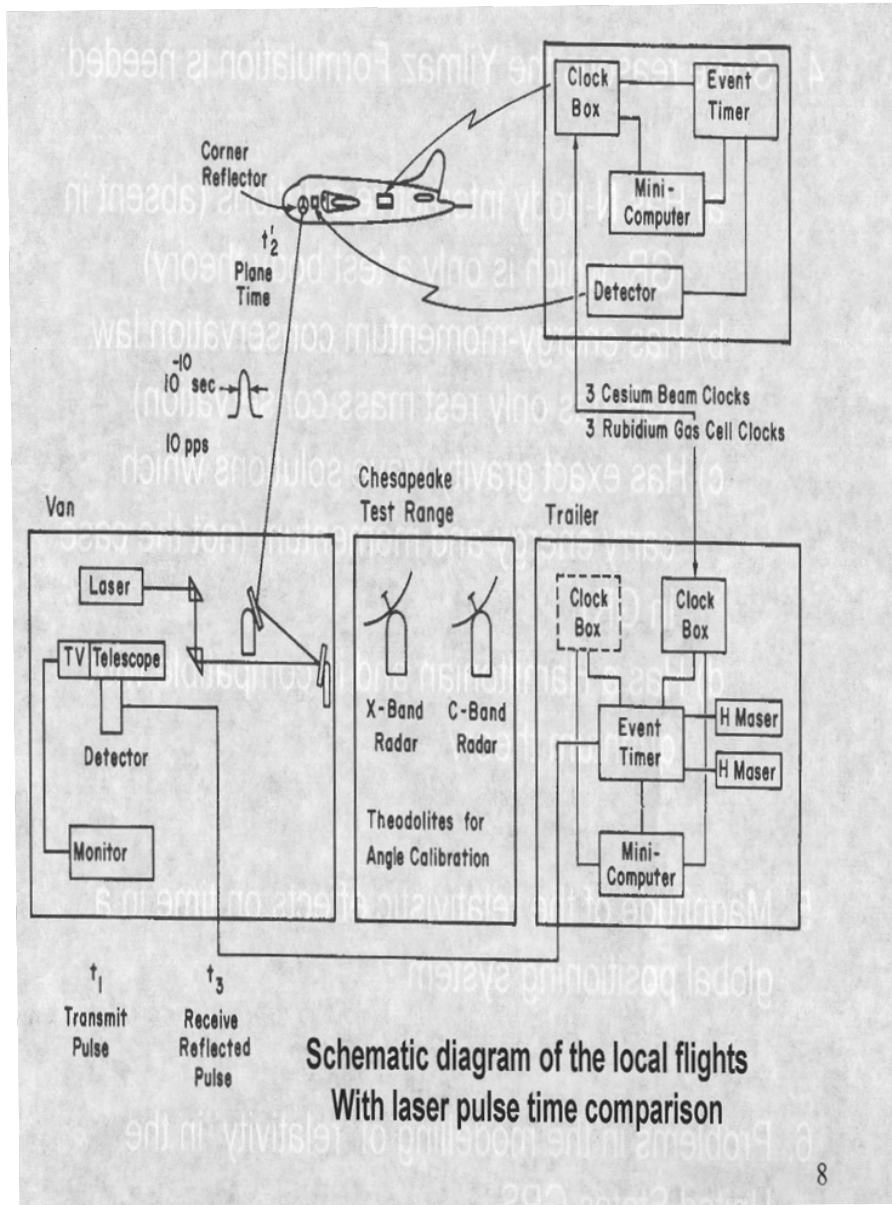
Univ. of Maryland Airborne Atomic Clock Experiment (C. O. Alley et al, 1975)



Gravitational redshift **52.8 ns**
Time dilation **-5.7 ns**
Net effect **47.1 ns**

