Lunar Laser Ranging

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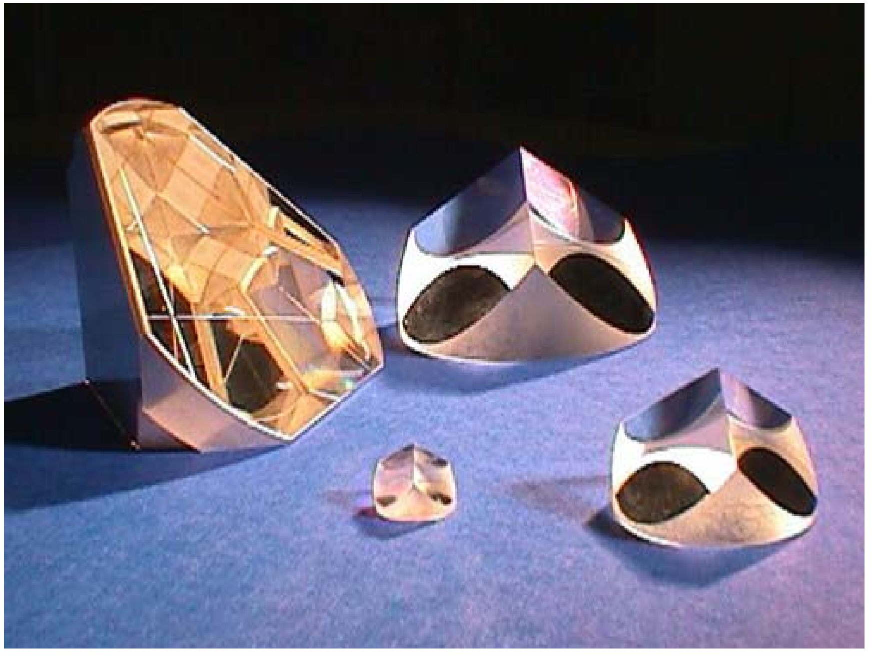
Overview

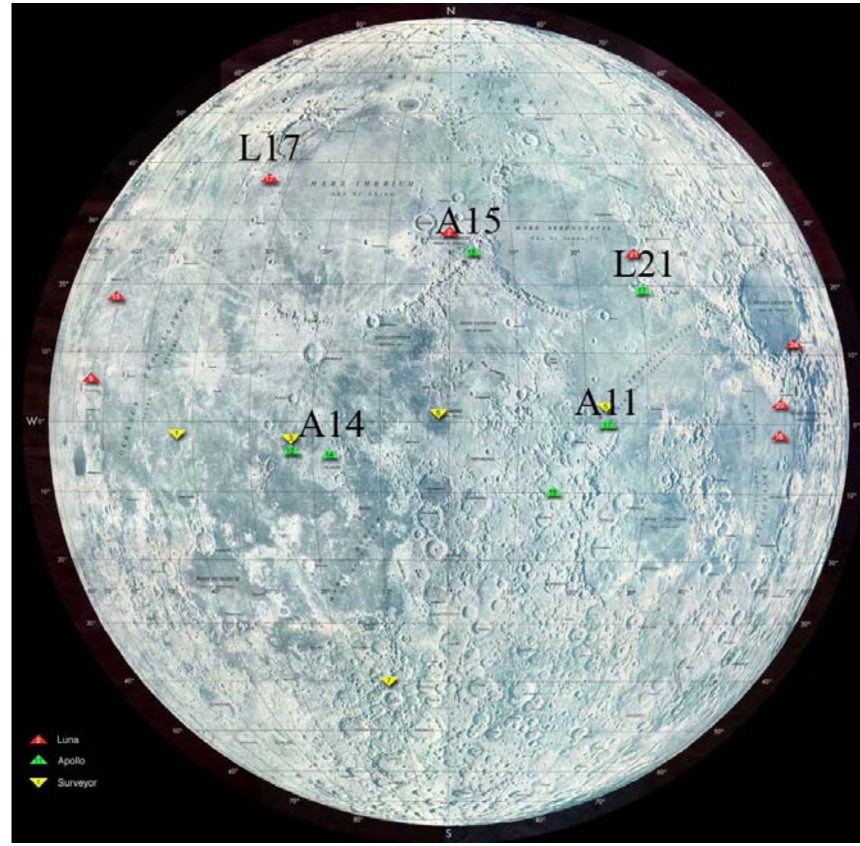
- History and Background
- Ranging System
- Science
- Next Steps

Bouncing Light Off The Moon

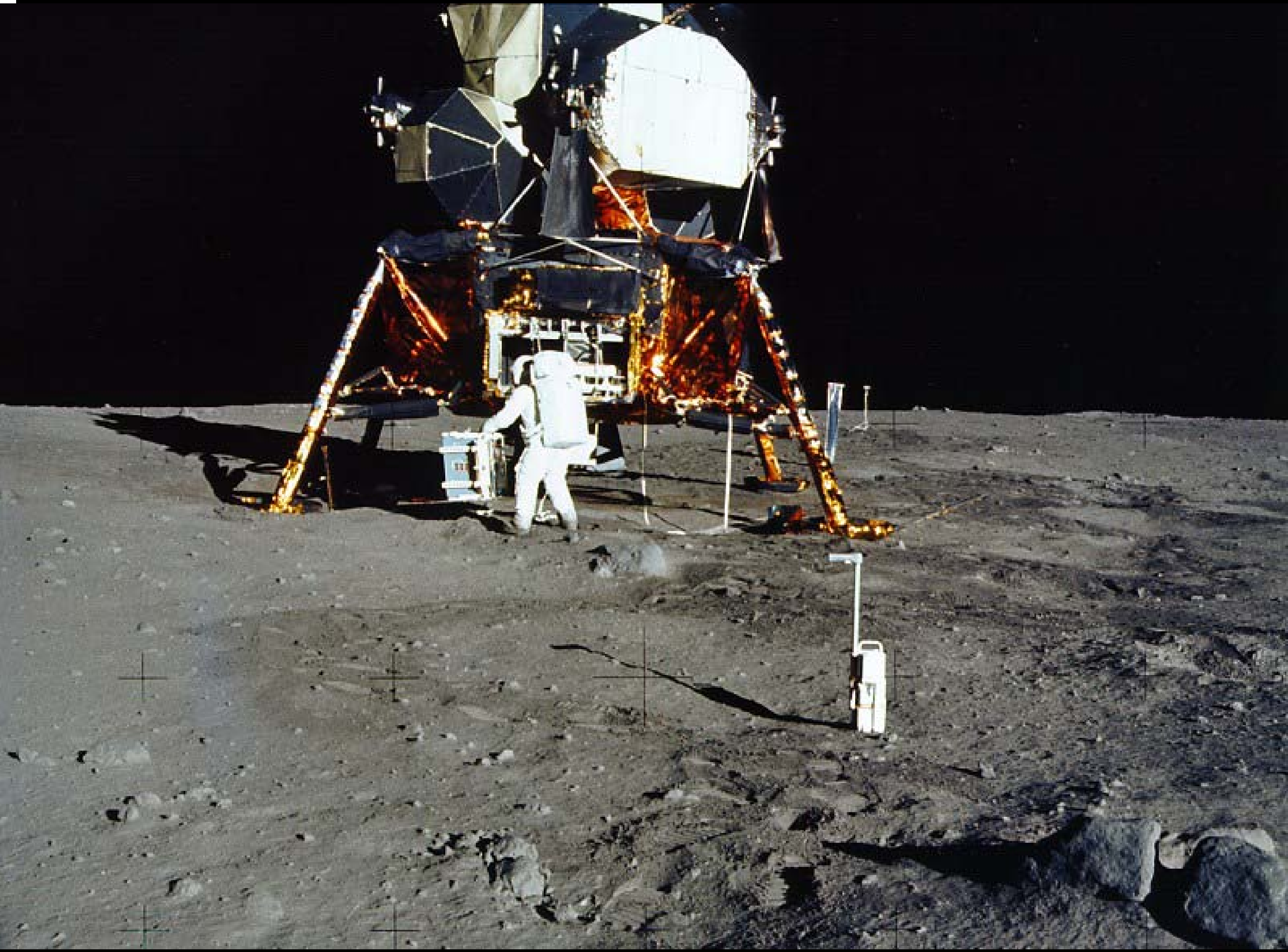
- First suggested by R. H. Dicke in early 1950s.
- MIT and soviet Union bounced laser light off lunar surface in 1960s.
- Retroreflectors proposed for Surveyor missions but not flown. Finally flown on Apollo.
- Retroreflectors will return light back to its source.
- Array of reflectors provide high cross section.
- Single photon detection required due to r^4 signal loss ($\sim 10^{-21}$ over the 2x385,000 km round trip).

