Testing Fundamental Gravitation
via
Laser Ranging to the Moon and Mars/Phobos

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with special thanks to

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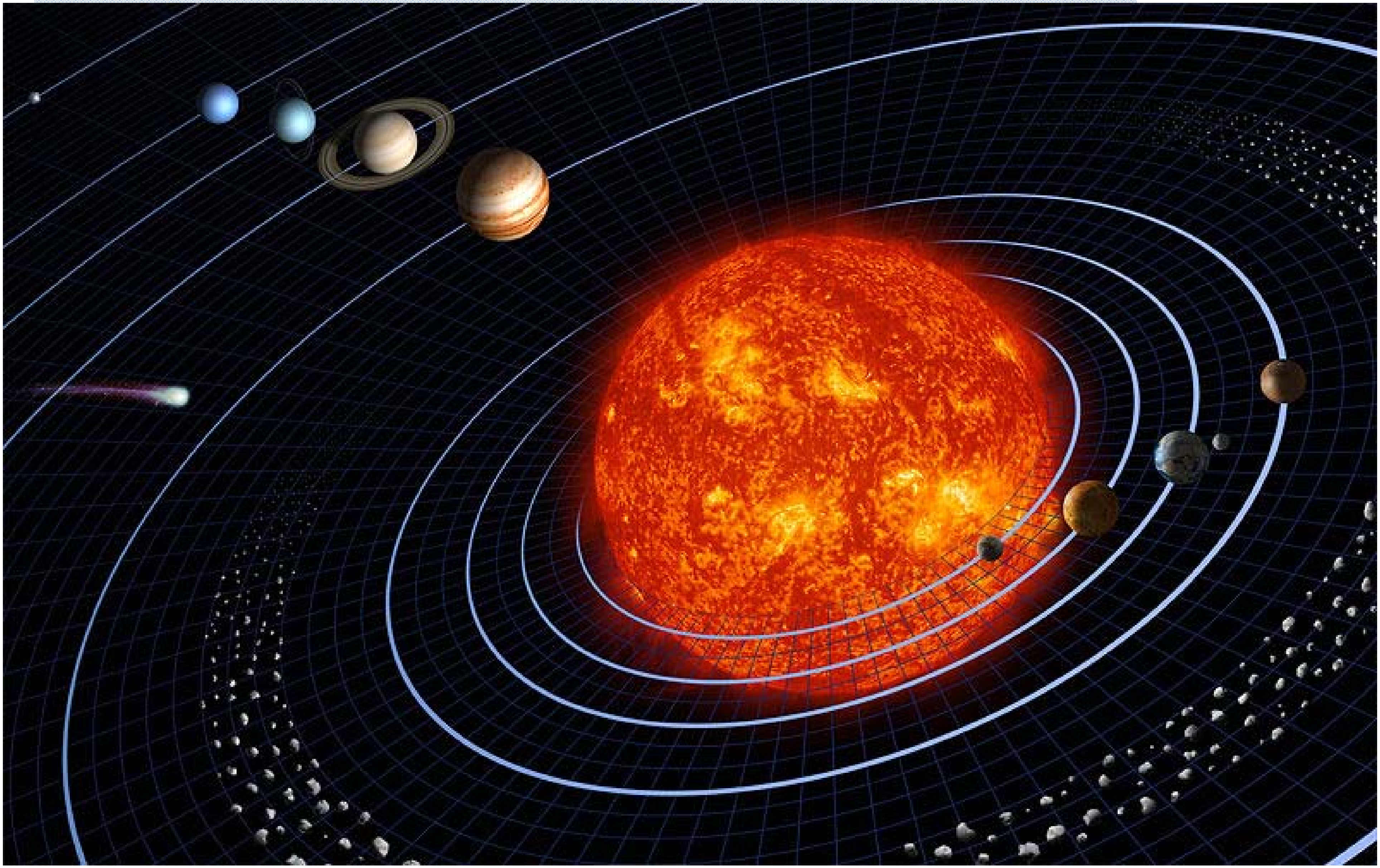
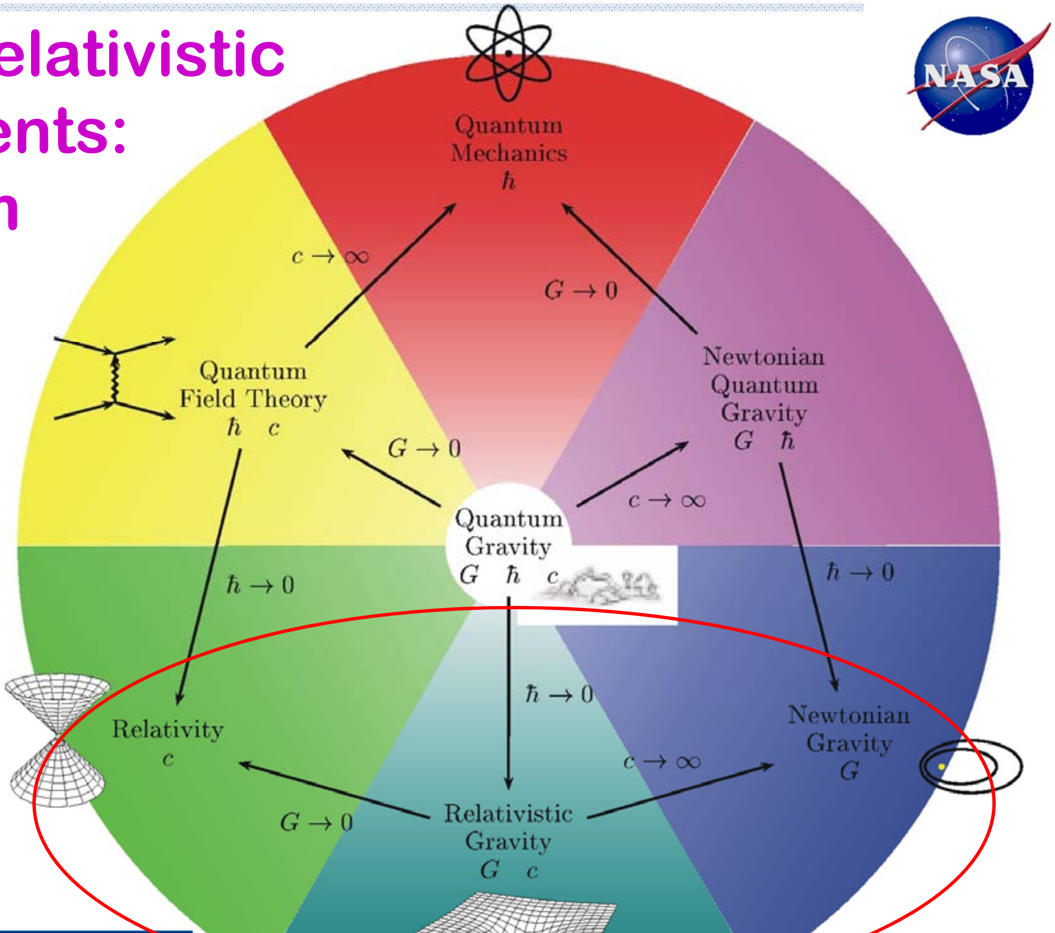
This talk will cover:

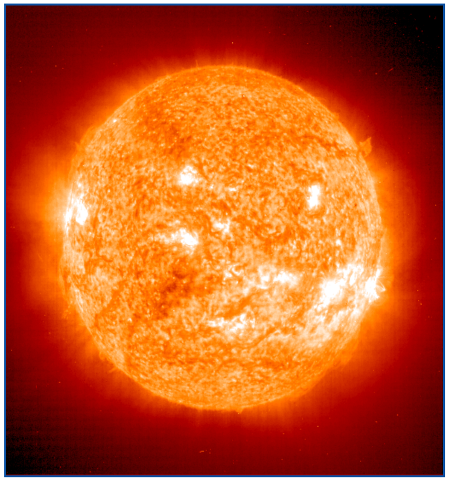
- Experimental techniques for space-based gravity tests:
  - Spacecraft Doppler tracking; planetary ranging
  - Recent progress in the tests of general relativity
  - Laser ranging techniques: satellite, lunar, and interplanetary
- Recent progress in lunar laser ranging (LLR):
  - Brief history, technique, data available, science results
  - Current situation with LLR
  - The need for new instruments on the Moon
- Advent of interplanetary laser ranging (IPLR):
  - Recent technology demonstrations
  - Instrument development for IPLR
  - Mars/Phobos laser ranging: instruments, science
- Conclusions and next steps

Our solar system and tests of gravity



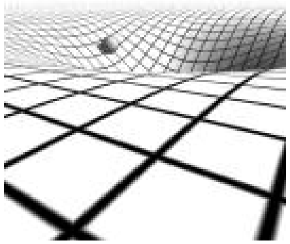
Laboratory for Relativistic Gravity Experiments: Our Solar System





Strongest gravity potential

$$\frac{GM_{Sun}}{c^2 R_{Sun}} \sim 10^{-6}$$



$$\frac{GM_{\oplus}}{c^2 R_{\oplus}} \sim 10^{-9}$$

Most accessible region for gravity tests in space:

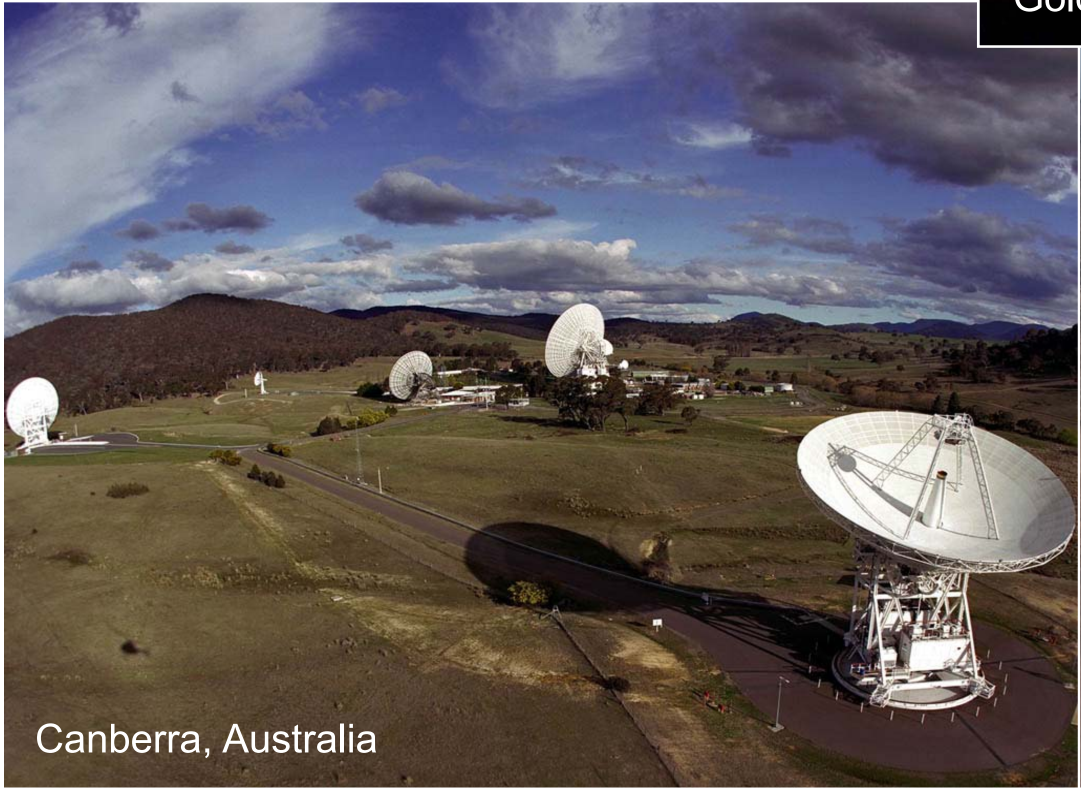
- ISS, LLR, SLR, free-fliers

Technology is available to conduct tests in the immediate solar proximity

Deep Space Network


Goldstone, California


Goldstone, California


Canberra, Australia


Madrid, Spain

PPN Equations of Motion (a part of the model)