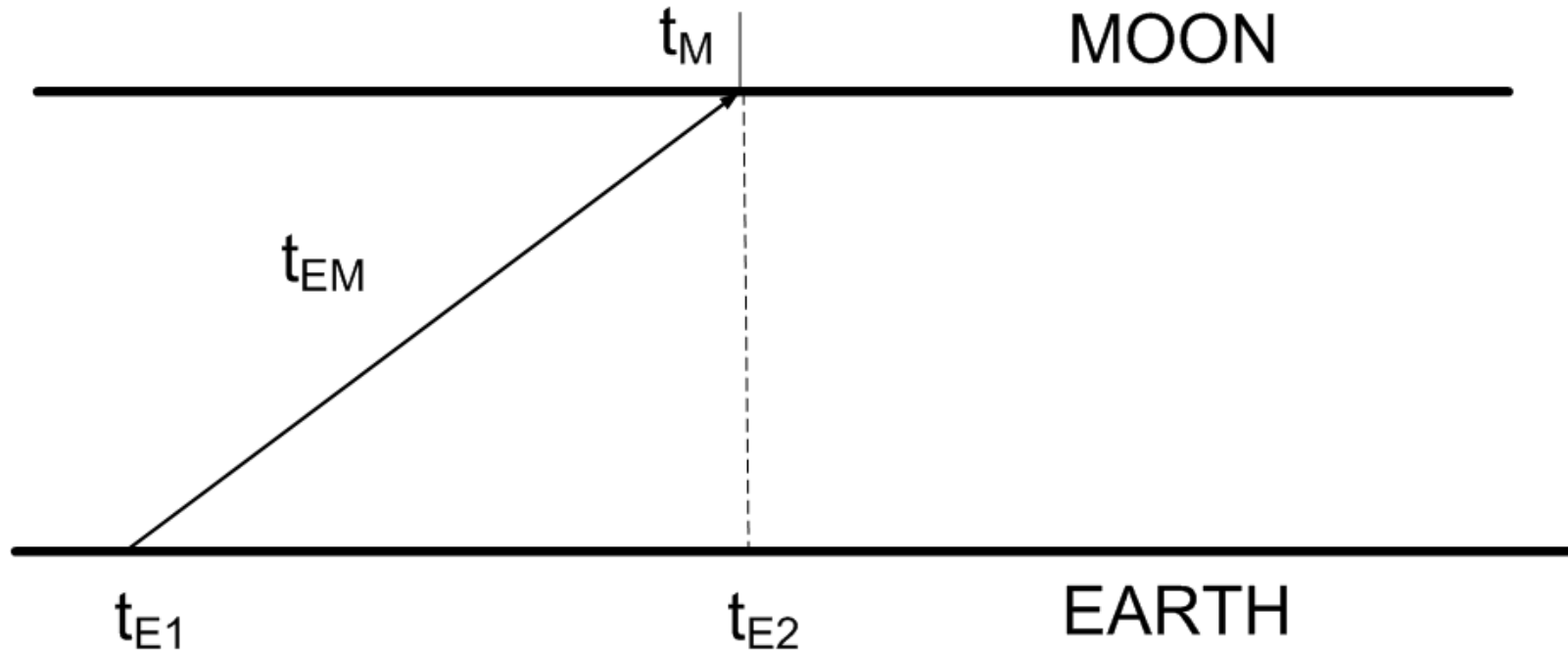


World's Most Expensive Altimeter



Transponders can sense the localized gravity field via its effect on an atomic clock. Average drift rate was 3 nsec/hr or 50 psec/min or 0.8 psec/sec or less than one part per trillion!

One Way Transponder



Actual Range $R = c(t_{E2} - t_{E1})$

Measured Range $R_m = c(t_M - t_{E1})$

Range Error $\Delta R = R_m - R = c(t_M - t_{E2}) = c\Delta t$

One-way ranging requires good synchronization between the Earth and spaceborne clocks
($\Delta t = 33$ psec for 1 cm ranging)

Transponder Experiment Summary

Early Attempts

- December, 1997: First two-way attempt between NASA/GSFC 1.2 meter telescope and Mars Orbiter Laser Altimeter (MOLA-2) on the NASA Mars Global Surveyor (MGS) spacecraft at a distance of 10 million km was unsuccessful due to exceptionally cloudy skies at GSFC.
- January, 1998: Two-way attempt between NASA/GSFC 1.2 meter telescope and a laser altimeter onboard the Near Earth Asteroid Rendezvous (NEAR) spacecraft, at a distance of 5 million km, was foiled again by heavy cloud cover during the period allocated to the experiment.
- 1998: Second attempt by GSFC between USAF Starfire 3.5 m telescope and MOLA-2, at 100 million km, was aborted when the MGS spacecraft went into several month "safe mode" just prior to experiment start.