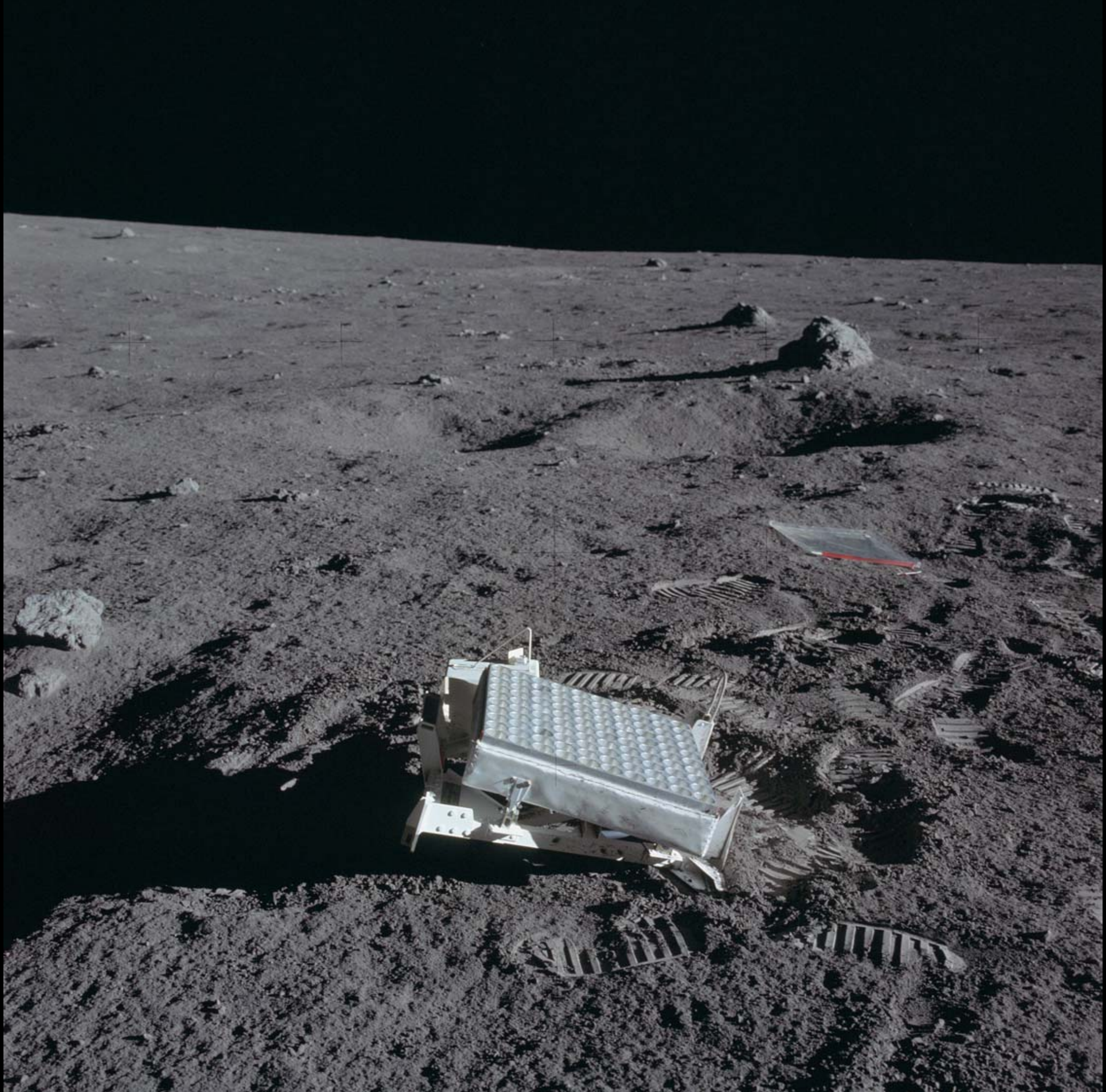


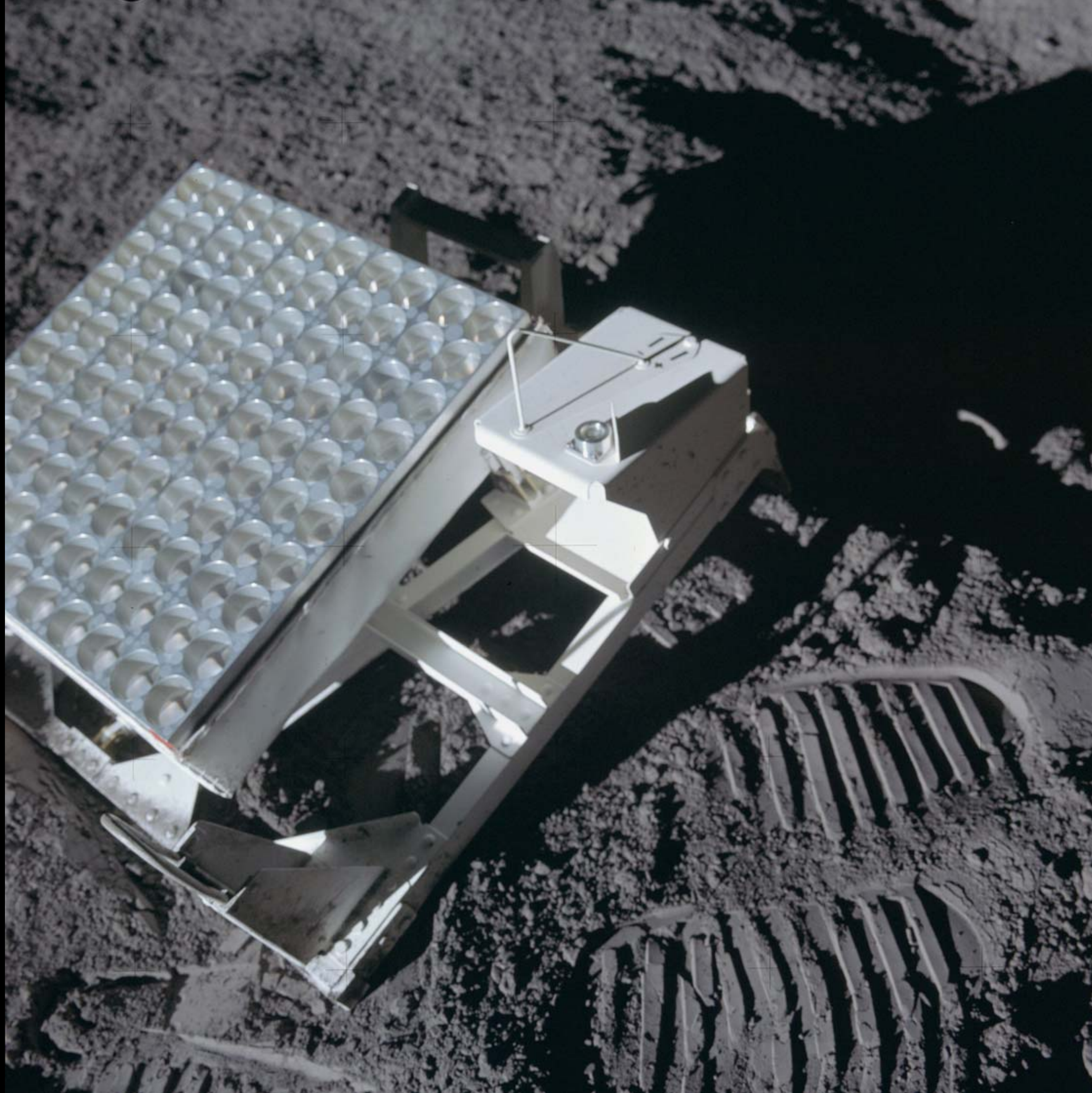
Apollo Missions



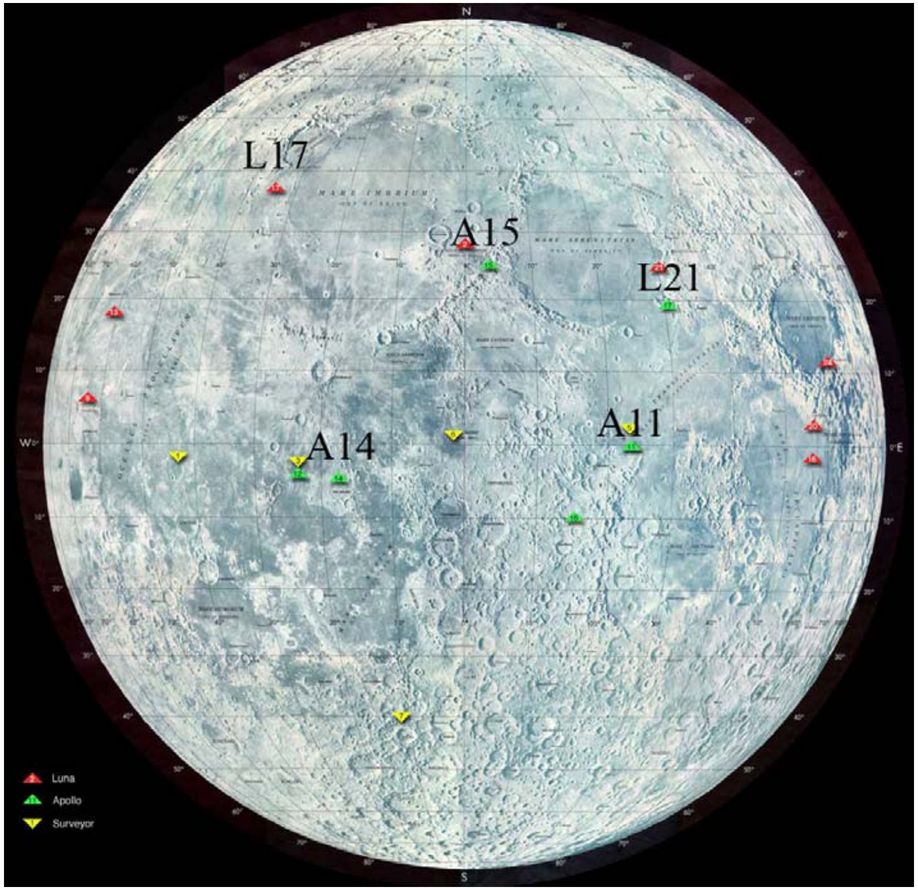
- Apollo arrays used fused silica "circular opening" cubes, 3.8 cm diameter each
- Apollo 11 and 14 arrays used 100 cubes
- Apollo 15 used 300 cubes