$$
\begin{aligned}
\ddot{\mathbf{r}}_i = {} & \sum_{j\neq i}\frac{Gm_j(\mathbf{r}_j-\mathbf{r}_i)}{r_{ij}^3}\Bigg\{\left[\frac{m_G}{m_I}\right]_i-\frac{2(\beta+\gamma)}{c^2}\sum_{l\neq i}\frac{Gm_l}{r_{il}}-\frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{Gm_k}{r_{jk}}+ \\
& +\gamma\left(\frac{\dot{r}_i}{c}\right)^2+(1+\gamma)\left(\frac{\dot{r}_j}{c}\right)^2-\frac{2(1+\gamma)}{c^2}\dot{\mathbf{r}}_i\dot{\mathbf{r}}_j+\frac{\dot{G}\cdot t}{G}- \\
& -\frac{3}{2c^2}\left[\frac{(\mathbf{r}_i-\mathbf{r}_j)\dot{\mathbf{r}}_j}{r_{ij}}\right]^2+\frac{1}{2c^2}(\mathbf{r}_j-\mathbf{r}_i)\ddot{\mathbf{r}}_j\Bigg\}+ \\
& +\frac{1}{c^2}\sum_{j\neq i}\frac{Gm_j}{r_{ij}^3}\Big\{\big[\mathbf{r}_i-\mathbf{r}_j\big]\cdot\big[(2+2\gamma)\dot{\mathbf{r}}_i-(1+2\gamma)\dot{\mathbf{r}}_j\big]\Big\}(\dot{\mathbf{r}}_i-\dot{\mathbf{r}}_j)+ \\
& +\frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{Gm_j\ddot{\mathbf{r}}_j}{r_{ij}}+\sum_{m=1}^{3}\frac{Gm_m(\mathbf{r}_m-\mathbf{r}_i)}{r_{im}^3}+\sum_{c,s,m}\mathbf{F}_{\text{asteroids}}
\end{aligned}
$$

Possible EP violation

Possible temporal dependence of *G*

$$\left[\frac{m_G}{m_I}\right]_{\text{SEP}}=1+\eta\left(\frac{E}{Mc^2}\right)$$

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

$$E_i=-\frac{G}{2}\int_i d^3x\,\rho_i U_i=-\frac{G}{2}\int_i d^3x\,d^3x'\,\frac{\rho_i(\mathbf{r})\rho_i(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}$$

- γ are β the parameterized post-Newtonian (PPN) parameters.
- In general theory of relativity $\gamma=\beta=1$, thus $\eta=0$. This is not the case for scalar-tensor theories of gravity, for instance.
- Assuming Lorentz invariance and position invariance hold, thus, preferred frame parameters α_1, α_2, α_3, α_4 are not included

Navigation Tracking-Metrics Requirements (12/2009)

Tracking Error Source (1σ accuracy)	units	current capability	2010 reqt	2020 reqt	2030 reqt
Doppler/random (60s)	μm/s	30	30	3	2
Doppler/systematic (60s)	μm/s	1	1	0.1	0.1
Range/random	m	0.3	0.3	0.3	0.1
Range/systematic	m	1.1	2	2	1
Angles	deg	0.01	0.04	0.04	0.04
ΔVLBI	nrad	2.5	2	1	0.5
Troposphere zenith delay	cm	0.8	0.5	0.5	0.3
Ionosphere	TECU	5	5	3	2
Earth orientation (real-time)	cm	7	5	3	2
Earth orientation (after update)	cm	5	3	2	0.5
Station locations (geocentric)	cm	3	2	2	1
Quasar coordinates	nrad	1	1	1	0.5
Mars ephemeris	nrad	2	3	2	1

40 Years of Solar System Gravity Tests

Techniques for Gravity Tests:

Radar Ranging:

- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Pioneers, Cassini, Mars Global Surveyor, Mars Orbiter, etc.
- VLBI, GPS, etc.

Laser:

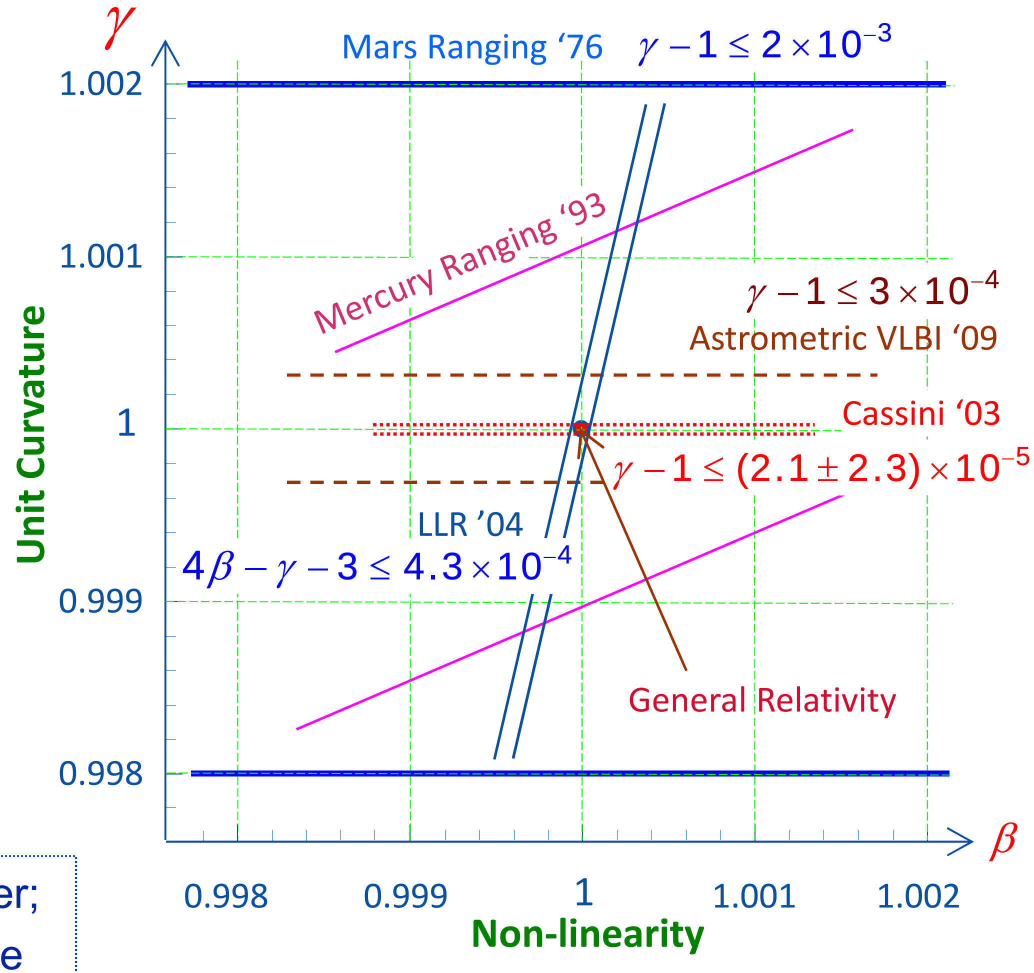
- SLR, LLR, interplanetary, etc.

Dedicated Gravity Missions:

- **LLR (1969 - on-going!!)**
- GP-A, '76; LAGEOS, '76,'92; GP-B, '04; LARES, '12; LISA, 2025+(?)

New Engineering Discipline – Applied General Relativity:

- Daily life: GPS, geodesy, time transfer;
- Precision measurements: deep-space navigation & astrometry (SIM, Gaia,....).



A factor of 100 in 40 years is impressive, but is not enough for the near future!