Successful Experiments and Operations

1. May-June, 2005: Successful two-way experiment between NASA/ GSFC and the Mercury Laser Altimeter (MLA) on the NASA Messenger spacecraft at a distance of 24 million km. Range measured to w20 cm
2. September 2005: Successful one-Way experiment from NASA GSFC to MOLA-2 in mars orbit at a distance of 80 million km. Several hundred Earth pulses detected. MOLA-2 laser had failed prior to the experiment.
3. Operational one-way ranging from multiple ILRS stations to the Lunar Orbiter Laser Altimeter (LOLA) on the NASA Lunar Reconnaissance Orbiter (LRO) spacecraft at a distance of 385,000 km.

Future Transponder Missions:

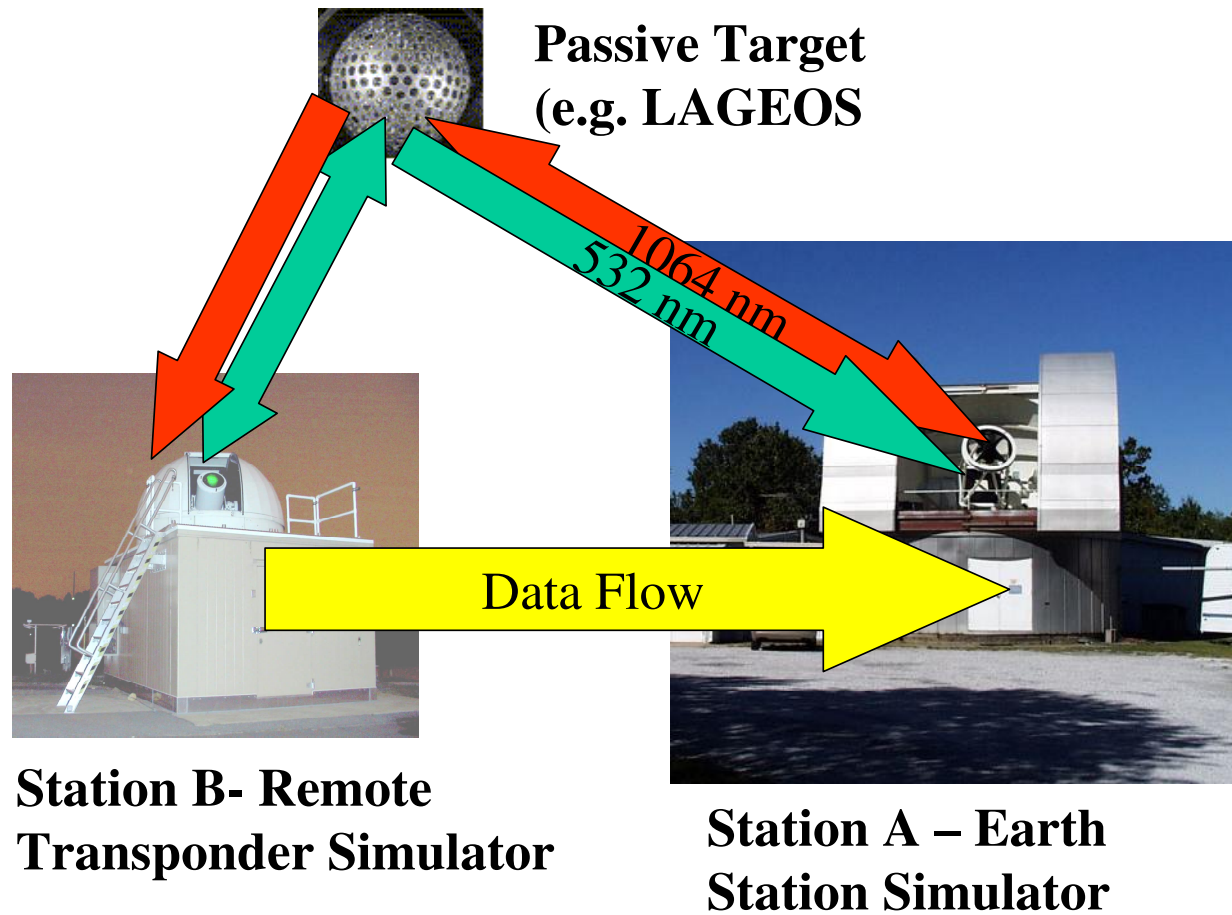
1. Continued one-way operations to LRO.
2. Further experiments to Messenger at Mercury likely.
3. ESA GETEMMEE Mission to Mars (Expected launch :2020-2022)
4. ESA Search for Anomalous Gravitation using Atomic Sensors (SAGAS)