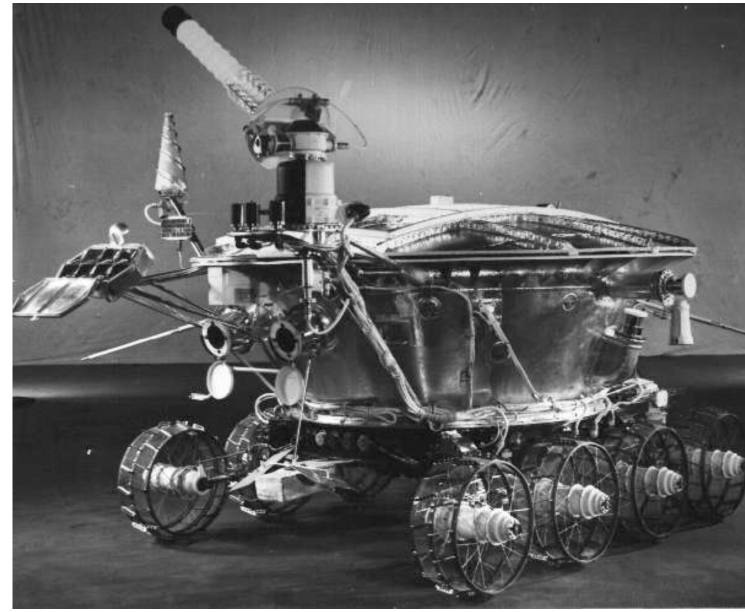




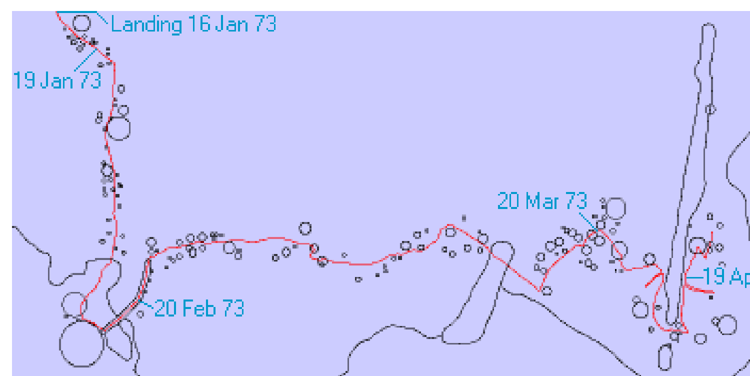


Soviet Luna Missions





Lunokhod

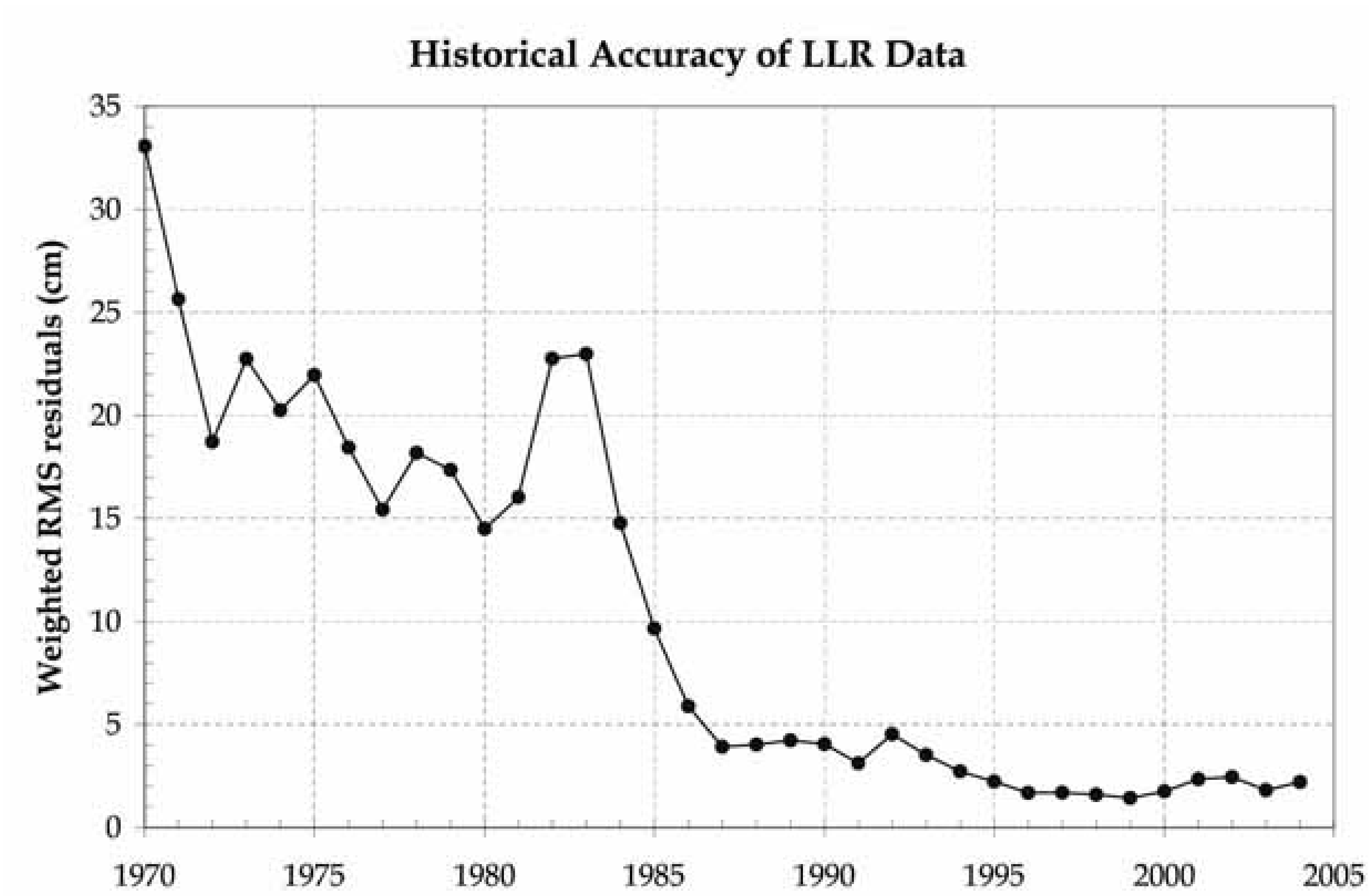


- Lunokhod arrays consist of 14 triangular shaped cubes, each side 11cm
- Only Lunokhod 2 is still visible

>35 Years of LLR

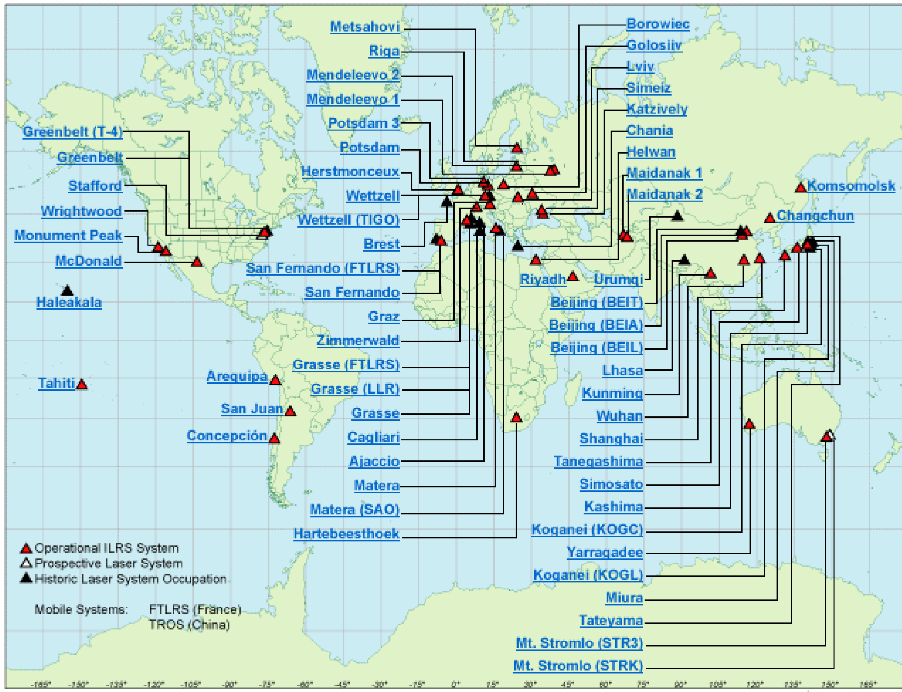
- Lick Observatory in California got first light in 1969.
- McDonald Observatory in Texas 1969 to present!
- Other early ranges:
  - Crimean astrophysical observatory in the Soviet Union,
  - Orroral Observatory in Australia,
  - Air Force Cambridge Research Laboratories Lunar Ranging Observatory in Arizona,
  - The Pic du Midi Observatory in France (Calame et al., 1970),
  - Tokyo Astronomical Observatory
- Orroral Observatory in Australia 1978 to 1980.
- Observatoire de la Côte d'Azur (OCA) in France 1984 to present.
- Haleakala Observatory on Maui in Hawaii 1984 to 1990.
- Apache Point Observatory in New Mexico is starting operation.

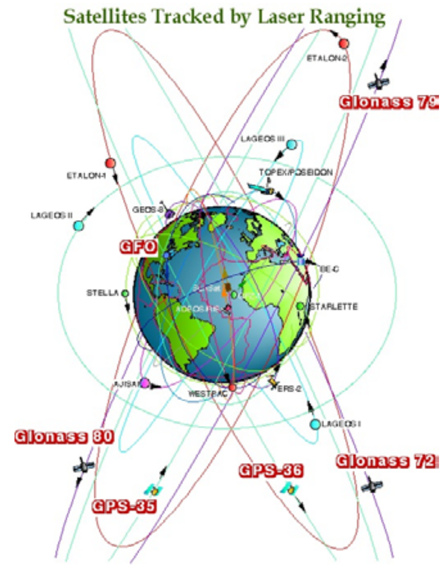
History of LLR

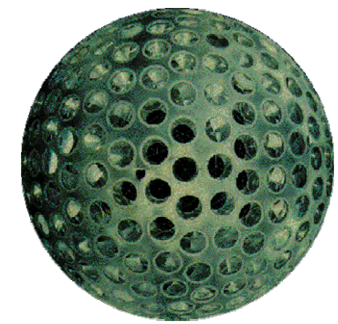


J. G. Williams *et al.*, gr-qc/0507083

Satellite Laser Ranging (SLR)