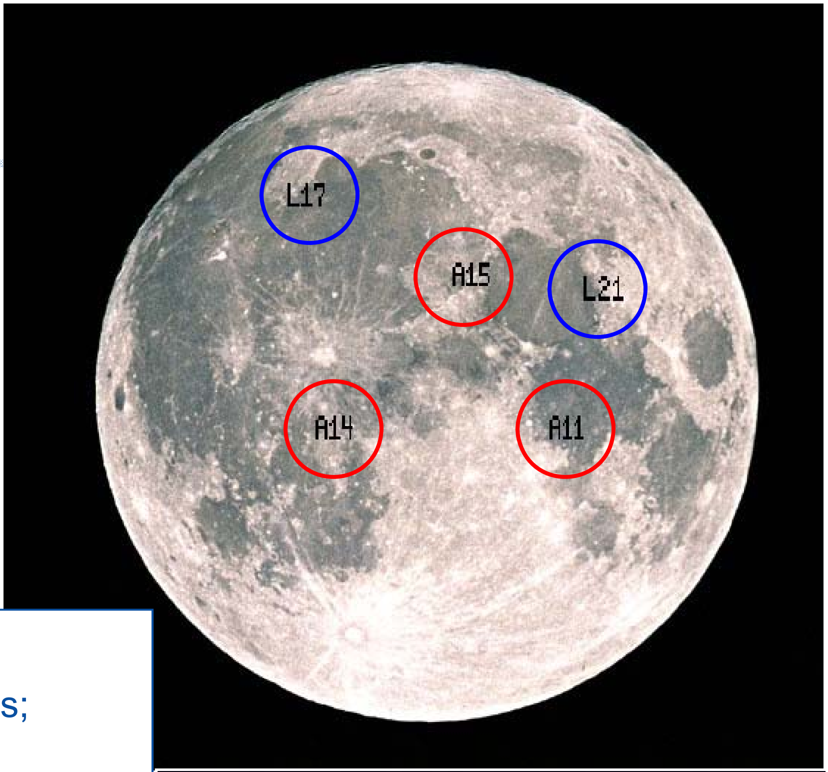
LUNAR LASER RANGING SCEINCE

Lunar Laser Ranging

Lunar laser ranging (LLR) begun over 42 year ago…

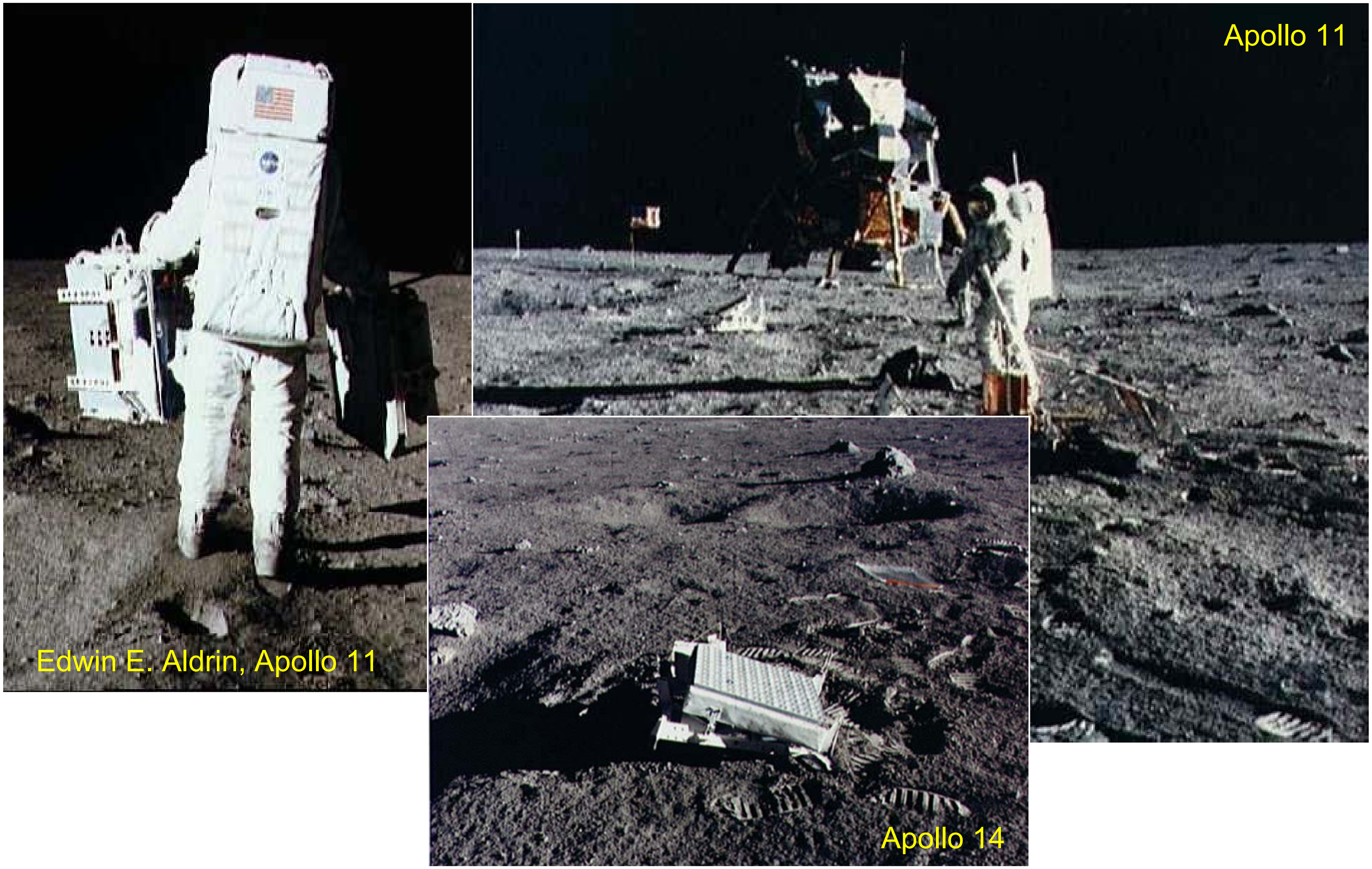
Laser ranges between observatories on the Earth and retroreflectors on the Moon started by Apollo in 1969 and continue to the present

- 4 reflectors are ranged:
  - Apollo 11, 14 & 15 sites;
  - Lunokhod 2 rover;
  - Lunokhod 1 rover (since 2010)
- Historically LLR conducted primarily from 3 observatories:
  - McDonald (Texas, USA)
  - OCA (Grasse, France)
  - Haleakala (Hawaii, USA)
- New LLR stations:
  - Apache Point (NM, USA)
  - Matera (Matera, Italy)



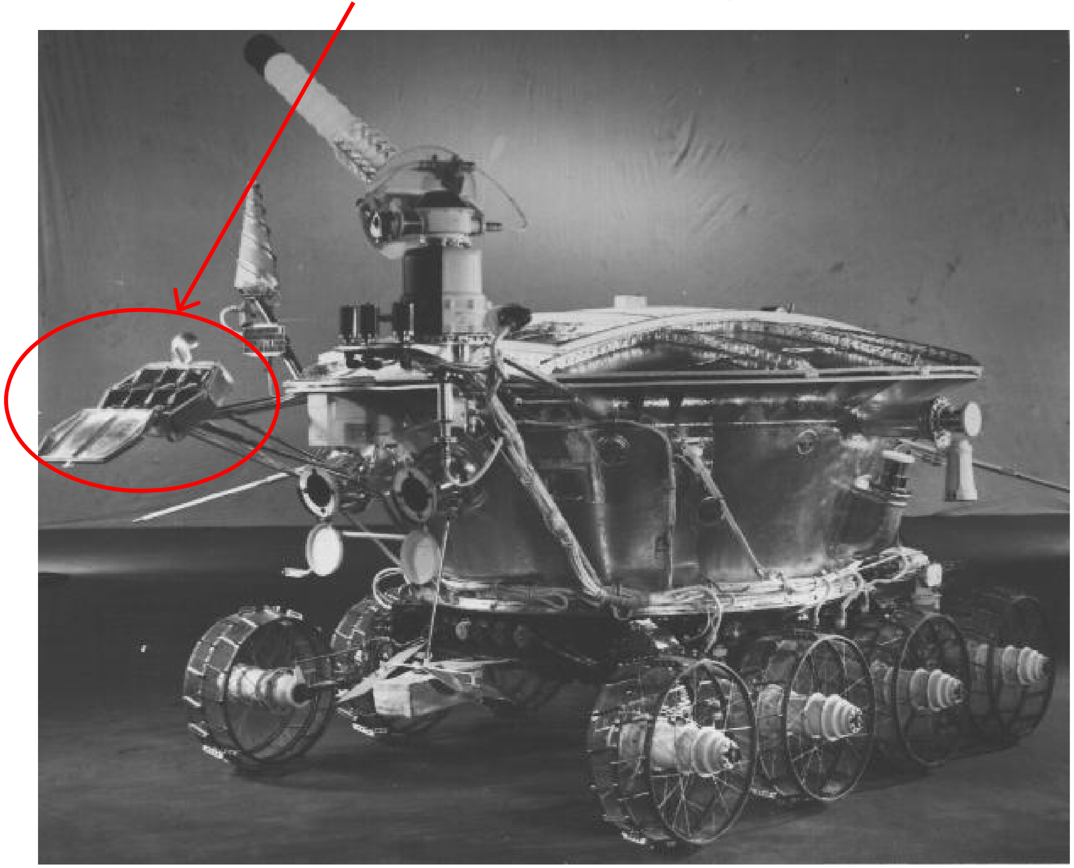
Excellent Legacy of the Apollo Program

The Apollo 11 retroreflector initiated a shift from analyzing lunar position angles to ranges. Today LLR is the **only** continuing experiment since the Apollo-Era.

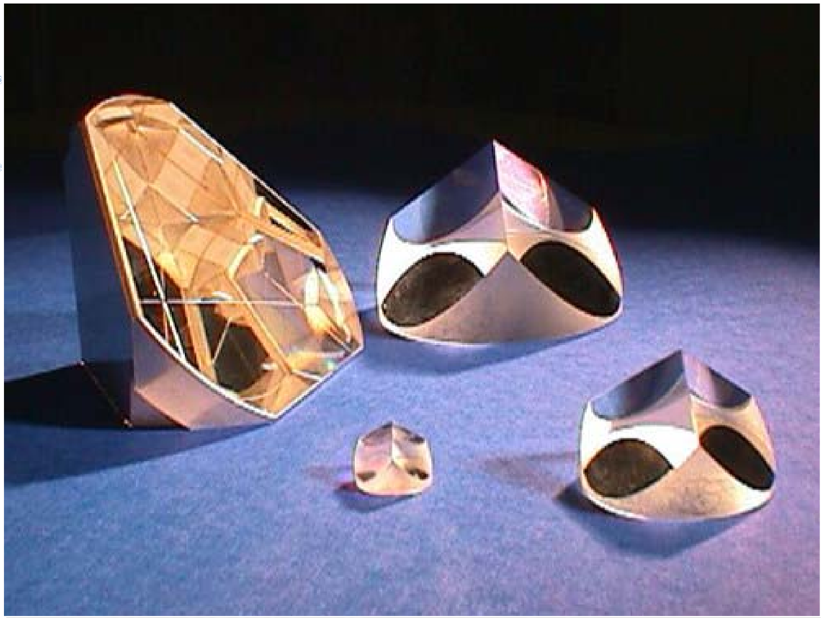


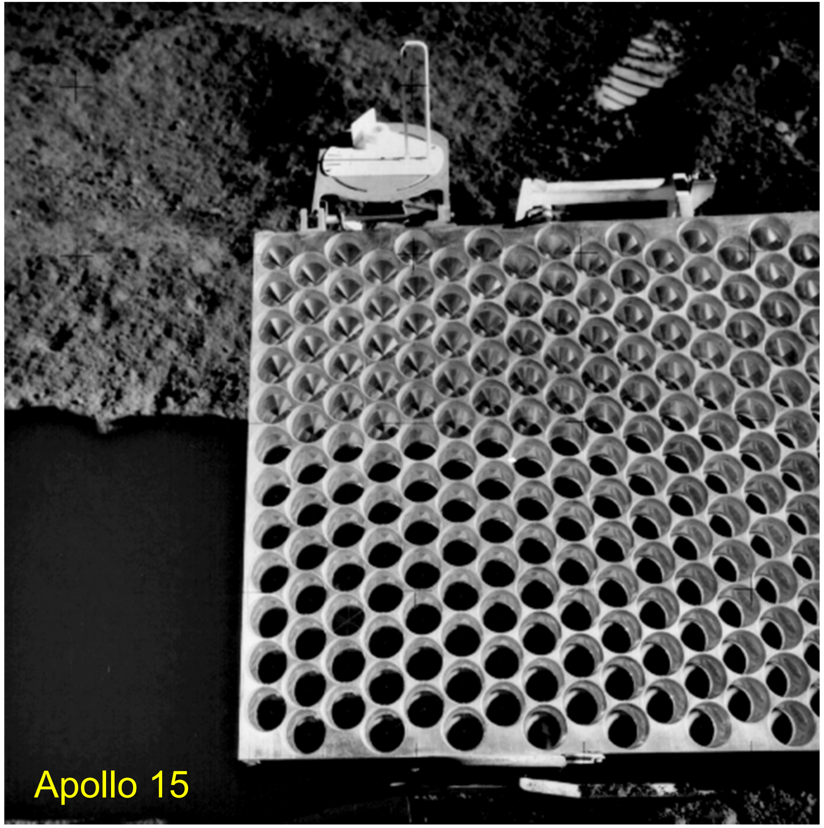
Lunar Retroreflectors

French-built retroreflector array



Lunokhod Rover (USSR, 1972)





Apollo 15

Beginning of the laser ranging technology.

