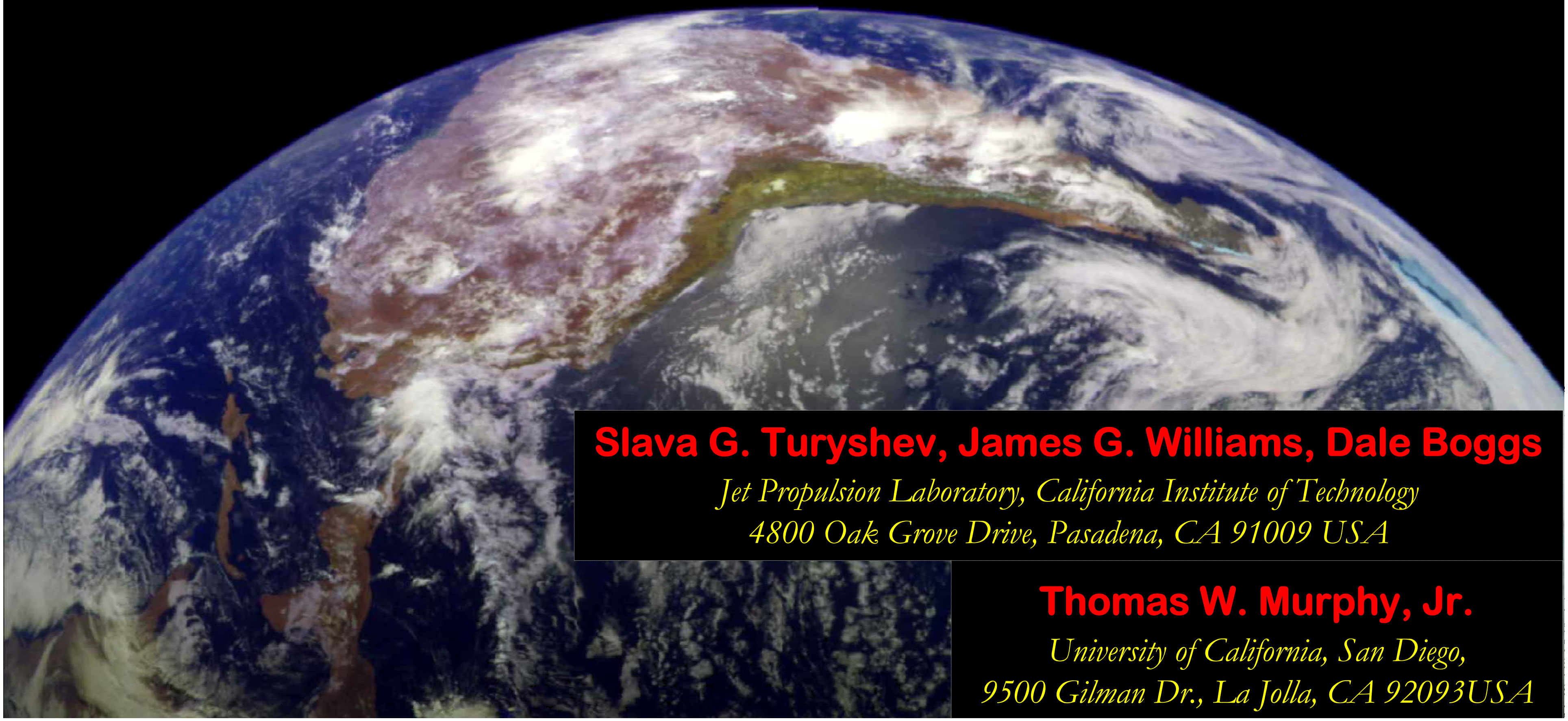
Проблемы Современной Астрометрии,
Всероссийская конференция-школа для молодых ученых
Звенигород, Россия - 22-26 октября 2007