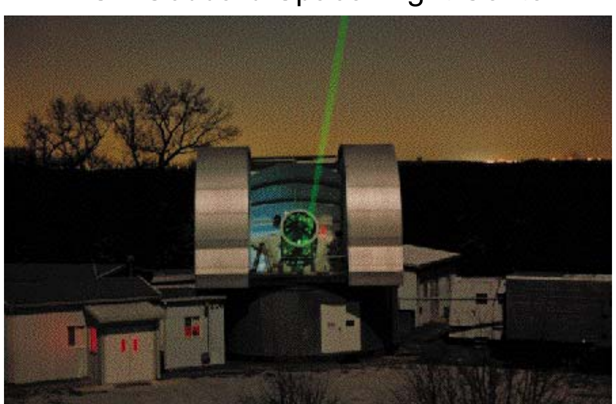


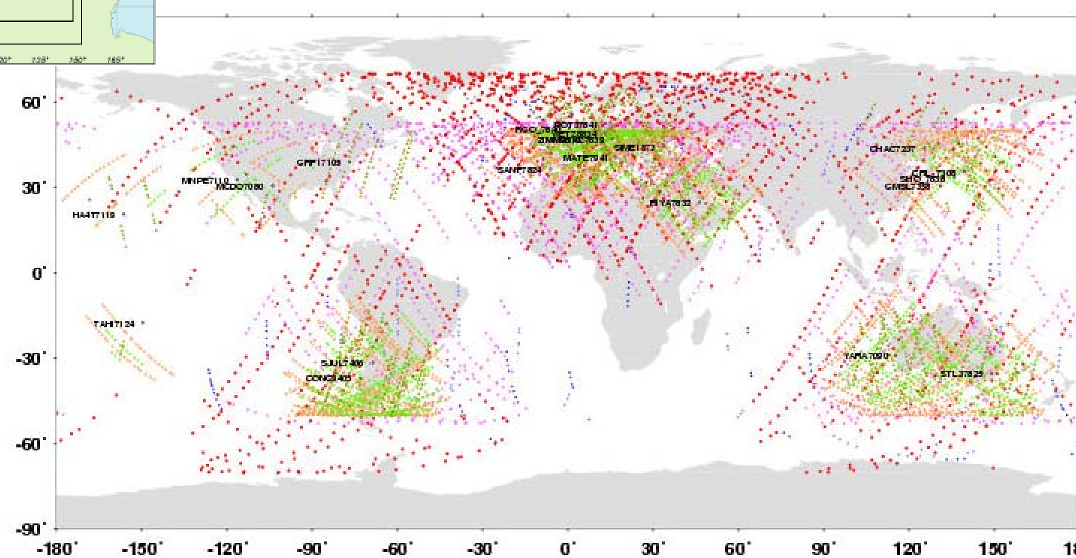


LAGEOS

~35 stations in operation tracking over 100 satellites

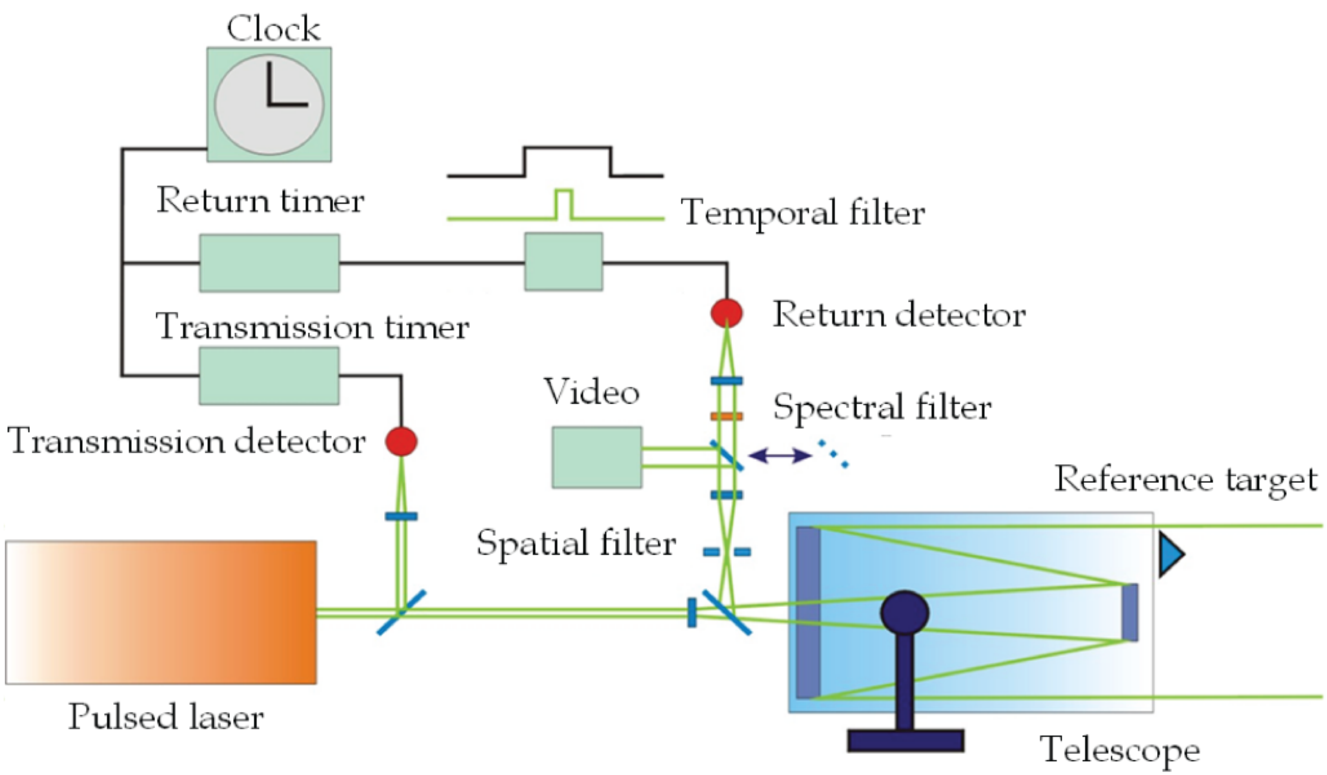
Satellite Laser Ranging began in 1964 at NASA Goddard Space Flight Center.



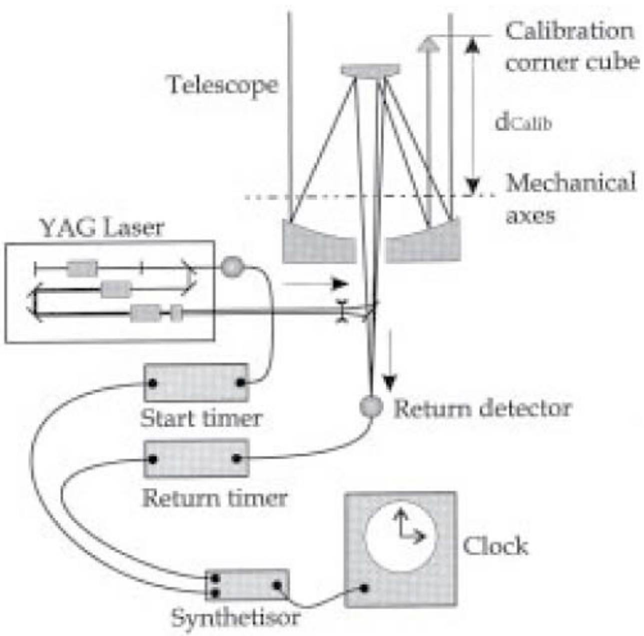


http://ilrs.gsfc.nasa.gov/

Ranging System



Measurement Statistical Error

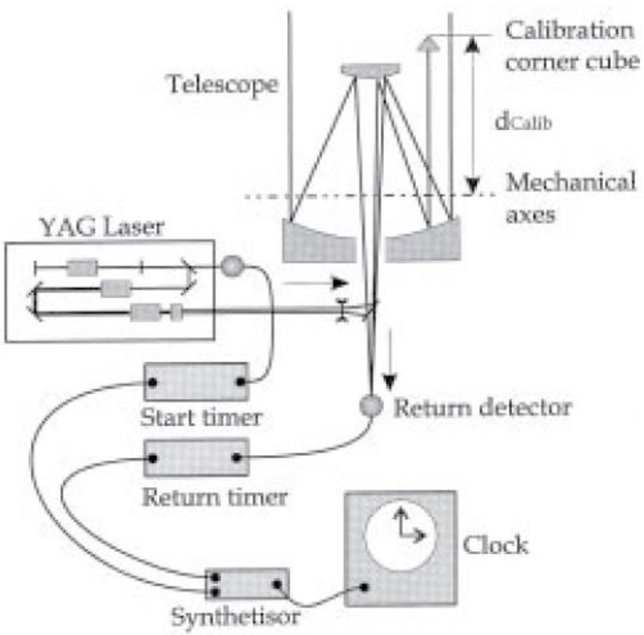


10 ps = 3 mm

Source	OCA Error (ps)
Laser pulse width	30
Laser pulse leading edge variations	4
Start pulse detection	5
Return detector position response	35-50
Timer precision and stability	5
Retroreflector orientation	0-350
Background light	0-300
Clock stability (Allan variance)	10
Calibration errors	4
Atmosphere	0
Best case total	**60**

E. Samain *et al.*, Astron. Astrophys. Suppl. Ser. **130**, 235 (1998).

Measurement Accuracy



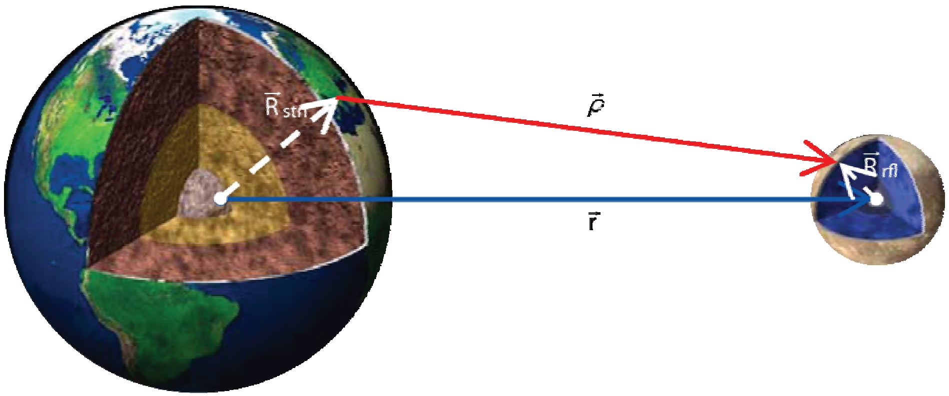
Source	OCA Error (ps)
Clock accuracy	3
Calibration cube reference point	10
Calibration return detector accuracy	65
Atmosphere	15-70
Statistical	65-350
Best case total	**350**
Typical normal point (averaged)	**160**

10 ps = 3 mm

E. Samain *et al.*, Astron. Astrophys. Suppl. Ser. **130**, 235 (1998).

Modeling

- Modeling orbit dynamics (r)
  - Gravitational interaction between Sun, Moon, Earth, Planets. Includes masses and relativity parameters.
  - Asteroid attractions
  - Newtonian attraction between bodies and gravitational harmonics
  - Tidal effects
- Lunar rotation dynamics
  - Torques from other bodies
  - Dissipative torque from fluid core
- Effects at Earth station
  - Plate motion
  - Tidal effects
  - Orientation of Earth's rotation axis
- Effects at lunar reflector
  - Tidal effects
  - Relative lunar orientation
- Time delays
  - Atmospheric
  - Relativistic time delay
- Other effects
  - Solar radiation pressure
  - Thermal expansion of reflectors



J. G. Williams *et al.*, gr-qc/0507083

Science of LLR

- Lunar ephemerides are a product of the LLR analysis used by current and future spacecraft missions.
  - Lunar ranging has greatly improved knowledge of the Moon's orbit, enough to permit accurate analyses of solar eclipses as far back as 1400 B.C.
- Gravitational physics:
  - Tests of the Equivalence principle
  - Accurate determination of the PPN parameter β,
  - Limits on the time variation of the gravitational constant G,
  - Relativistic precession of lunar orbit (geodetic precession).
- Lunar Science:
  - Lunar tides
  - Interior structure

Testing the Equivalence Principle

- A violation of the Equivalence Principle would cause the Earth and Moon to fall at different rates toward the Sun resulting in a polarization of the lunar orbit.
- This polarization shows up in LLR as a displacement along the Earth-Sun line with a 29.53 day synodic period.
- Torsion pendulum measurements at UW on Earth & Moon like test bodies separates out composition dependence.
- The current limit on the Strong Equivalence Principle:

$$\Delta(M_G/M_I)_{EP} = (-1.0 \pm 1.4)\times 10^{-13}$$
$$\eta = (4.4 \pm 4.5)\times 10^{-4}$$

$$\frac{\Delta a}{a} = \left(\frac{M_G}{M_I}\right)_1 - \left(\frac{M_G}{M_I}\right)_2$$

$$\frac{M_G}{M_I} = 1 + \eta \frac{U}{Mc^2}$$

$$\frac{U}{Mc^2} \approx -\frac{3GM}{5Rc^2}$$

$$\eta \equiv 4\beta - \gamma - 3$$

$$\frac{\Delta a}{a} = \eta \cdot \left(\frac{U_e}{M_e c^2} - \frac{U_m}{M_m c^2}\right) = -\eta \cdot 4.45 \times 10^{-10}$$

$$\delta r(t) = 13.1\eta \cos\left(\omega_m - \omega_s\right)t$$

J. G. Williams *et al.*, Phys. Rev. Lett. **93**, 261101 (2004).
S. Baeßler *et al.*, Phys. Rev. Lett. **83**, 3585 (1999).