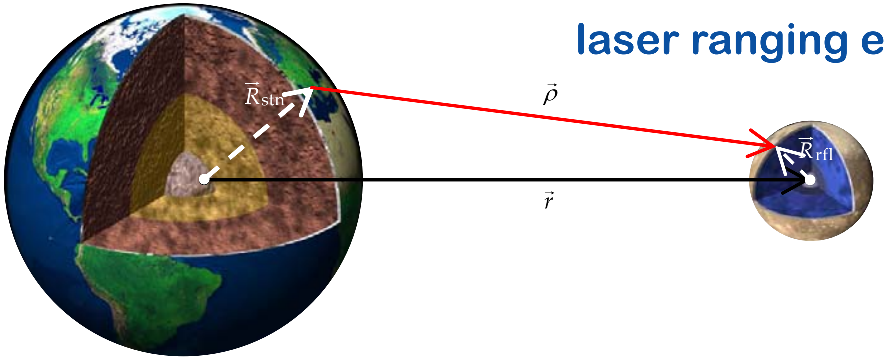
Today, laser ranging has many applications:

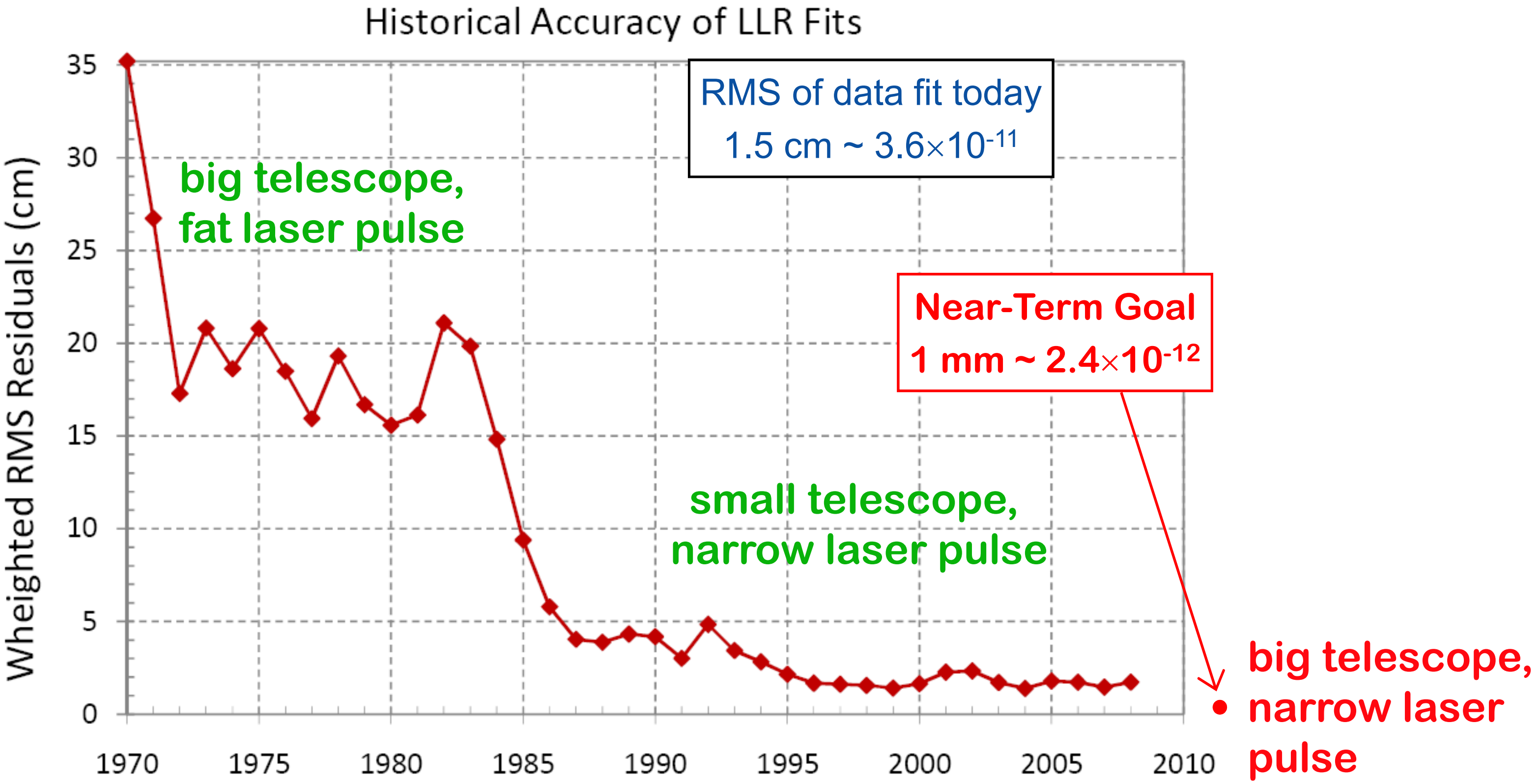
- Satellite laser ranging, communication systems, metrology, 3-D scanning, altimetry, etc.

LUNAR LASER RANGING SCEINCE

Historical Accuracy of LLR

Schematics of the lunar laser ranging experiment





RMS of data fit today
1.5 cm ~ 3.6×10^{-11}

big telescope,
fat laser pulse

Near-Term Goal
1 mm ~ 2.4×10^{-12}

small telescope,
narrow laser pulse

- big telescope, narrow laser pulse

Largest Effects in Lunar Orbit

Largest Radial Amplitudes by Cause

Cause	**Amplitude**
Ellipticity	20,905 & 570 km
Solar perturbations	3,699 & 2,956 km
Jupiter perturbation	1.06 km
Venus perturbations	0.73, 0.68 & 0.60 km
Earth J_2	0.46 & 0.45 km
Moon J_2 & C_{22}	0.2 m
Earth C_{22}	0.5 mm
Solar radiation pressure	4 mm

Relativistic Effects on Orbit

Cause	**Amplitude**
Lorentz contraction	0.95 m
Solar potential	6 cm
Time transformation	5 & 5 cm
Other relativity	5 cm

Sources: Chapront-Touzé and Chapront, Vokrouhlicky, Williams and Dickey

LLR Modeling and Related Science

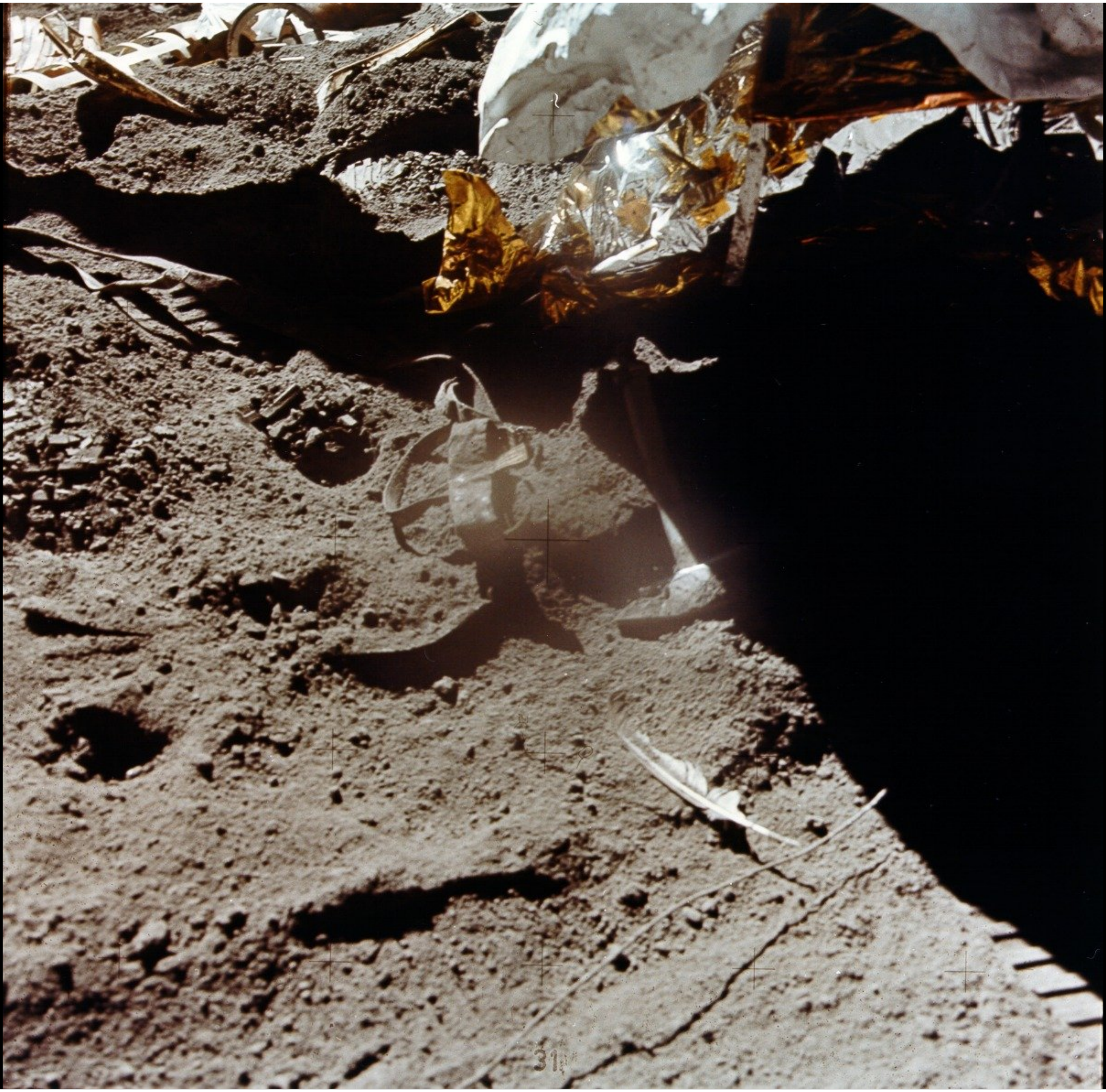
Effects in the Model:

- Modeling orbit dynamics:
  - Gravitational interaction between Sun, Moon, Earth, planets. Includes masses and general relativity.
  - Asteroid Newtonian attractions
  - Newtonian attraction between bodies and gravitational harmonics of extended bodies
  - Tidal effects
- Lunar rotation dynamics:
  - Torques from other bodies acting on gravity field
  - Tidal distortion of gravity field and moments
  - Mantle-fluid core interaction: dissipation & flattening
- Effects at Earth station:
  - Plate motion
  - Tidal displacements
  - Orientation of Earth's rotation axis and rotation
- Effects at lunar reflector:
  - Tidal displacements
  - Lunar orientation and rotation
- Time delays:
  - Atmospheric and Relativistic time delay
- Other effects:
  - Relativistic transformations: time & station positions
  - Solar radiation pressure
  - Thermal expansion of reflectors

Science Products:

- Lunar ephemerides and orbit:
  - are a product of the LLR analysis used by current and future spacecraft missions.
  - LLR greatly improved knowledge of the Moon's orbit: permits analyses of solar eclipses as far back as 1400 B.C.
- Lunar Science:
  - Lunar tides, characterized by Love numbers & Qs, sensitive to interior properties
  - Interior structure is revealed by the LLR solutions that are sensitive to strong lunar rotation dissipations suggesting 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 precession frequency.
  - Free rotation modes indicate stimulation.
- Gravitational physics:
  - Tests of the Equivalence principle
  - Accurate determination of the PPN parameter β
  - Determination of the PPN parameter γ
  - Limits on the time variation of the gravitational constant G,
  - Gravitational inverse square law
  - Relativistic precession of lunar orbit (geodetic precession)


STATES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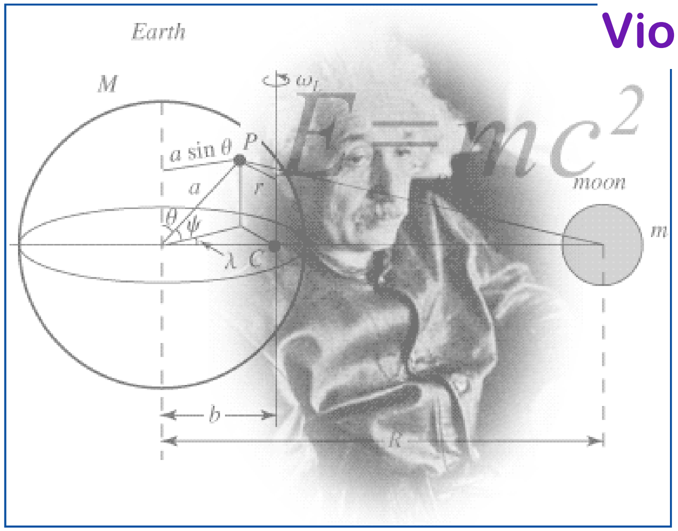
Testing General Relativity with LLR



Violation of the Equivalence Principle in PPN formalism:

$$\frac{\Delta a}{a} \equiv \frac{2(a_1-a_2)}{(a_1+a_2)} = \left(\frac{m_G}{m_I}\right)_1 - \left(\frac{m_G}{m_I}\right)_2, \qquad \frac{m_G}{m_I} = 1+(4\beta-\gamma-3)\frac{\Omega}{mc^2}$$

$$\frac{\Delta a}{a} = \eta\cdot\left(\frac{\Omega_e}{m_e c^2} - \frac{\Omega_m}{m_m c^2}\right) = -\eta\cdot 4.45\times10^{-10}, \qquad \eta \equiv 4\beta-\gamma-3.$$

If η =1, this would produce a 13 m displacement of lunar orbit. By 2007, range accuracy is ~15 mm, the effect was not seen.