Lunar Laser Ranging & Tests of General Relativity



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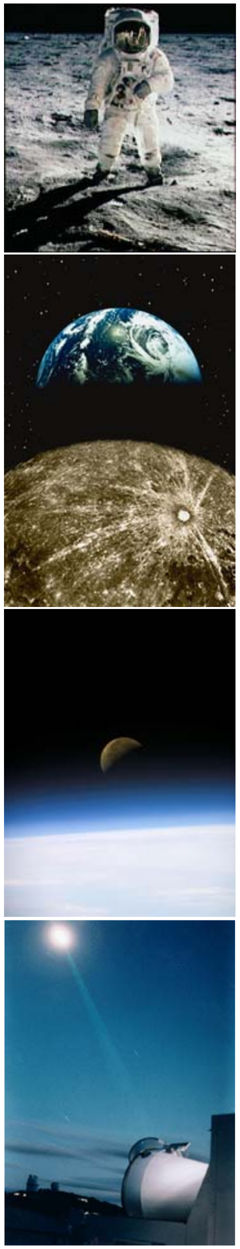
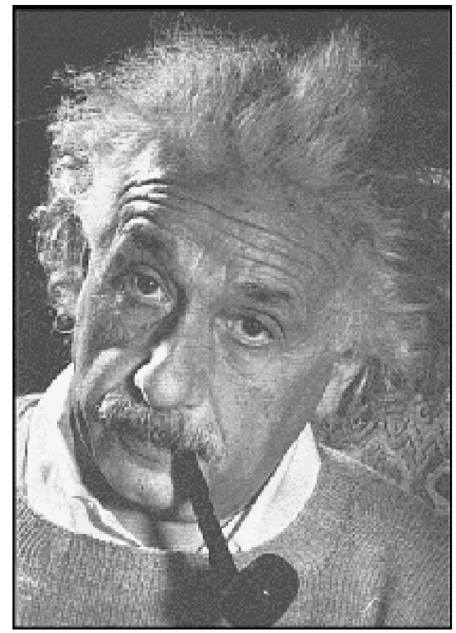
The Purpose:



Lunar Laser Ranging currently is the only means to Test the Strong Equivalence Principle

Talk will cover:

- LLR History & Current State
- LLR Tests of Relativistic Gravity:
  - Recent Results of EP Tests
- The Future:
  - APOLLO Facility
  - Modeling Challenge



Take-Away Message:

LLR is one of the best tools for comprehensive gravity tests.
LLR enables robust advances in lunar science & fundamental physics.
LLR is about to go through a renaissance with APOLLO.