Time Variation of G

- The strength of gravity is given by Newton's gravitational constant G.
- Some scalar-tensor theories of gravity predict some level of time variation in G. This will lead to an evolving scale of the solar system and a change in the mass of compact bodies due to a variable gravitational binding energy.
- The current limit on the time variation of G is given by LLR:

$$\dot{G}/G = (4 \pm 9) \times 10^{-13} \text{ /year}$$

J. G. Williams *et al.*, Phys. Rev. Lett. **93**, 261101 (2004).

Geodetic (de Sitter) precession

- A gyroscope moving through curved spacetime will precess with respect to the rest frame.
- Earth-Moon system behaves as a gyroscope with a predicted geodetic precession of 19.2 msec/year.
- Observed using LLR by measuring the lunar perigee precession.
- The current limit on the deviation of the geodetic procession is: $K_{gp}=(-1.9\pm6.4)\text{x}10^{-3}$.

J. G. Williams *et al.*, Phys. Rev. Lett. **93**, 261101 (2004).

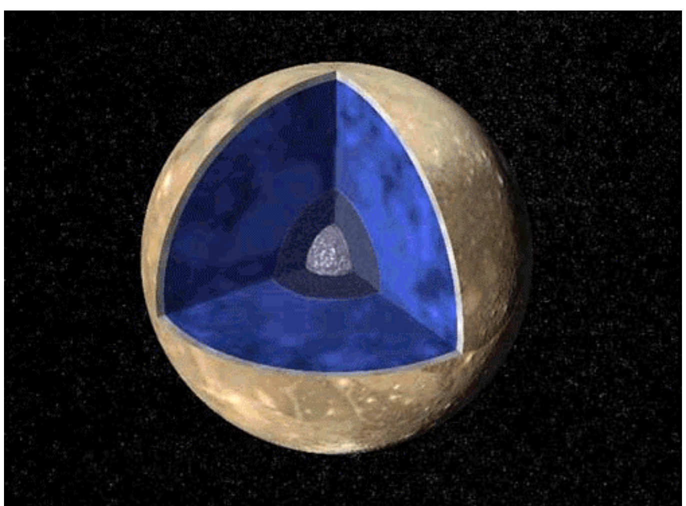
Parameterized Post-Newtonian Limits

- In weak field limit (post-Newtonian) the metric can be parameterized to describe most metric theories.
- γ indicates how much spacetime curvature is produced per unit mass,
- β indicates how nonlinear gravity is (self-interaction).
- $\gamma = \beta = 1$ in General Relativity.
- Limits on γ can be set from geodetic procession measurements, but the best limits come from measurements of the gravitational time delay of light (Shapiro effect). Ranging measurement to the Cassini spacecraft set the current limit on γ:
  $(\gamma - 1) = (2.1 \pm 2.3) \times 10^{-5}$
- γ combined with LLR data provides the best limit on β:
  $(\beta - 1) = (1.2 \pm 1.1) \times 10^{-4}$.

B. Bertotti *et al.*, Nature **425**, 374 (2003).
J. G. Williams *et al.*, Phys. Rev. Lett. **93**, 261101 (2004).

Lunar Science

- Lunar tides, characterized by Love numbers, are measured by LLR.
  - Love numbers give information on the elastic properties of the lunar interior.
  - k2 has an accuracy of 11%.
- The LLR solutions are also sensitive to the lunar tidal dissipation
- Strong tidal and lunar rotation dissipations suggest a fluid core of ~20% the Moon's radius.
- Evidence for the oblateness of the lunar fluid-core/solid-mantle boundary may be reflected in a century-scale polar wobble frequency.

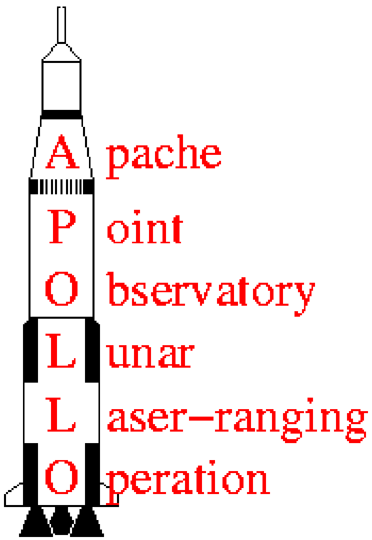


QuickTime™ and a
GIF decompressor
are needed to see this picture.

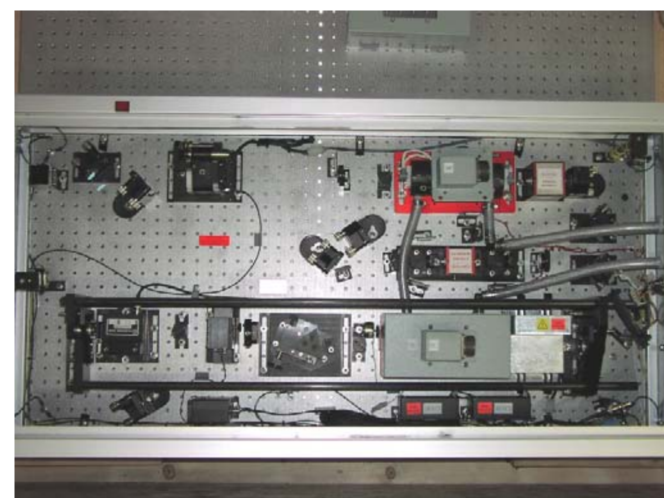
What’s Next

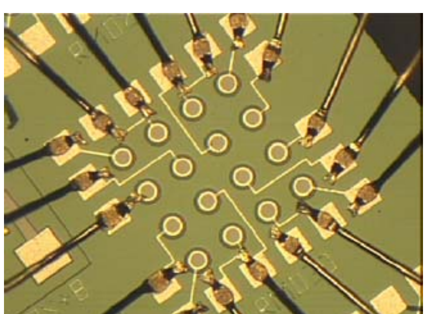
- Better ground stations
- More retroreflectors
- Laser transponders

APOLLO



- Apache Point Observatory in New Mexico is starting operation with goal of mm accuracy.
- 3.5 meter telescope
- 2.3 Watt NdYAG laser
  - λ = 530 nm
  - 20 pulses/sec
  - 90 ps pulse width
  - 110 mJ per pulse
- Lincoln Lab prototype APD arrays
  - 4×4 array of 30 μm elements
  - Lenslet array in front



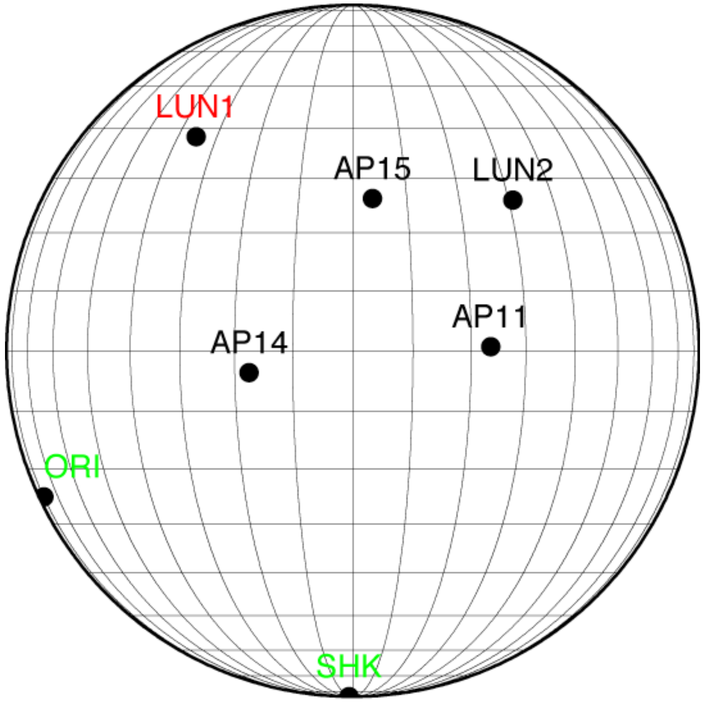


APOLLO Random Error Budget

Error Source	Time Uncert. (ps) (round trip)	Range error (mm) (one way)
Retro Array Orient.	100–300	15–45
APD Illumination	60	9
APD Intrinsic	<50	< 7
Laser Pulse Width	45	6.5
Timing Electronics	20	3
GPS-slaved Clock	7	1
Total Random Uncert	**136–314**	**20–47**

New Sites - New Retroreflectors

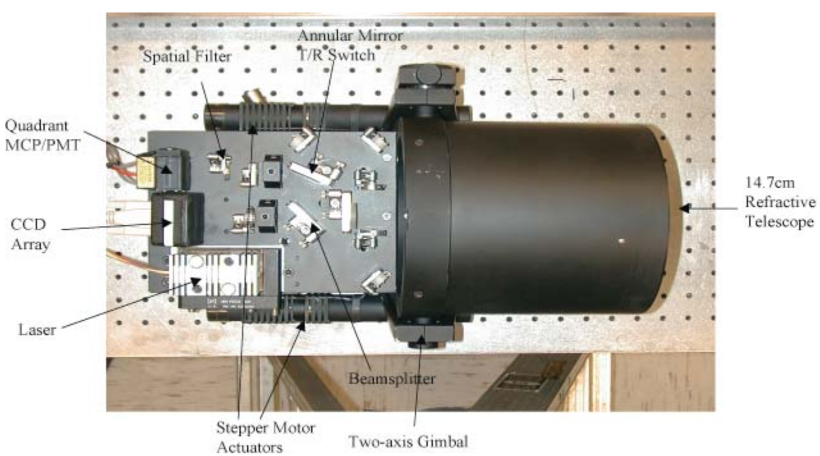
- Available retroreflectors all lie within 26 degrees latitude of the equator, and the most useful ones within 24 degrees longitude of the sub-earth meridian.
- Operating LLR stations are at similar northern latitudes.
- The addition of one or more reflectors would improve the geometrical precision of a normal point by a factor of 1.5 to nearly 4 at the same level of ranging precision.
- Better retroreflectors
  - Hollow cubes which weigh much less than their solid counterparts so arrays could be made larger.
  - Smaller thermal distortions, especially in hollow cubes made of beryllium, so the cubes can be made larger without sacrificing optical performance.