Where do we go from here?

- **Messenger and MOLA were experiments of opportunity rather than design.**
 - Since the spacecraft had no ability to lock onto the opposite terminal or even the Earth image, the spaceborne lasers and receiver FOV's were scanned across the Earth terminal providing only a few seconds of data.
 - Detection thresholds were relatively high due to the choice of wavelength (1064 nm) and analog detectors
 - Precision was limited to roughly a decimeter by the long laser pulsewidths (6 nsec) and comparably “slow” receiver bandwidths.
- **The physical size, weight, and accuracy of future interplanetary transponder experiments will benefit from current SLR photon-counting technologies, including:**
 - Multi-kHz, low energy, ultrashort pulse lasers (10 to 300 psec)
 - Single photon sensitivity, picosecond resolution, photon-counting receivers
 - Automated transmitter point ahead and receiver pointing correction via photon-counting quadrant detectors (e.g. NASA's NGSLR).
- **Pre-launch testing and evaluation of advanced transponder and lasercom concepts for lunar or interplanetary missions can be conducted on passive SLR assets in space via simultaneous two station ranging.**

Dual Station Laser Ranging

(both stations lie within each other's reflected spot)



Equivalent Transponder/Lasercom Range for Two Station SLR

Link Equations (A to B)

Transponder/Lasercom System:

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

Two-Station Ranging to a Satellite:

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

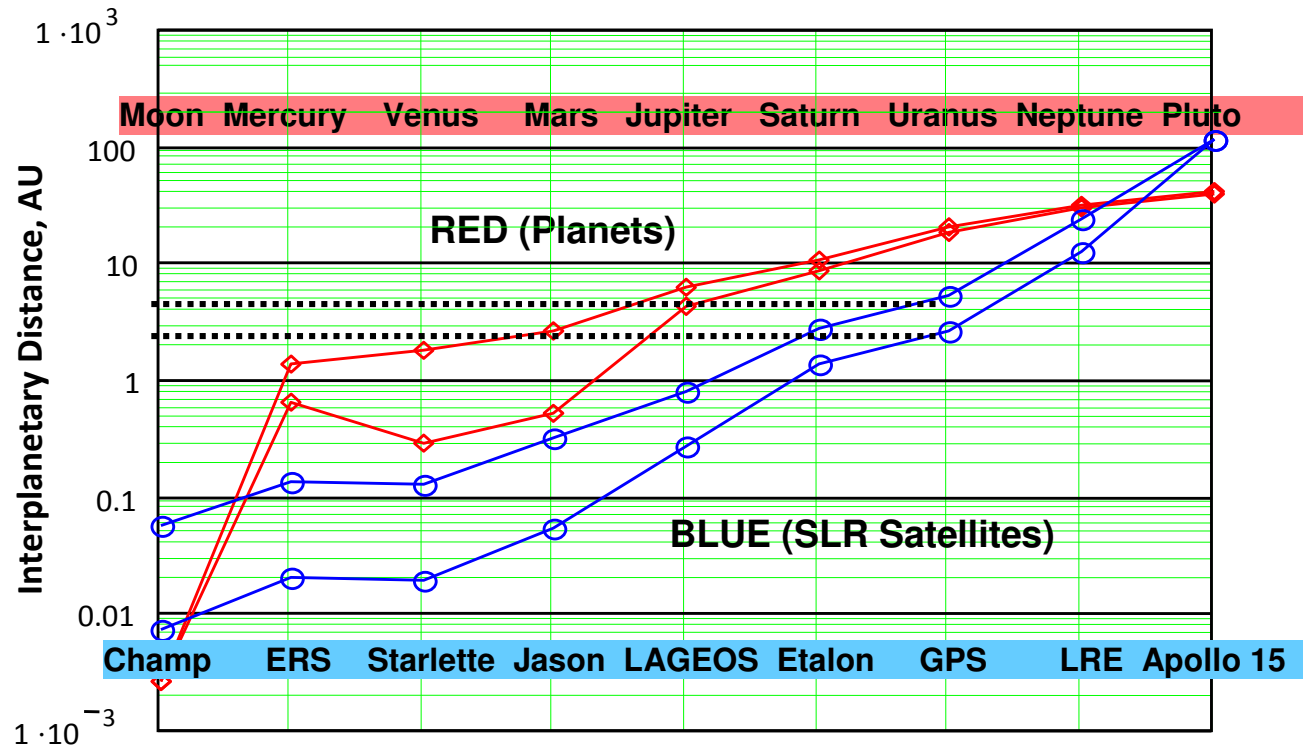
Setting $n_T^{AB} = n_R^{AB}$ gives us an equivalent transponder range for the two-station SLR experiment