LLR results:

16,471 normal points through May 29, 2007, including
147 APOLLO points plus MLRS, OCA, and HALA

$\Delta\left(\frac{m_G}{m_I}\right) = (-0.95\pm1.30)\times10^{-13}$ – corrected for solar radiation pressure from Vokrouhlicky (1997).

$\frac{\Delta a}{a} = (-1.95\pm1.91)\times10^{-13}$ – test of the Strong Equivalence Principle with Adelberger (2008) results for WEP $\quad \eta = 4\beta-\gamma-3 = (4.4\pm4.3)\times10^{-4}$

Using Cassini '03 result $\gamma-1 = (2.1\pm2.3)\times10^{-5} \;\Rightarrow\; \beta-1 = (1.2\pm1.1)\times10^{-4}$

$K_{\mathrm{GP}} = -0.0007\pm0.0047$ – Geodetic / de Sitter-Fokker precession

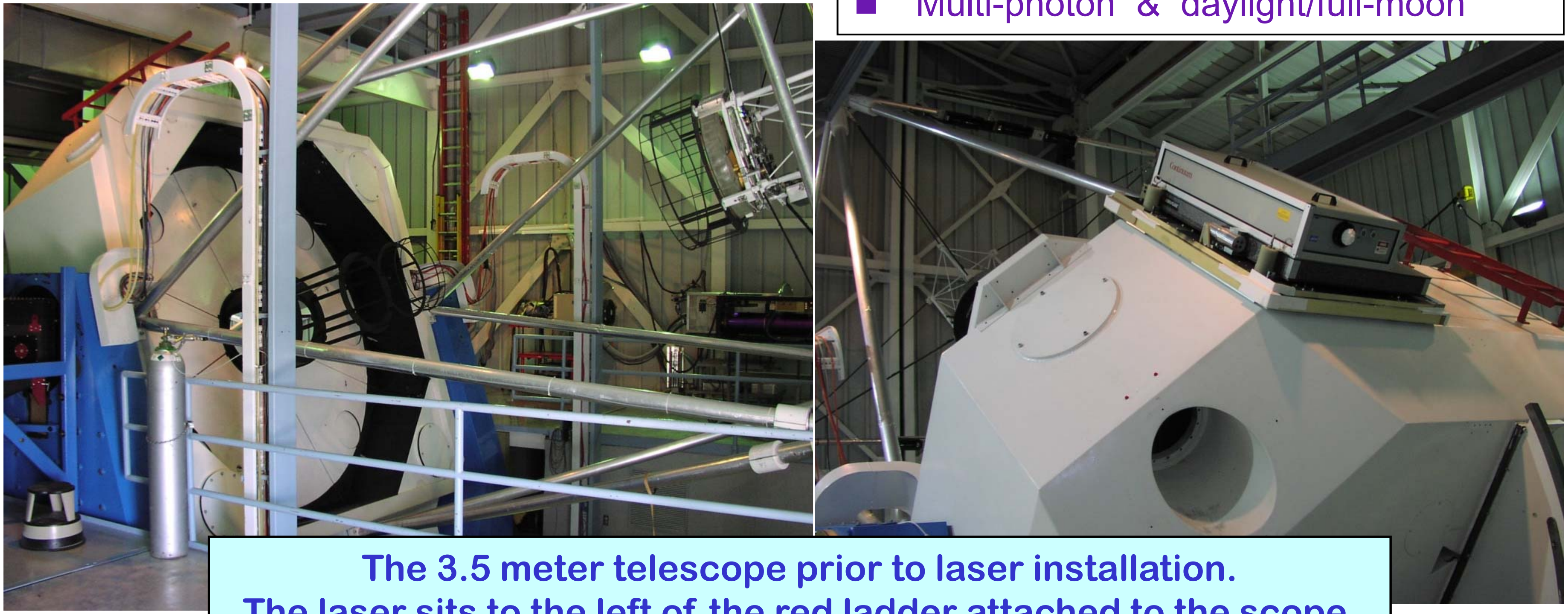
$$\boxed{\dot{G}/G = (4.9\pm5.7)\times10^{-13}\ \mathrm{yr}^{-1}}$$

The APOLLO Project & Apparatus:

Apache Point Observatory Lunar Laser-ranging Operation

- Move LLR back to a large-aperture telescope
  - 3.5-meter: more photons!
- Incorporate modern technology
  - Detectors, precision timing, laser
- Re-couple data collection to analysis/science
  - Scientific enthusiasm drives progress

- Uses 3.5-meter telescope at 9200-ft Apache Point, NM
- Excellent atmospheric "seeing": 1as
- 532 nm Nd:YAG, 100 ps, 115 mJ/pulse, 20 Hz laser
- Integrated avalanche photodiode (APD) arrays
- Multi-photon & daylight/full-moon



The 3.5 meter telescope prior to laser installation.
The laser sits to the left of the red ladder attached to the scope.

Laser Mounted on Telescope

First Light: July 24, 2005

First Light: July 24, 2005

Blasting the Moon

The Basic Link Equation

$$N_{\rm rx} = N_{\rm tx}\eta_c^2\eta_r Q n_{\rm refl}\left(\frac{d}{\phi r}\right)^2\left(\frac{D}{\Phi r}\right)^2$$

η_c = one-way optical throughput (encountered twice)

η_r = receiver throughput (dominated by narrow-band filter)

Q = detector quantum efficiency

$n_{\rm refl}$ = number of corner cubes in array (100 or 300)

d = diameter of corner cubes (3.8 cm)

ϕ = outgoing beam divergence (atmospheric “seeing”)

r = distance to moon

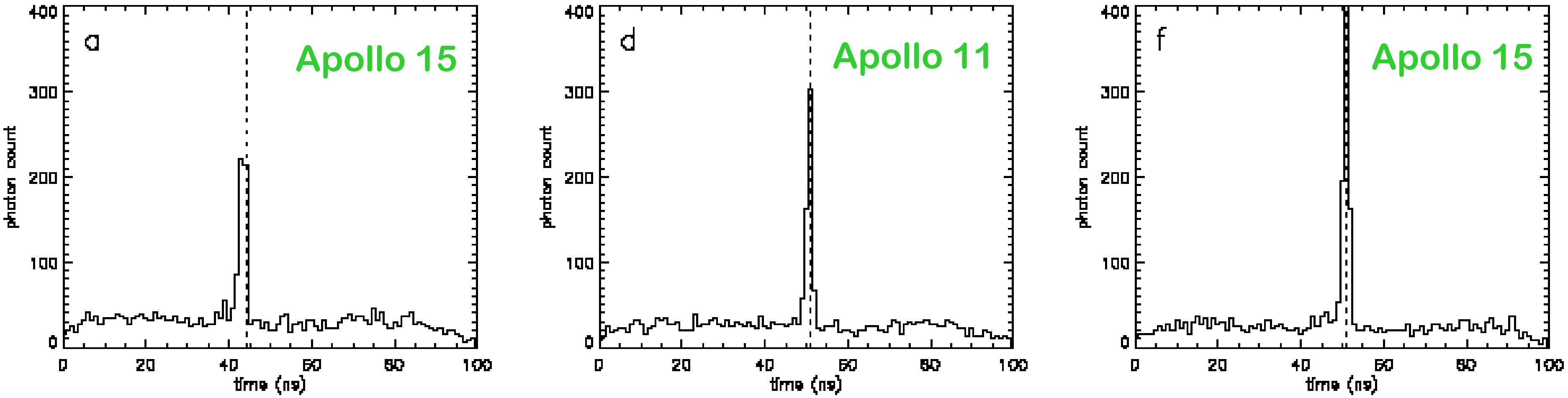
Φ = return beam divergence (diffraction from cubes)

D = telescope aperture (diameter; 3.5 m)

$$N_{\rm rx} = 5.4\left(\frac{E_{\rm pulse}}{115\ {\rm mJ}}\right)\left(\frac{\eta_c}{0.4}\right)^2\left(\frac{\eta_r}{0.25}\right)\left(\frac{Q}{0.3}\right)\left(\frac{n_{\rm refl}}{100}\right)\left(\frac{1\ {\rm arcsec}}{\phi}\right)^2\left(\frac{10\ {\rm arcsec}}{\Phi}\right)^2\left(\frac{385000\ {\rm km}}{r}\right)^4$$

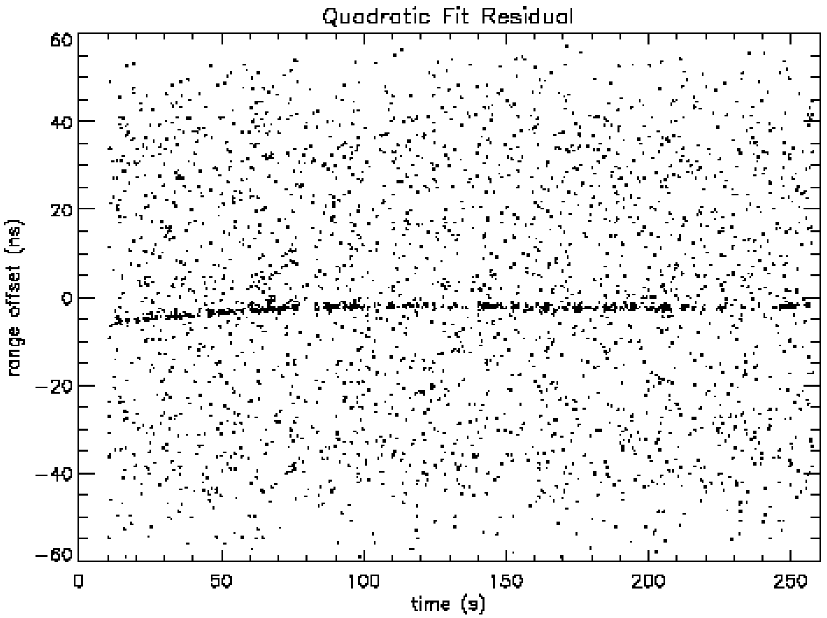
- APOLLO should see 5 photons per pulse on Apollo 11 & 14; 15 on Apollo 15

APOLLO First Lunar Returns: October 19, 2005



30 min: 5 consecutive 5 min runs – 2,400 protons; MLRS got as many for 2000-2002.