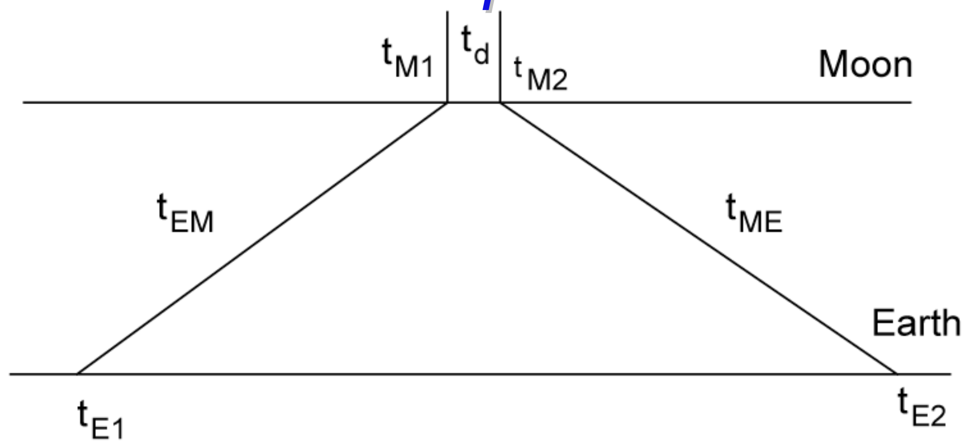
S. M. Merkowitz *et al.*, in Proceedings of the International Workshop "From Quantum to Cosmos: Fundamental Physics Research in Space" (2006).

Transponders

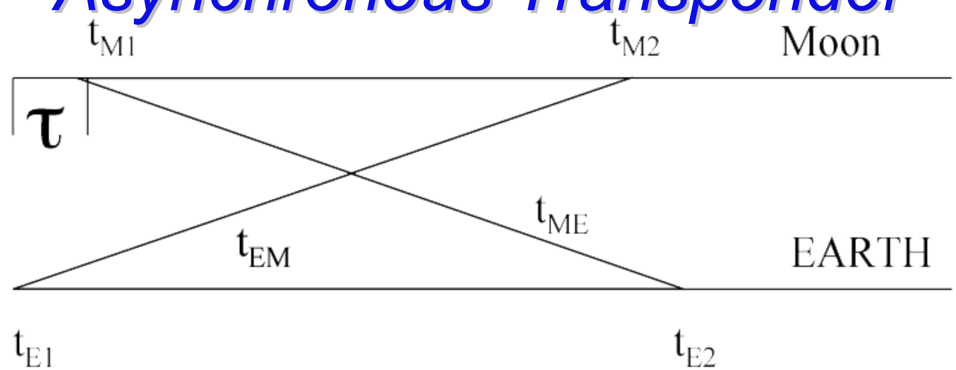
- Transponders have only r^2 signal loss compared to r^4 for retroreflectors.
- Transponder would not have large orientation errors.
- Asynchronous Transponder could be used with existing SLR systems with little modification



Echo Transponder



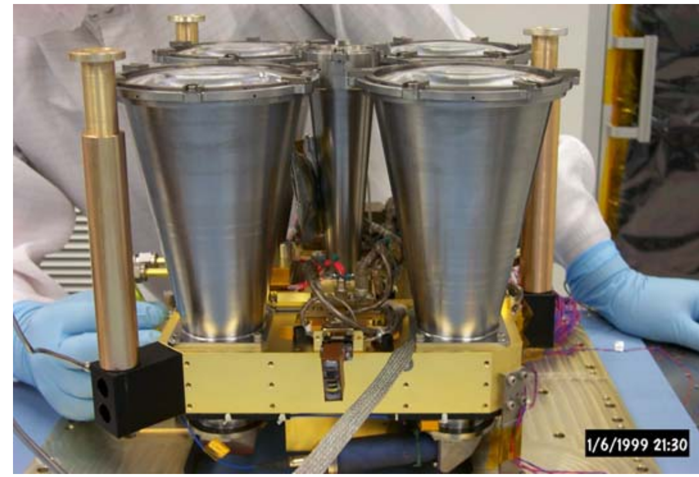
Asynchronous Transponder



J. J. Degnan, J. Geodyn. **34**, 551 (2002).

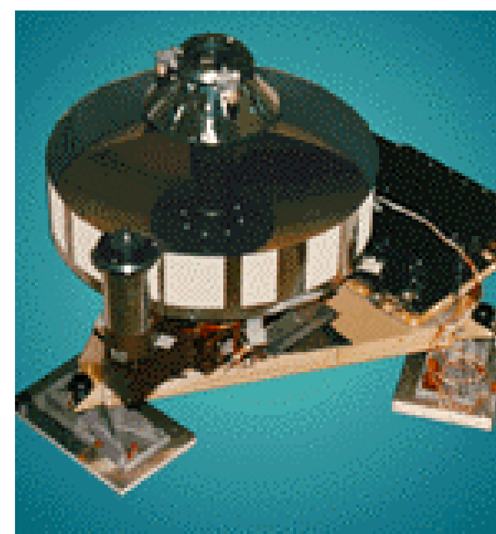
Interplanetary Range Demonstrations

- Two-Way Transponder Experiment to the Messenger Spacecraft (May/June 2005)
  - 24.3 Million Km
  - Range solution demonstrated



Parameter	Laser link solution	Spacecraft ephemeris	Difference
Range (m)	23,964,675,433.9 T 0.2	23,964,675,381.3	52.6
Range rate (m j s 1)	4,154.663 T 0.144	4,154.601	0.062
Acceleration (mm j s2)	–0.0102 T 0.0004	–0.0087	–0.0015
Time (s)	71,163.729670967 T 6.6 × 10j 10	71,163.730019659	0.000348692
Clock drift rate (ppb)	1.00000001559 T 4.8 × 10j 10	1.00000001564	–3.2 × 10j 10

- One-Way Earth-to-Mars Transponder Experiment to MOLA on Mars Global Surveyor (September 2005)
  - 80 Million Km
  - 100's of pulses observed at Mars



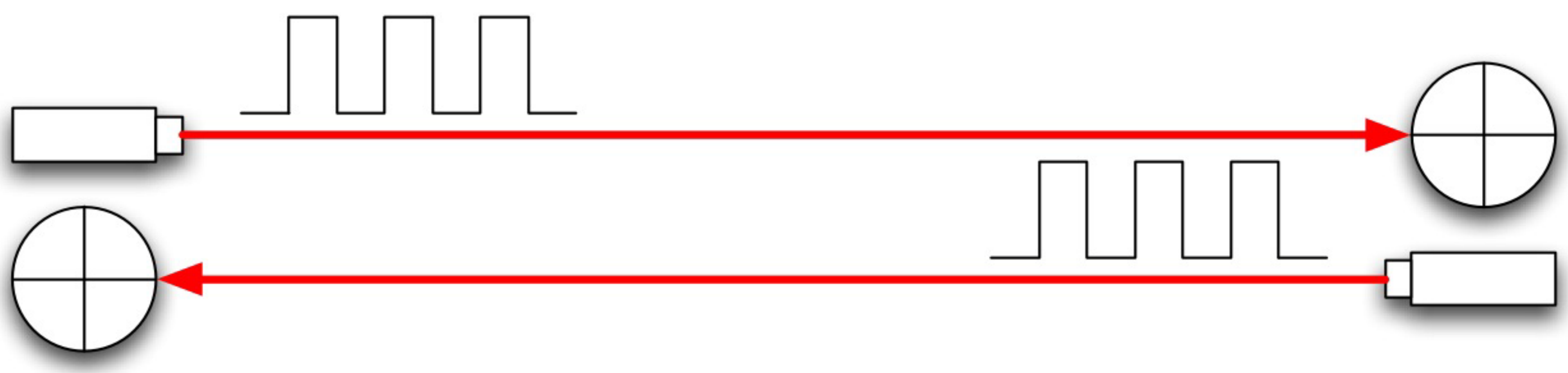
D. E. Smith *et al.*, Science **311**, 53 (2006).

Combine with Optical Communications

- With an optical link it is natural to use it for communications in addition to ranging.
  - Mercury Laser Altimeter instrument on Messenger has demonstrated the basics of laser communication over interplanetary distances.
- Mission data requirements are increasing
  - Free-space optical communications potentially has higher capacity over large distances than RF communications,
  - Interplanetary missions may stress both range and data rate,
  - Typically, optical communications is most cost effective at high data rates.

Low Light Option

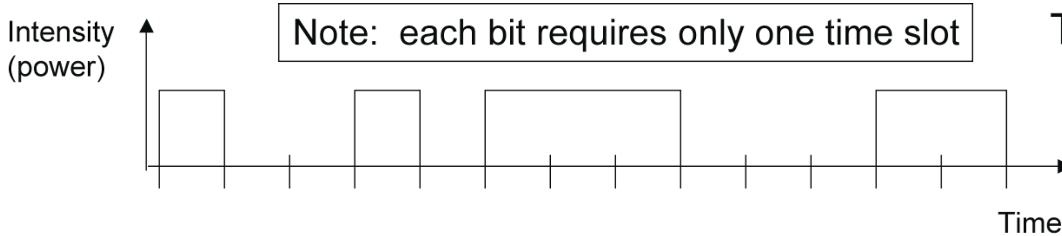
- Small inexpensive instruments,
- Heritage in laser altimeters and current satellite & lunar ranging,
- Asynchronous allows some loss of pulses,
- Q-switched or MOPA lasers offer good power,
- Photon counting detection,
- Modest communications possible,
- Ranging limited by clock stability.