Lunar Laser Ranging

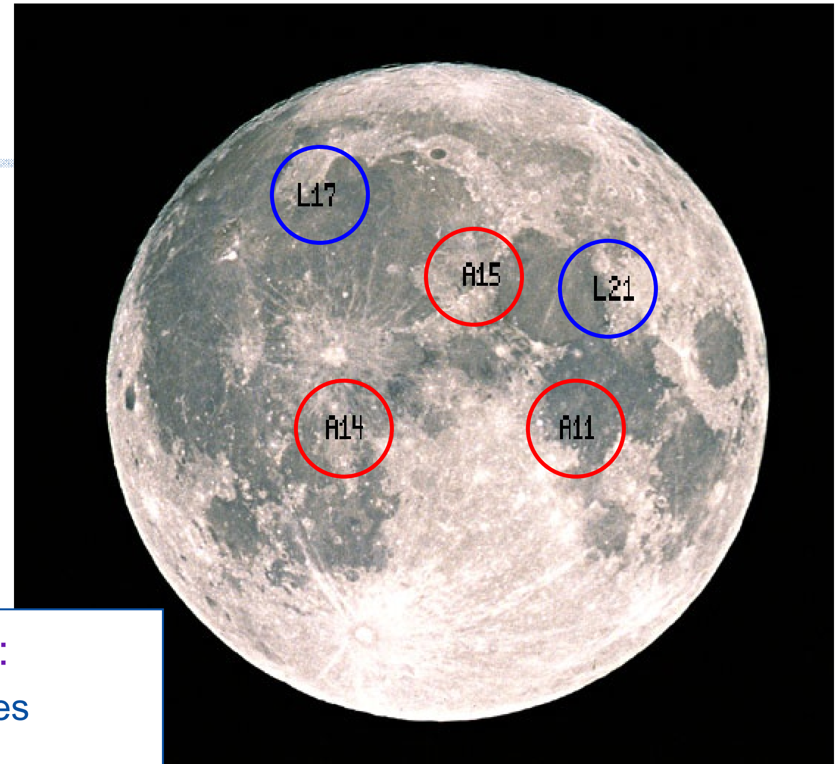
It is all begun 38 year ago…

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
  - Lunakhod 2 Rover

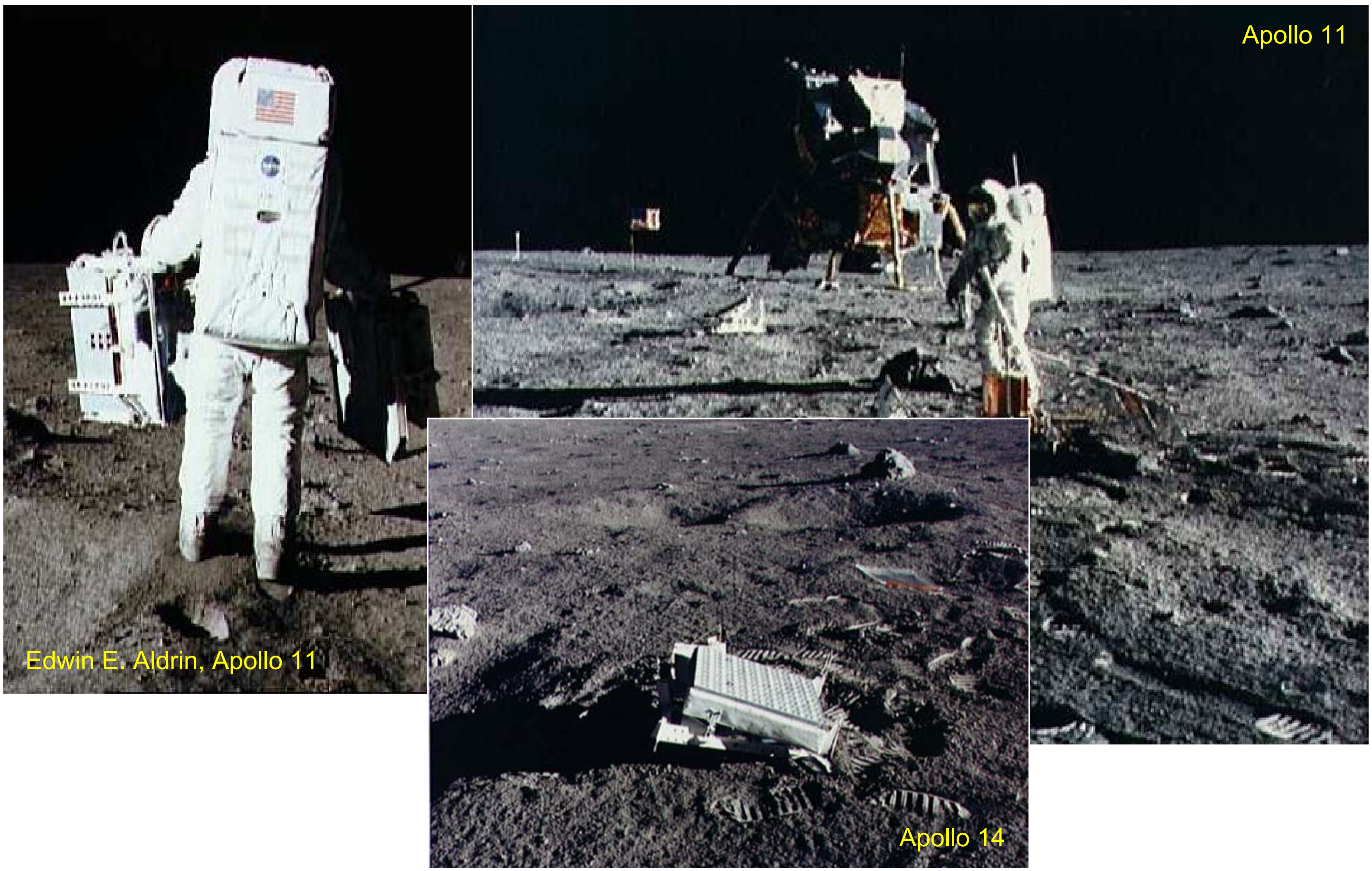
- LLR conducted primarily from 3 observatories:
  - McDonald (Texas, USA)
  - OCA (Grasse, France)
  - Haleakala (Hawaii, USA)