APOLLO can operate in full-moon; no other LLR station can do that.

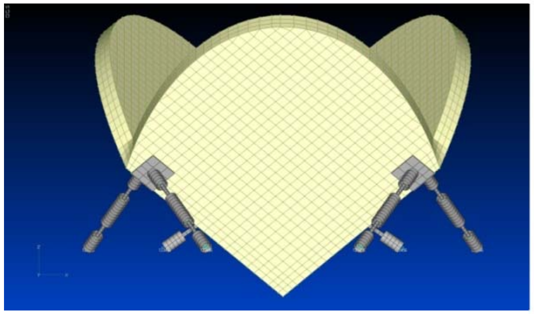


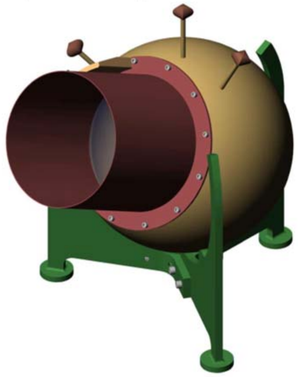
Error Source	**Round-Trip Time Uncertainty, [ps]**	**One-Way Range Error, [mm]**
Retro Array Orientation	100–300	15–45
APD Illumination	60	9
APD Intrinsic	<50	< 7
Laser Pulse Width	45	6.5
Timing Electronics	20	3
GPS-slaved Clock	7	1
Total Random Uncert.	136–314	20–47

Single-photon random error budget

Future Lunar Laser Ranging

- Future LLR sites & corner cube retro-reflectors (CCR):
  - A wider spread of future LLR site locations would improve the determination of 3-D rotation and tides to the benefit of lunar science.
  - Old reflectors are degraded (perhaps due to dust ?) and are inefficient
  - New CCRs should give strong signals with no spread of laser pulse, must have low mass and allow for robotic deployment...





- Improvements in LLR Science:
  - **Properties of the lunar interior**, including liquid core & solid inner core can be determined from lunar rotation, orientation, and tidal response.
  - **Earth geophysics/geodesy**: positions & rates for the Earth stations, Earth rotation, precession rate, nutation, tidal influences on the orbit.
  - Improvements are also expected in several **tests of general relativity**.
  - **Perhaps delivered to the Moon by next generation of Vega ELV?**

Advanced LLR: anticipated results

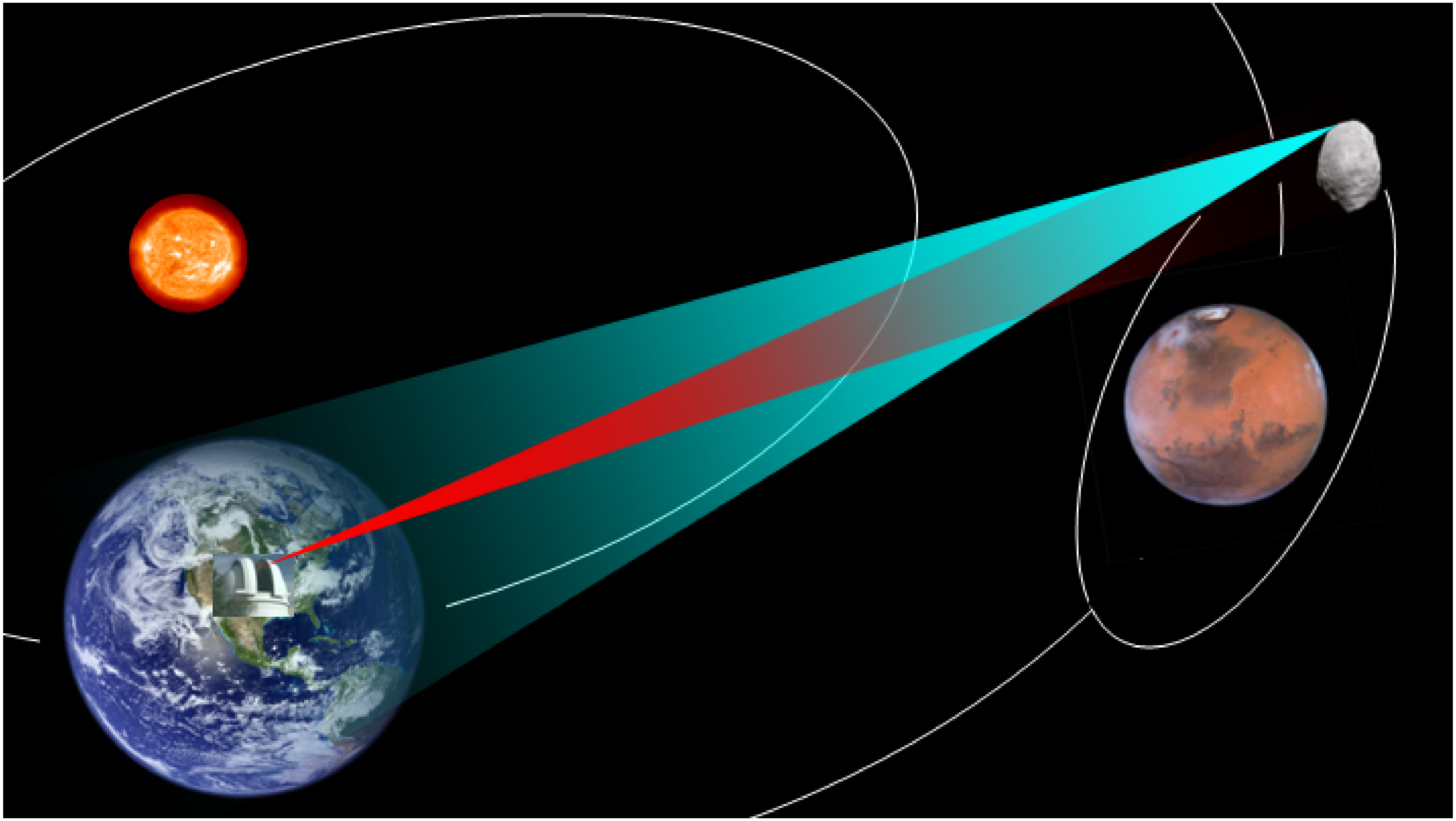
Tests of GR

Science	Timescale	Current (cm)	1 mm	0.1 mm
Weak Equivalence Principle	Few years	$\|\Delta a/a\|<1.3\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle	Few years	$\|\eta\|<4.3\times10^{-4}$	3×10^{-5}	3×10^{-6}
PPN parameter β	Few years	$\|\beta-1\|<1.1\times10^{-4}$	10^{-5}	10^{-6}
Time variation of G	~10 years	5.7×10^{-13} yr^{-1}	5×10^{-14}	5×10^{-15}
Inverse Square Law	~10 years	$\|\alpha\|<3\times10^{-11}$	10^{-12}	10^{-13}

Lunar science

Effect	Current	Future Goals
Positions on Moon	yes	More locations
Low-degree gravity field	yes	Distinguish mantle from inner core for gravity and moments
3 free libration mantle modes	yes	Seek stimulating events
Solid-body tides	yes	Improve Love number accuracies
Tidal dissipation	yes	Improve tidal Q vs frequency
Core/mantle boundary dissipation	yes	Improve uncertainty, used to limit fluid core size
Core/mantle boundary flattening	yes	Improve uncertainty
Fluid core moment of inertia	no	Detect and determine
Fluid core free precession mode	no	Detect mode, determine amplitude & period
Inner solid core	no	Detect inner core, determine gravity
3 inner core free libration modes	no	Detect modes, determine amplitudes & periods
Inner core boundary dissipation	no	Limit inner core size

Phobos Laser Ranging Architecture



Next Step – a mm-class Interplanetary Laser Ranging

Recent Interplanetary Laser Transponder Experiments

Key Instrument parameters for recent deep space laser transponder experiments

MESSENGER Laser Altimeter (MLA): 2-way

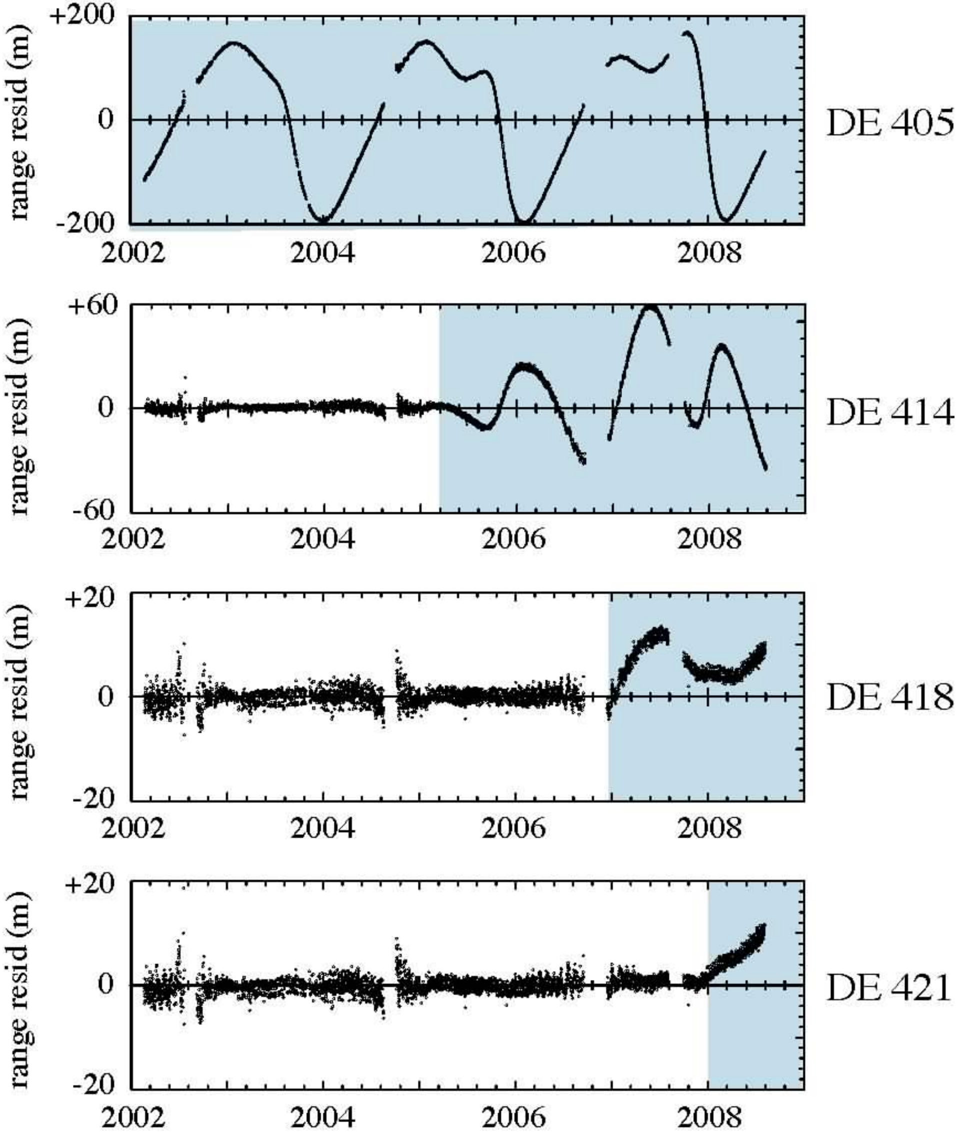
Mars Orbiter Laser Altimeter (MOLA): 1- way

Experiment	MLA (cruise)		MOLA (Mars)
Range (10^6 km)	24.3		~80.0
Wavelength, nm	1064		1064
	Uplink	Downlink	Uplink
Pulsewidth, nsec	10	6	5
Pulse Energy, mJ	16	20	150
Repetition Rate, Hz	240	8	56
Laser Power, W	3.84	0.16	8.4
Full Divergence, μrad	60	100	50
Receive Area, m^2	0.042	1.003	0.196
EA-Product, J-m^2	0.00067	0.020	.0294
PA-Product, W-m^2	0.161	0.160	1.64

- Note, these were experiments of opportunity and not design
- At the same time, the accuracy of MLA range determination was 12 cm at the distance of 24 mln km from the Earth (Sun et al., 2005, Smith et al., 2005)

Initial Target was Mars. Why?