Simple Encoding

On-Off Keying

Note: each bit requires only one time slot



Threshold

Binary
Decision

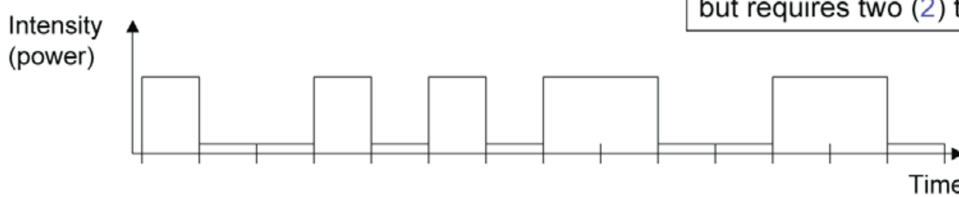
Compare intensity (level) in each bit time slot to an "absolute" threshold

1 0 0 1 0 1 1 1 0 0 0 1 1

Pulse Position Modulation

0 =  1 = 

Note: each "word" represents one (1) bit, but requires two (2) time slots

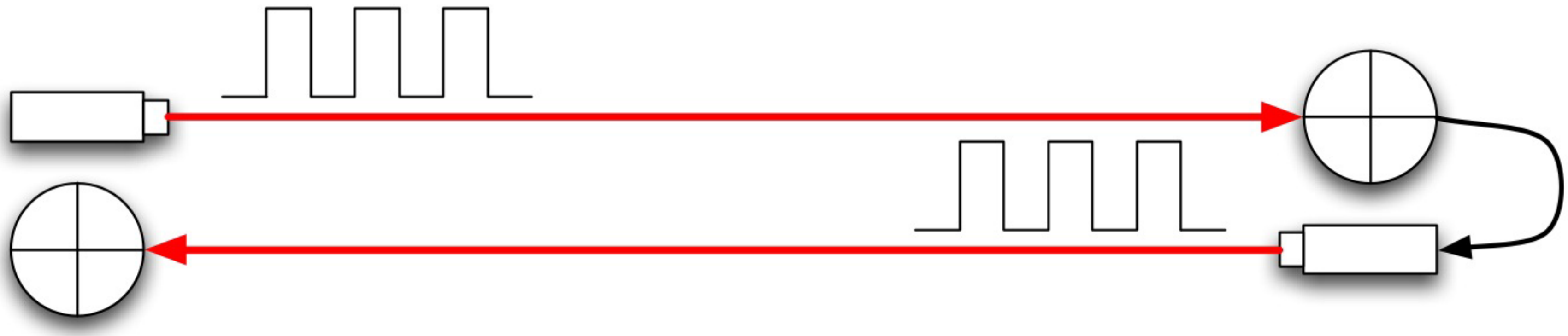


Compare energy in bit time slot 1 to bit time slot 2 for each "word"
Note: No "absolute" threshold

1 0 0 0 1 0 1

Higher Power Option

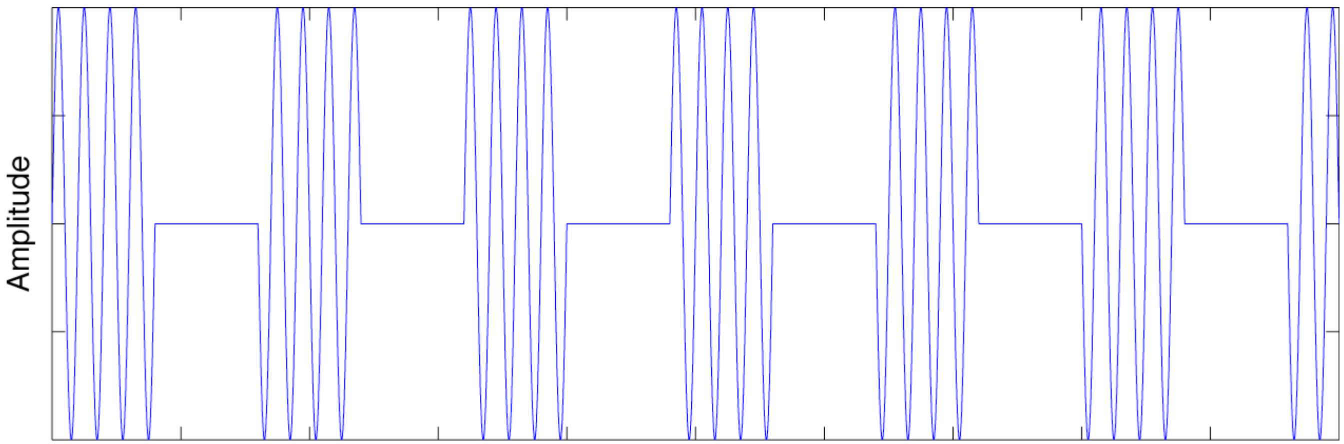
- Stronger signals enable use of phase in comm and ranging measurement,
- Heritage in telecommunication systems and precision interferometers,
- Master laser followed by optical amplifier offer reasonable power,
- Pulse shaping maximizes power usage,
- Direct detection offers fast response, but requires more light,
- Fast communications with low bits/photon possible,
- Encoding ranging signal removes distance ambiguity,
- End-stations can be phase locked to improve performance,
- Frequency stabilized master laser can act as precision clock,
- Very sensitive differential ranging possible using a phasemeter.

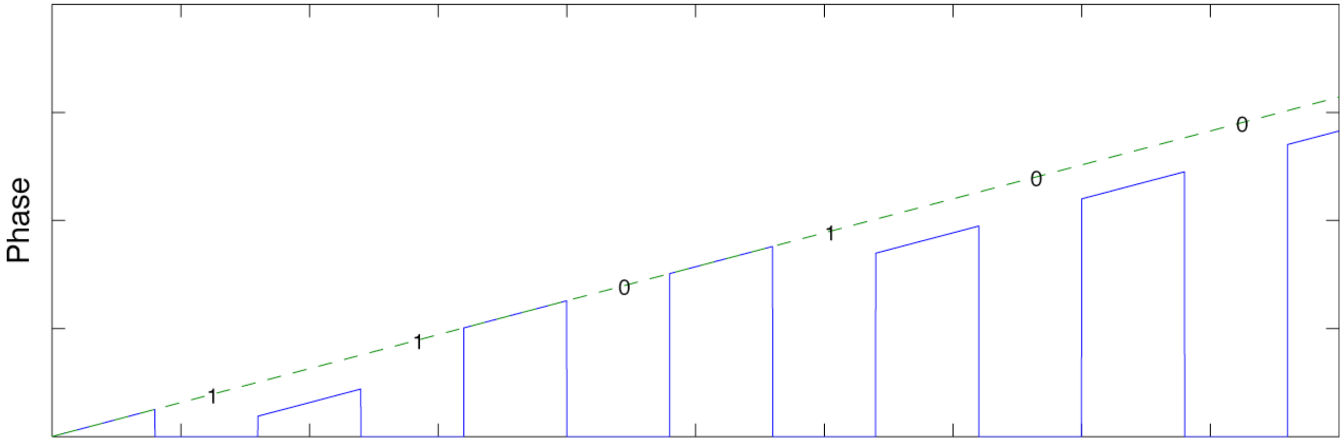


Practical Approach

- Take advantage of commercial telecomm technology
  - Externally modulated CW lasers,
  - Low cost parts.
- Use master oscillator/power amplifier (MOPA) architecture to separately optimize by function
  - Enables use of quite laser,
  - Clean modulator,
  - High output power.
- Use a fast sensitive receiver
  - Implement a low photons/bit modulation format such as return to zero differential phase shift keying (RZ-DPSK).
- RZ can be short period/high energy
  - Enable more photons out of amplifier,
  - Improves receiver sensitivity.
- Optical phase locking should improve precision.

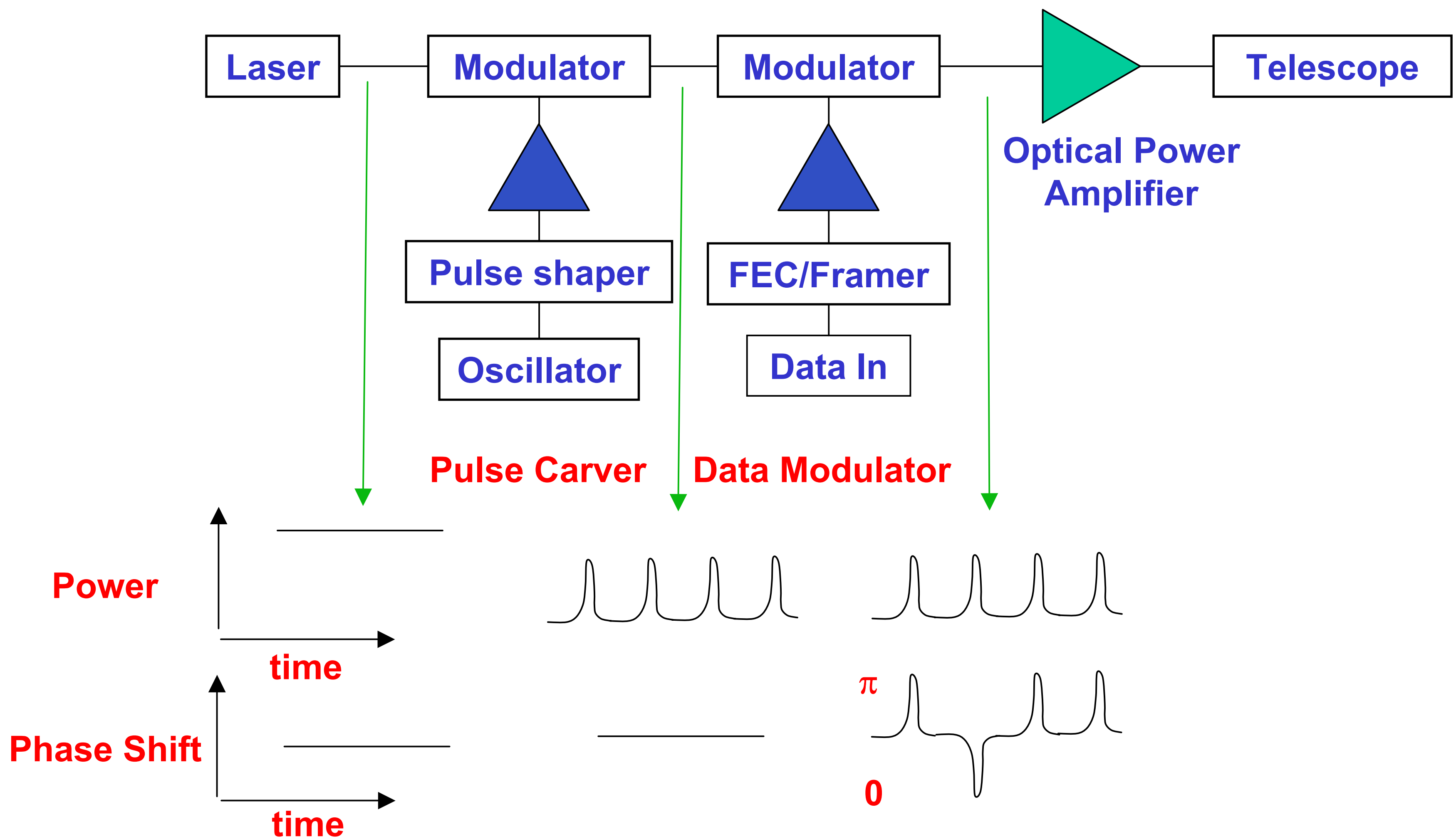
Return to zero differential phase shift keying