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

$$\cong R_R^2(h, \theta_A) \sqrt{\frac{4\pi}{\sigma_s} \frac{1}{T_A^{\sec\theta_A}}}$$

Simulations can also be performed from a single SLR site as in the Wettzell experiments.

SLR Satellite Simulations of Transponder/Lasercom Links throughout the Solar System



Red curves bound the Earth-planetary distance (1AU ~150 million km)

Blue curves bound the equivalent transponder range at satellite elevations of 90 and 20 degrees respectively.

The Apollo 15 reflector can be used to simulate transponder/lasercom experiments to 100 AU, i.e., beyond Pluto (at 40 AU) and the Kuiper Belt

Some Transponder Applications

- **Solar System Science**
 - Solar and Planetary Physics: gravity field, internal mass distribution and rotation
 - Few mm accuracy lunar ephemerides and librations
 - Improves ranging accuracy and temporal sampling over current lunar laser ranging (LLR) operations to Apollo retroreflectors on the Moon with small, low energy, ground stations
 - Decimeter or better accuracy planetary ephemerides
 - Mass distribution within the asteroid belt
- **General Relativity**
 - Provides more accurate (2 to 3 orders of magnitude) tests of relativity and constraints on its metrics than LLR or microwave radar ranging to the planets, e.g.
 - Precession of Mercury's perihelion
 - Constraints on the magnitude of \dot{G} (1×10^{-12} from LLR)
 - Gravitational and velocity effects on spacecraft clocks
 - Shapiro Time Delay
- **Lunar and Planetary Mission Operations**
 - Decimeter or better accuracy spacecraft ranging
 - Calibration/validation/backup for DSN microwave tracking
 - Subnanosecond transfer of GPS time to interplanetary spacecraft for improved synchronization of Earth/spacecraft operations
 - Transponder can serve as independent self-locking beacon for collocated laser communications systems

Summary

- The ability of laser transponders to simultaneously measure range, transfer time between distant clocks, and indirectly monitor the local gravity field at the spacecraft via the relativistic gravity effect on atomic clock rates make it a useful tool for fundamental physics studies within the Solar System.
- Based on the recent successful 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.
- Retroreflectors on international SLR spacecraft are available for simulating interplanetary transponder and high bandwidth lasercom links through the Earth's atmosphere and for testing the ground and spacecraft terminals prior to mission launch .
- The International Laser Ranging Service (ILRS) established an Ad-Hoc Transponder Working Group (Current Co-chairs: Ulrich Schreiber and John Degnan) which is presently developing hardware and software guidelines for member stations interested in participating in future transponder experiments. We invite your ideas and participation.