- New LLR stations:
  - Apache Point, (NM, USA)
  - Matera (Matera, Italy)
  - South Africa, former OCA LLR equipment



Excellent Legacy of the Apollo Program

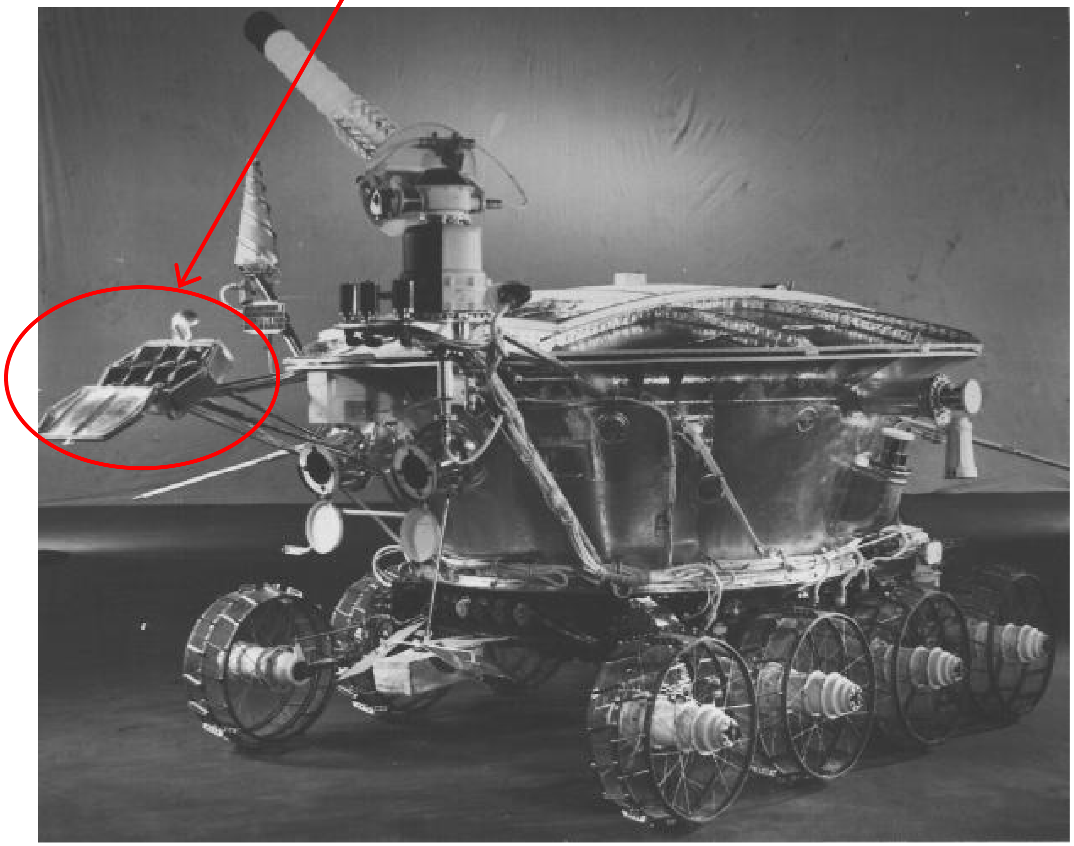
The Apollo 11 retroreflector initiated a shift from analyzing lunar position angles to ranges. Today LLR is the **only** continuing experiment since the Apollo-Era