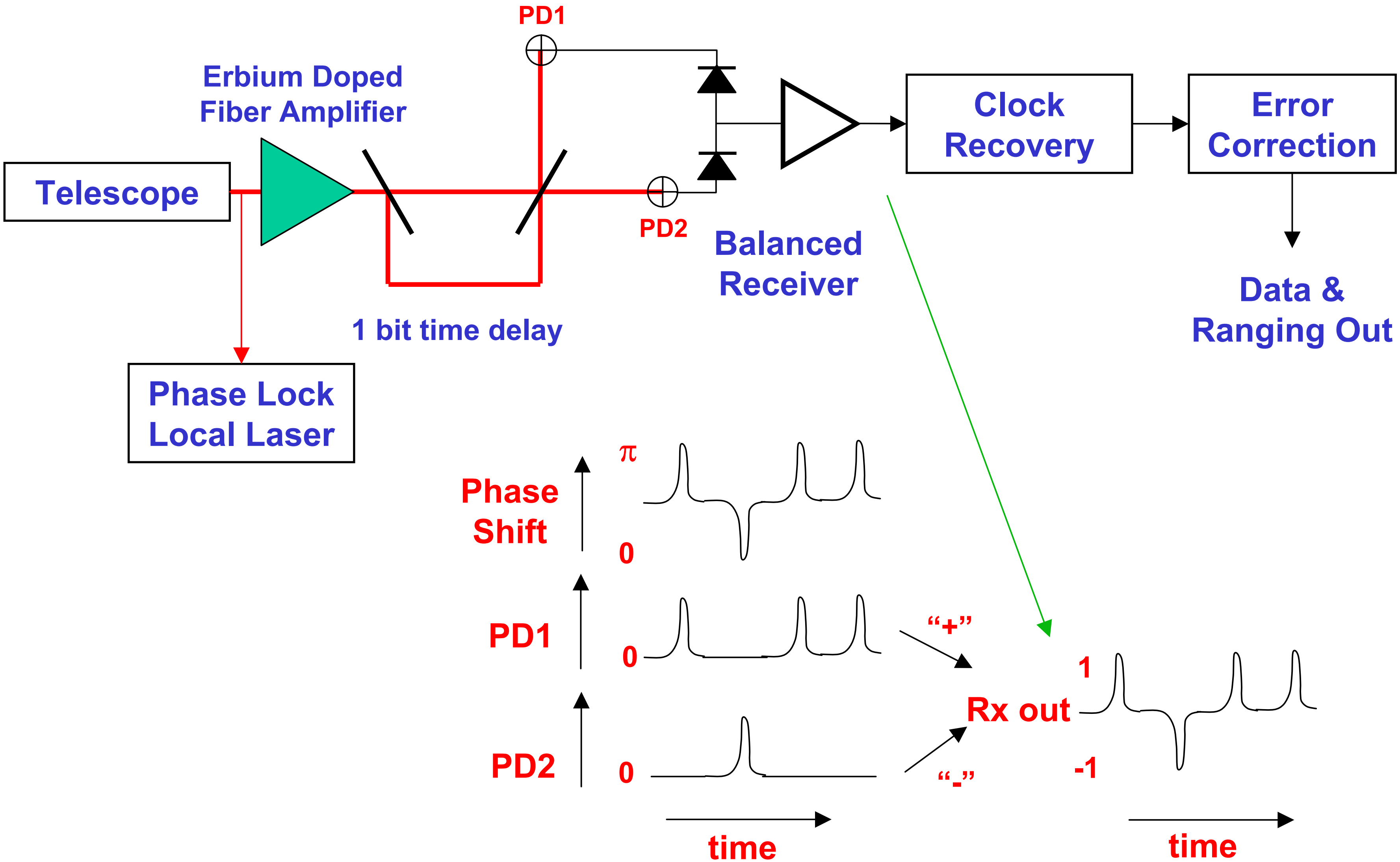


- ➢Demonstrated ~25 photons/bit receiver sensitivity at 10 Gb/s

MOPA Transmitter



Receiver/Demodulator

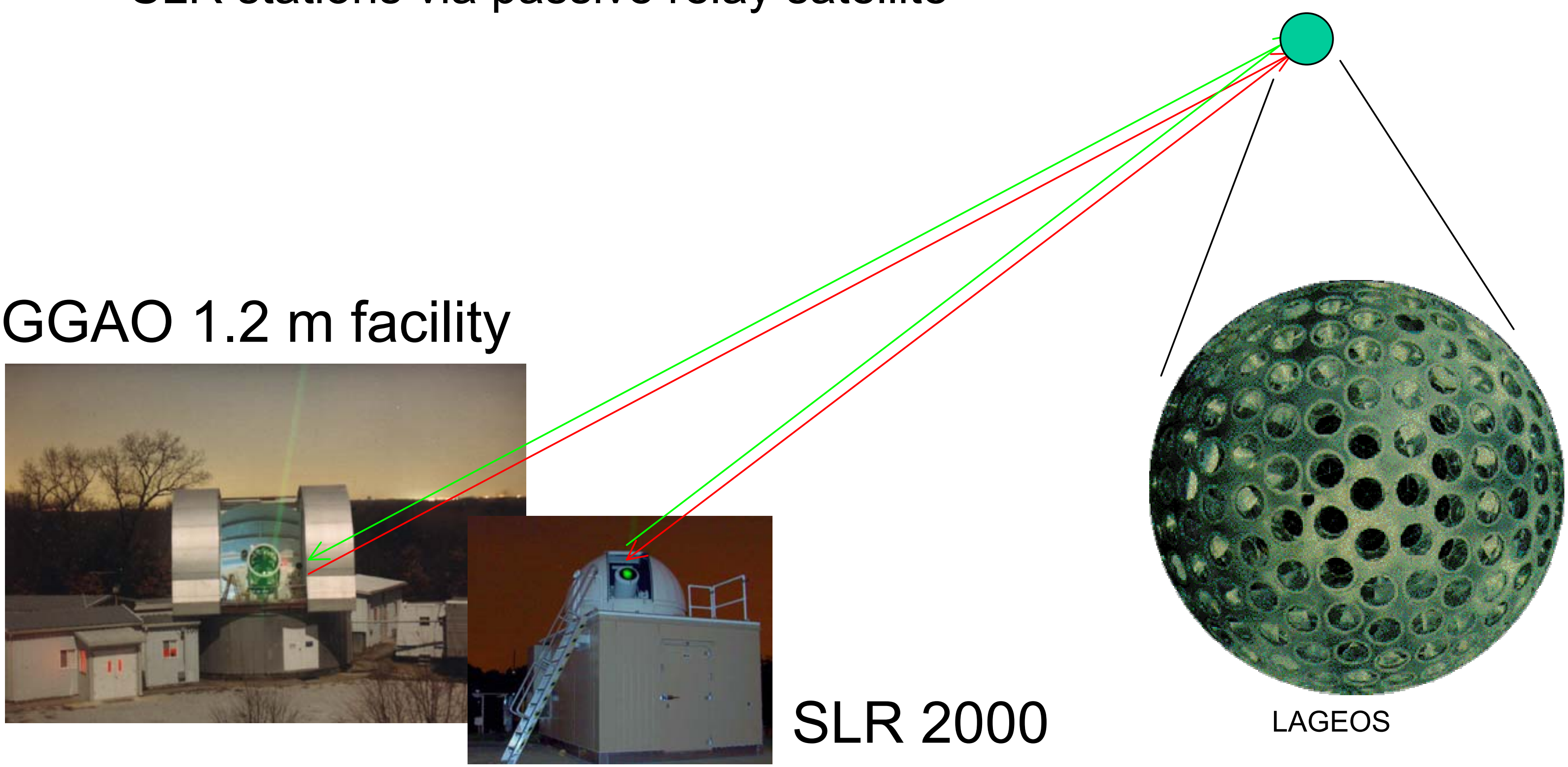


Two-Station Demonstration

- Demonstrate both laser communication and PN code ranging between the two SLR stations via passive relay satellite

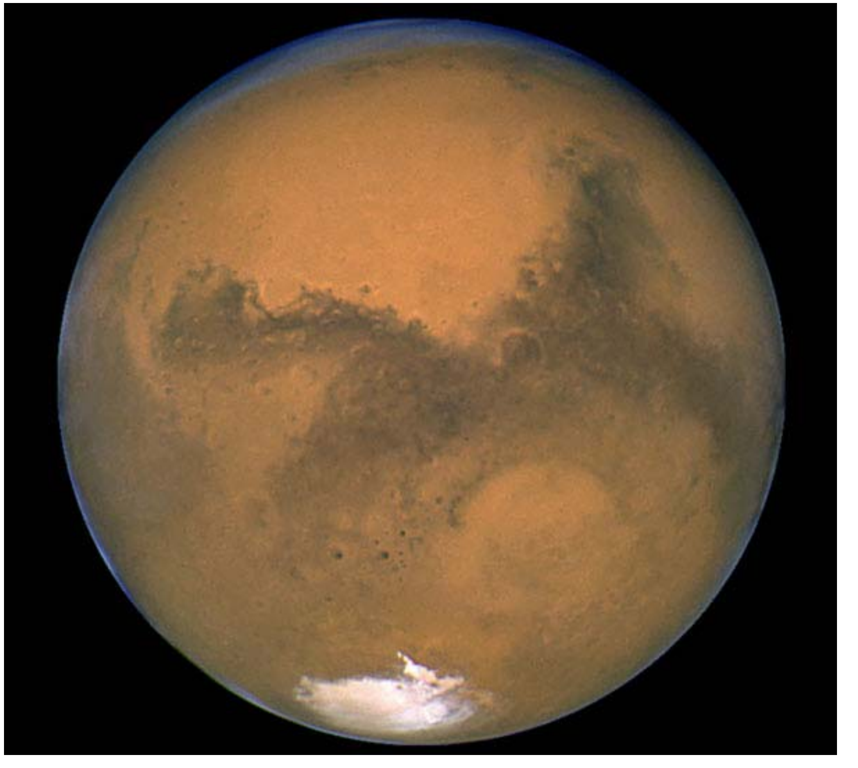
Satellites

500 to 25,000 km altitude



Moon to Mars

- Current Mars ranging achieves only meter level accuracy.
- Sun-Earth-Mars-Jupiter system tests SEP qualitatively different from LLR.
- With 1 cm precision ranging, the PPN parameter γ can be measured to about 10^{-6}, ten times better than the Cassini result.
- SEP polarization effect is ~100 times larger for Earth-Mars orbits than for lunar orbit.
  - With 1 cm precision ranging, η can be measured to between 6×10^{-6} and 2×10^{-6} for observations ranging between one and ten years.
  - Combined with the time delay measurements this leads to a measurement of PPN parameter β to the 10^{-6} level.
- Mass of Jupiter can be determined more accurately than from Pioneer & Voyager data combined.
- Better measurements of Mars' rotational dynamics could provide estimates of the size of the core.



Summary

- More precise lunar ranging will enable unprecedented tests of Einstein's theory of General Relativity in addition to providing valuable data on the interior structure of the Moon and Earth-Moon interactions (tidal effects, etc.).
- Precision ranging to Mars would provide additional tests of Einstein's theory of General Relativity, unique data on the structure of Mars, and even provide the most accurate determination of the mass of Jupiter.
- Laser communications is likely to be required for advanced interplanetary missions.
- Several technology options exist for combining optical communications with precision ranging.