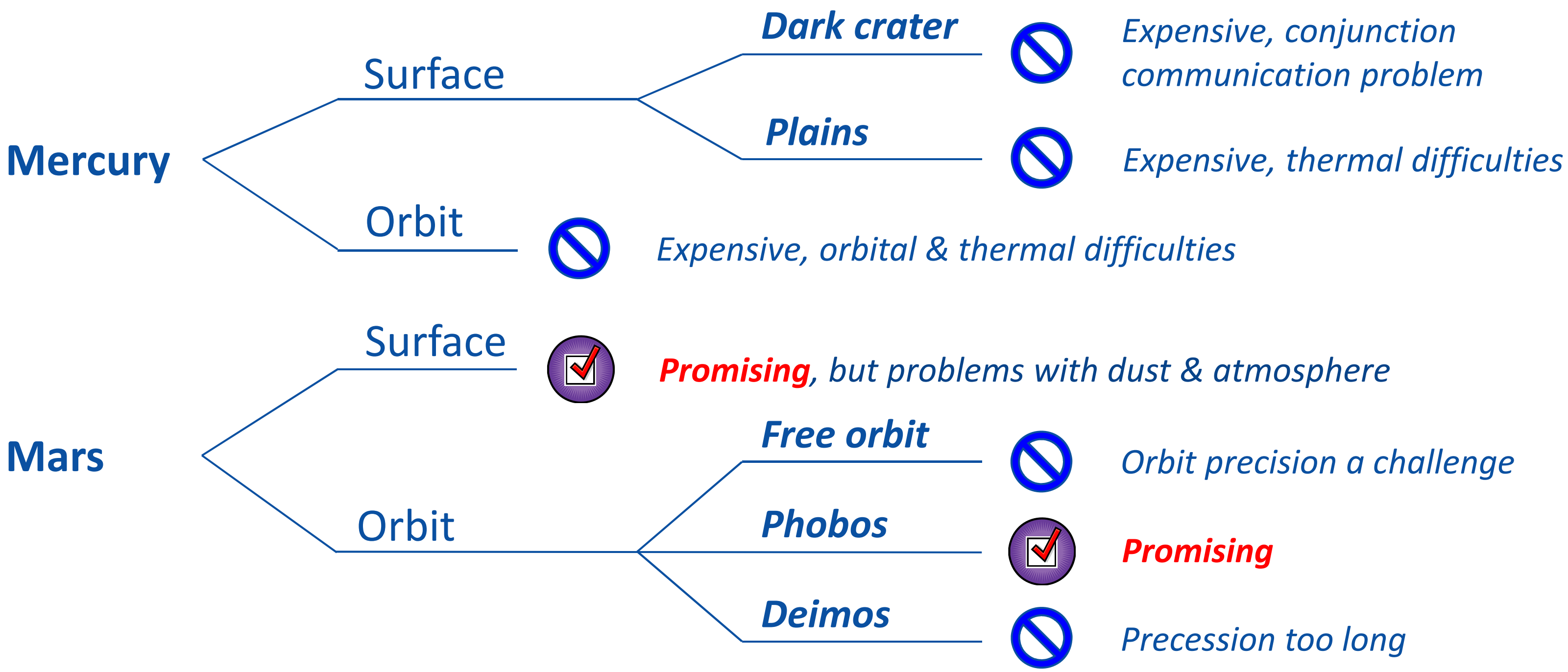
- Mars has 20-year history of range measurements
  - Helps in estimation of long-term/secular effects
- Rich history of technology for Mars landers
  - Many landers & orbiters operated for long times (e.g. Viking)
- Mars distance from Sun compatible with normal electronics & solar power
- On down-side, Mars is more perturbed by asteroids
  - But Earth is also perturbed, so sets lower limit when looking at any solar system body



JPL Planetary Ephemeris Fit

Typical atmosphere on Mars...

Interplanetary Laser Ranging Trade Space



Mercury
- Surface
  - ***Dark crater*** ⊘ *Expensive, conjunction communication problem*
  - ***Plains*** ⊘ *Expensive, thermal difficulties*
- Orbit ⊘ *Expensive, orbital & thermal difficulties*

Mars
- Surface ☑ ***Promising****, but problems with dust & atmosphere*
- Orbit
  - ***Free orbit*** ⊘ *Orbit precision a challenge*
  - ***Phobos*** ☑ ***Promising***
  - ***Deimos*** ⊘ *Precession too long*

Asteroid ⊘ *No suitable candidate with enough conjunctions*

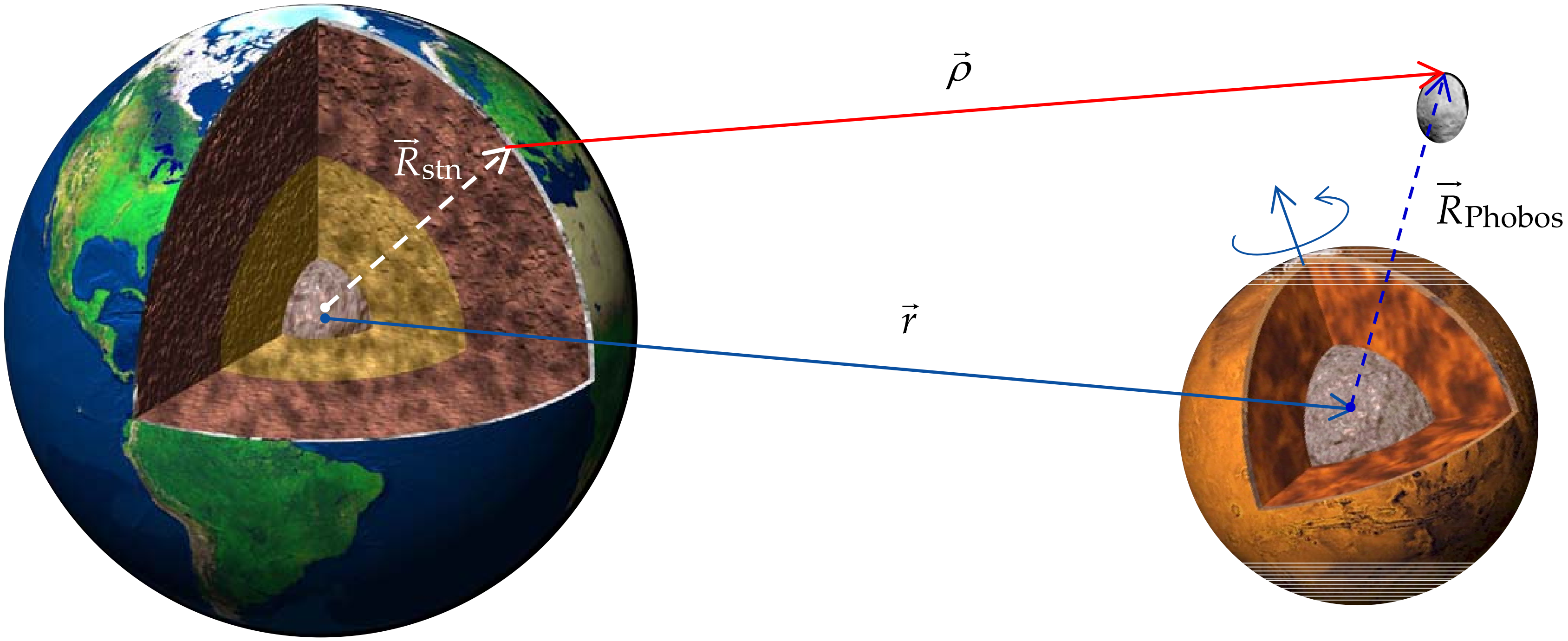
Free-flyer ⊘ *Expensive, as a single spacecraft architecture would need a drag-free platform; Insufficient science with a time-of-flight transponder (need for coherent detection).*

Simulated: laser ranging over 1-6 years of operation based on daily 1 mm range points.

Estimated parameters (total up to 230) include orbital elements (60), up to 67 individual asteroid GMs, asteroid class densities (3), spacecraft biases (8), solar corona corrections (8), planetary features (Mars, Mercury, Phobos, etc.) and others.

Phobos Laser Ranging: the Principle

1 mm range accuracy with PLR is possible

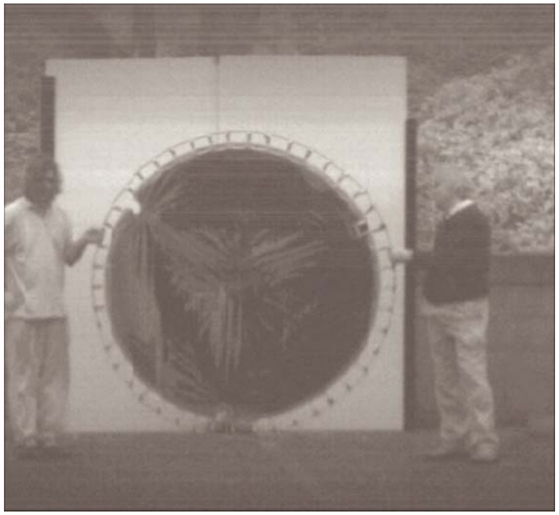


Impact on:

- Test of general relativity
- The science of Phobos, especially its interior

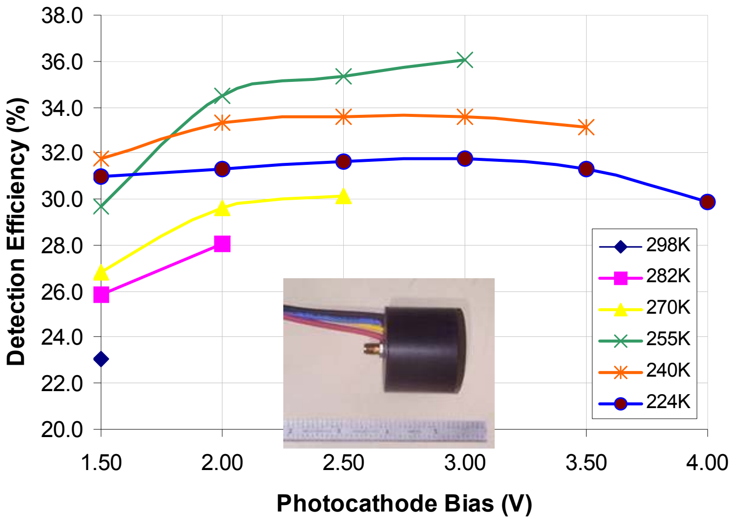
Interplanetary Laser Ranging Segments

- Earth side
  - 1 m telescopes, subset of the SLR network
    - Transmits 1 KHz / 3 mJ / 12 ps pulses at 532 nm
    - 25 μrad transmit beam divergence
    - Photon counting detection of received 1064 nm signal from Mars/Phobos using InGaAsP intensified photodiode (35% SPDE)
    - Solar rejection filter across telescope aperture for operations to 3° of sun