STATES

Lunar Retroreflectors

French-built retroreflector array

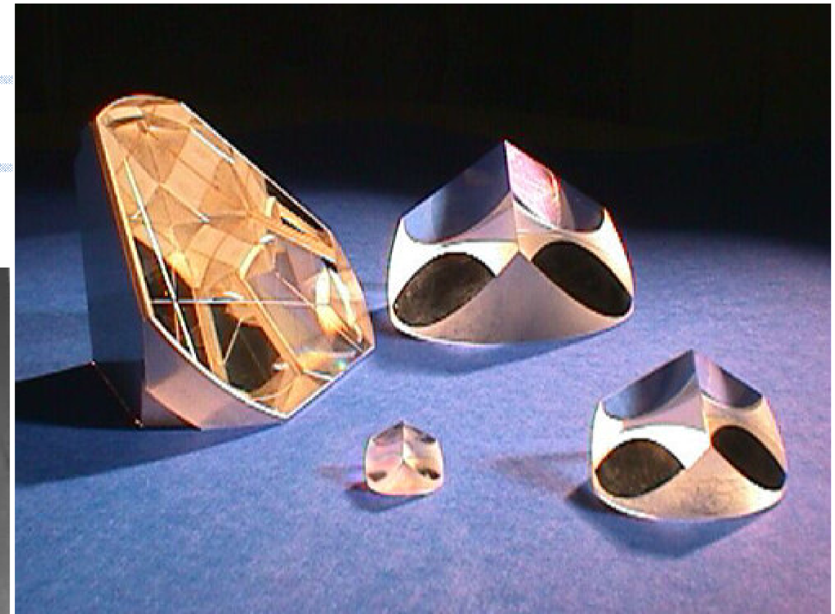


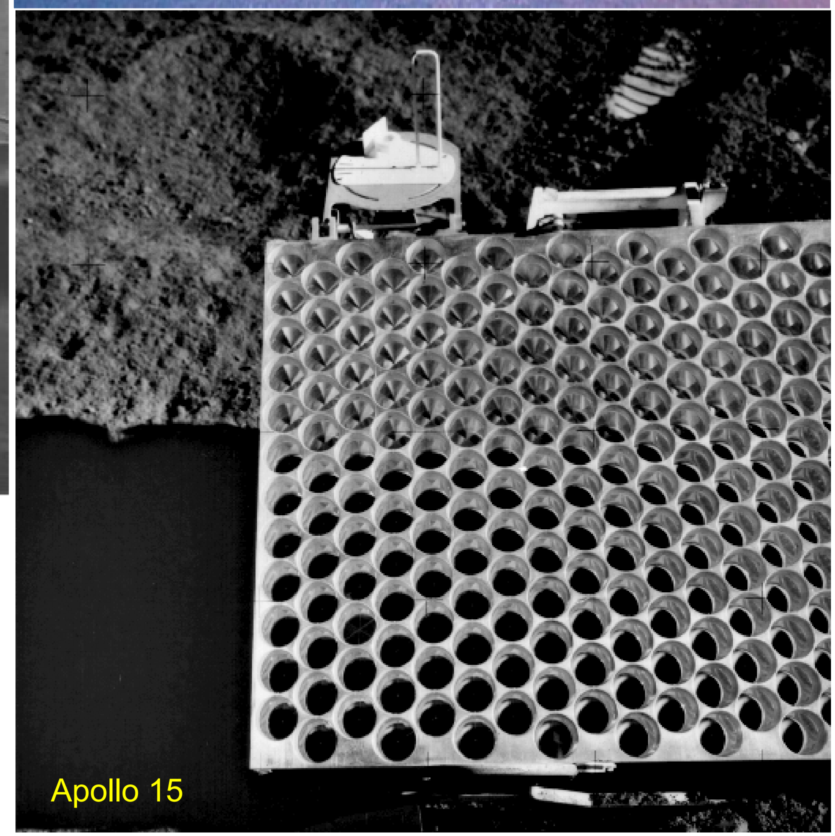
Lunokhod Rover (USSR, 1972)

Beginning of the laser ranging technology.

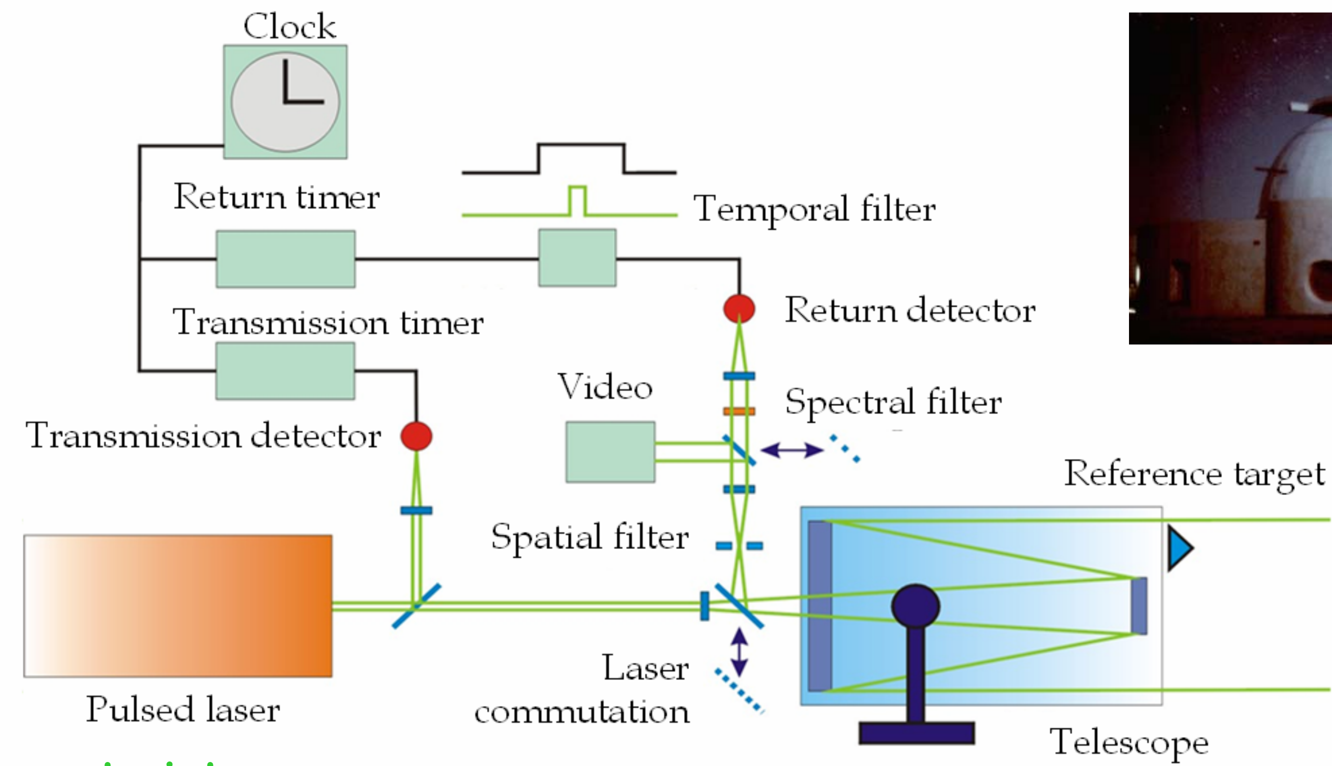
Today, laser ranging has many applications:

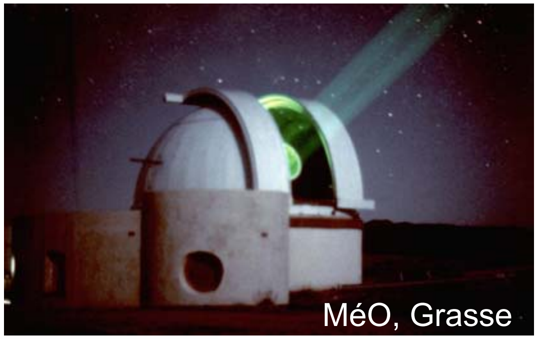
- Satellite laser ranging, communication systems, metrology, 3-D scanning, altimetry, etc.





Time-of-flight measurements: SLR and LLR



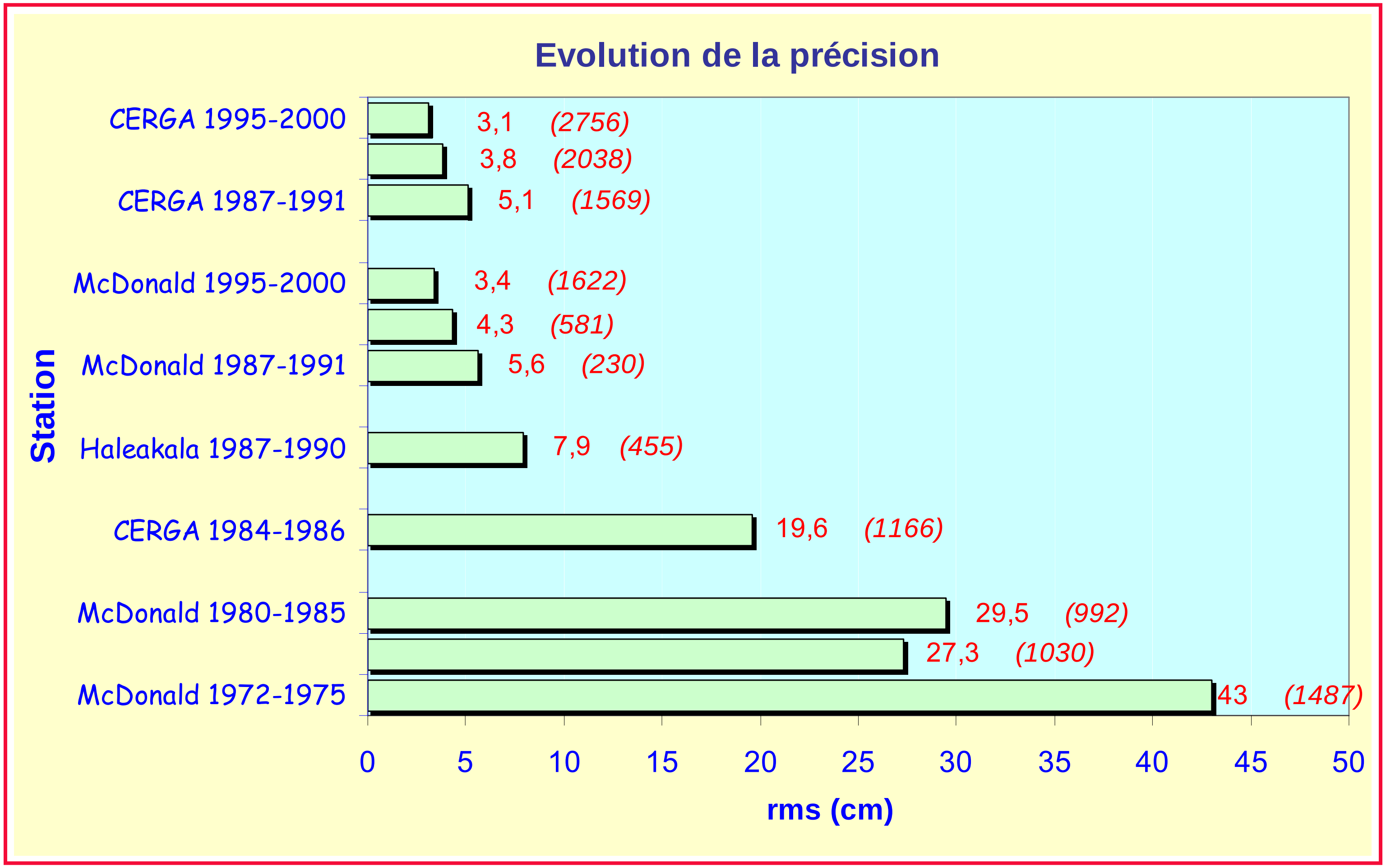


Major constraints:

- Atmospheric delay prediction:
  - accuracy 15 ps for zenith
  - accuracy 70 ps at 15° elevation