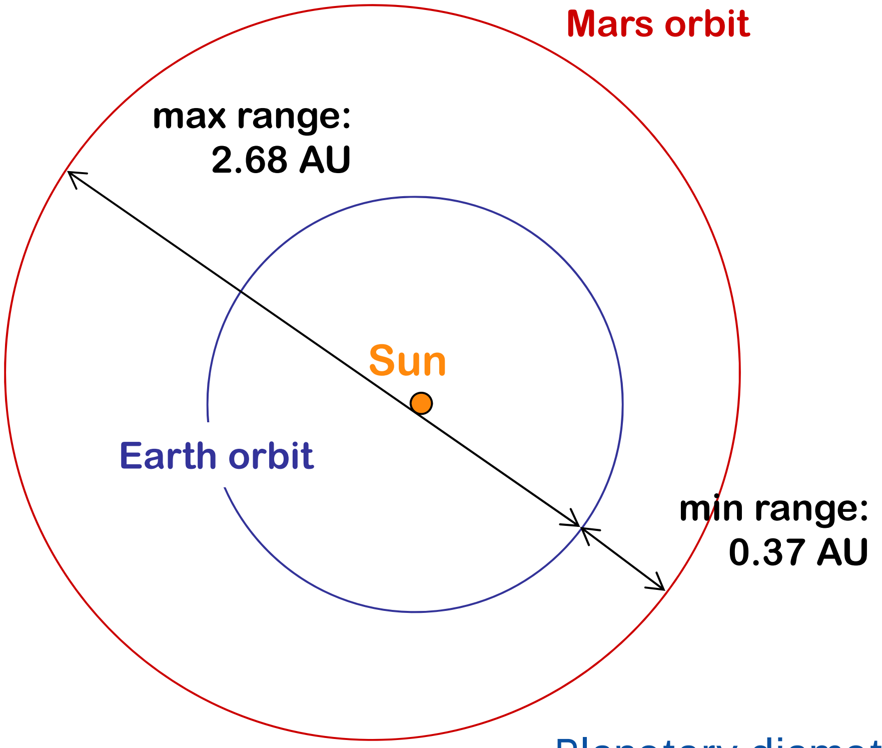
Prototype 1.5 m diameter solar protection filter

- Mars/Phobos side
  - Landed asset: MLR/PLR Transceiver
    - Transmits 1 KHz / 0.25 mJ / 12 ps pulses at 1064 nm
    - 160 μrad transmit beam divergence
    - Photon counting detection of received 532 nm signal from Earth using Si GM-APD (50% SPDE)
    - Solar rejection filter for operations to 2° of sun



Intensified Photodiode SPDE at 1064 nm

Ranging Parameters & Link Budget



- Opposition can be from 0.37 to 0.68 AU
- Conjunction can be from 2.37 to 2.68 AU

Planetary diameters:

- @max distance:
  Mars 17 μrad,
  Earth 32 μrad
- @min distance:
  Mars 122 μrad,
  Earth 229 μrad

Input Parameters	Earth to Phobos	Phobos to Earth
wavelength (nm)	532	1064
transmit power (w)	3	0.25
tx efficiency	0.5	0.5
tx beam divergence (µrad)	25	160
tx pointing loss (dB)	-2	-2
tx atmospheric loss	-3	-3
tx pulse frequency (kHz)	1	1
rx atmospheric loss (dB)	-4.3	-4.3
rx diameter (m)	0.1	1
rx efficiency	0.3	0.3
rx field of view (µrad)	240	20
rx detector efficiency	0.4	0.4
background (W/m/m/sr/µm)	32	32
scattered light radiance (W/m/m/sr,	100	100
Earth sky radiance (W/m/m/sr/µm)	0	1000
bandpass FWHM (nm)	0.2	0.2
range(AU)	2.6	2.6
Derived Parameters		
photon energy (aJ)	0.37	0.18
space loss (dB)	-166	-162
rx signal power (aW)	9.3	1.9
planet background power (pW)	0.05	2
scattered light power (W)	0.15	6.9
sky radiance power (pW)	0	69
timing window (µs)	1024	27
Summary Results		
incident signal power (aW)	2.8	5.70E-01
incident noise power (pW)	2.7	21.3
SNR (dB)	-60	-76
detected signal rate (Hz)	3	1.2
detected noise rate (MHz)	3	46
timing window (ns)	10	10
data volume (MB/day)	100	1570

PLR Tests of Gravity vs Experiment Duration

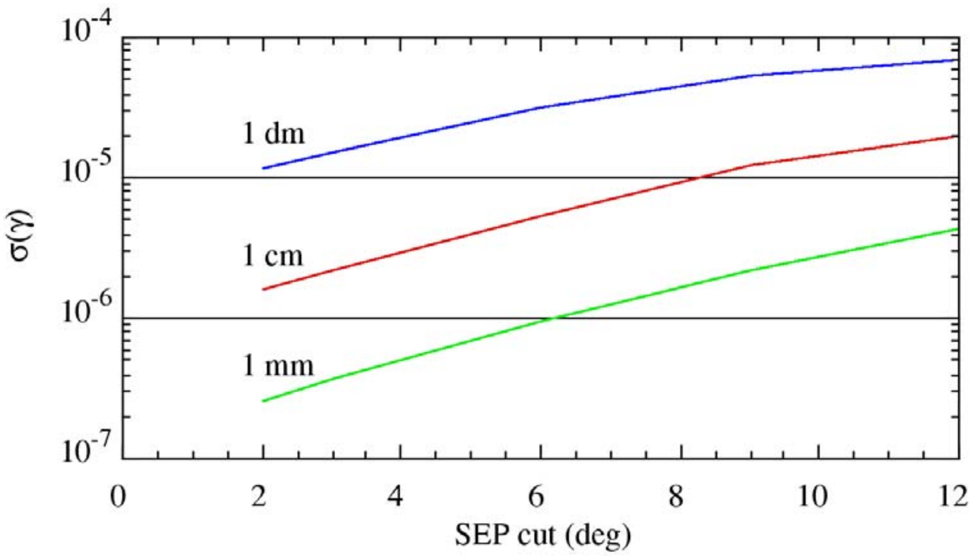
Relativistic Effect	Current best	Mission duration / N of conjunctions		
		1 yr / 1 cnj	3 yr / 2 cnj	6 yr / 3 cnj
PPN parameter γ	2.3×10^{-5}	3.1×10^{-7}	1.4×10^{-7}	7.9×10^{-8}
PPN parameter β	1.1×10^{-4}	4.3×10^{-4}	1.6×10^{-4}	9.4×10^{-5}
Test of Strong Equiv. Principle, η	4.3×10^{-4}	1.5×10^{-3}	2.8×10^{-4}	8.8×10^{-5}
Solar oblateness, J_2	2.0×10^{-7}	6.9×10^{-8}	3.2×10^{-8}	2.3×10^{-8}
Search for time variation in the grav. constant G, $dG/dt/G$, yr^{-1}	7×10^{-13}	1.7×10^{-14}	2.8×10^{-15}	1.0×10^{-15}
Gravitational inverse square law	2×10^{-9} @ 1.5 AU	4×10^{-11} @ 1.5 AU	2×10^{-11} @ 1.5 AU	1×10^{-11} @ 1.5 AU

Estimated uncertainties for parameters of interest as a function of Phobos lander mission duration, with 1 mm laser ranging once per day with 2° SEP cut-off and 67 asteroid mass parameters estimated.

Simulations by W.M. Folkner, JPL

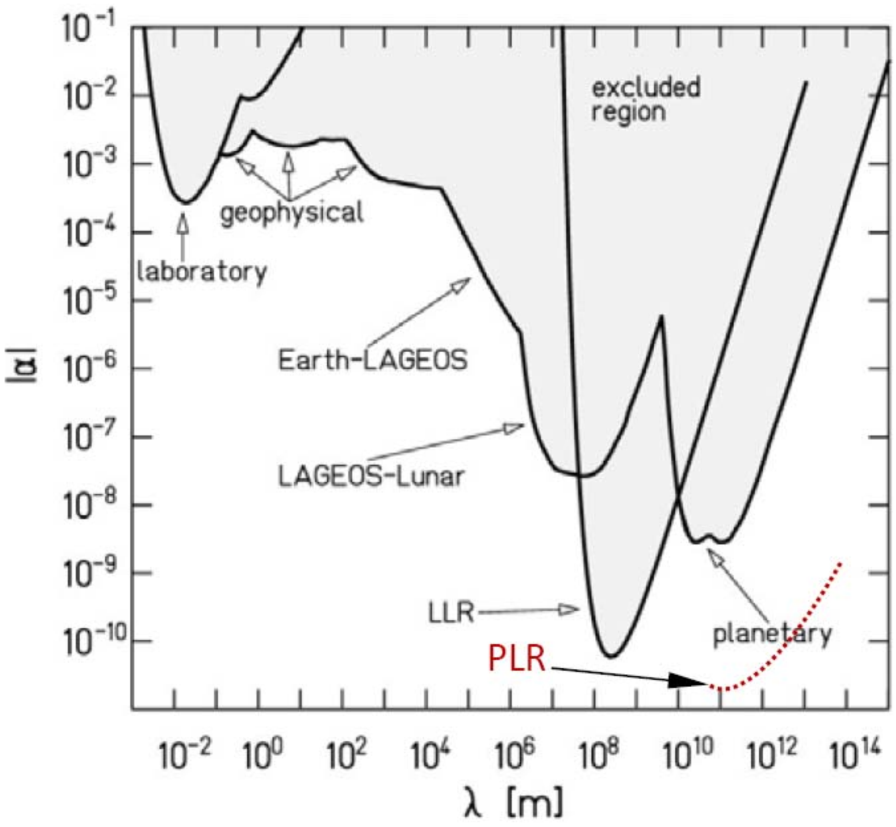
Gravity Tests with PLR: PPN γ and the ISL

Estimated uncertainty in PPN γ



Estimated uncertainty in PPN γ as a function of data accuracy and data cut-off with angular separation from the Sun as viewed from Earth.

Limits on the ISL violations



Simulations by W.M. Folkner;
background graphics from (Adelberger et al., 2003)

Summary

- Laser ranging to Mars/Phobos offers significant potential for the tests of relativistic gravity in the solar system:
  - 1 mm ranging is possible, with photon link rates spanning a few Hz to kHz
  - Existing SLR stations on Earth only with minor modifications may be involved in the experiment
- Phobos Laser Ranging (PLR) is a medium-class space mission designed to advance tests of relativistic gravity in the solar system
  - A baseline instrument and mission design exist, complete with mass, power, and price estimates
  - Same mission and instrument designs could be used to advance the goals of planetary exploration (studies of Phobos, Mars, etc.)
  - We are continuing to refine studies of the instrument and science case for both planetary studies and tests of gravity
  - **Perfect candidate for Vega's first interplanetary flight!**