  - atmosphere affect precision by increasing the time constant to $\tau < 0.5$ s or $\tau > 1000$ s

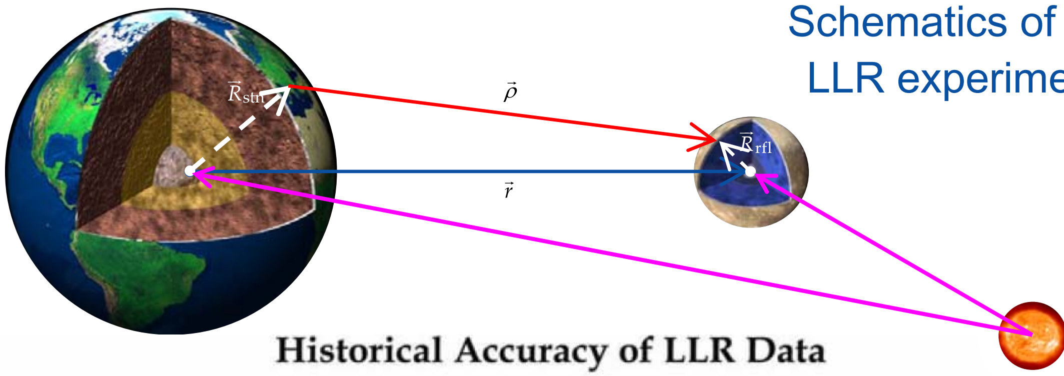
- Targets on moon and satellites:
  - size w/ orientation: contribution to uncertainty, e.g. $\sigma_{ApolloXV}$ = 0-350 ps
- Return detector (in photon mode):
  - precision some 10s ps (detector / spot size, location)

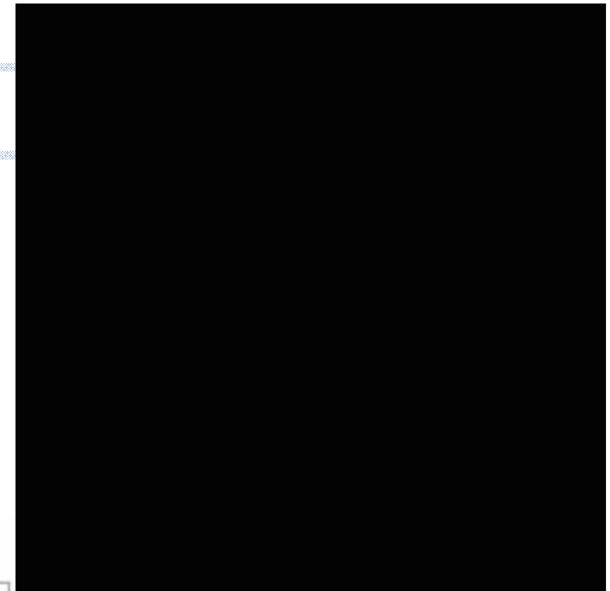
Historical Precision (rms residuals)



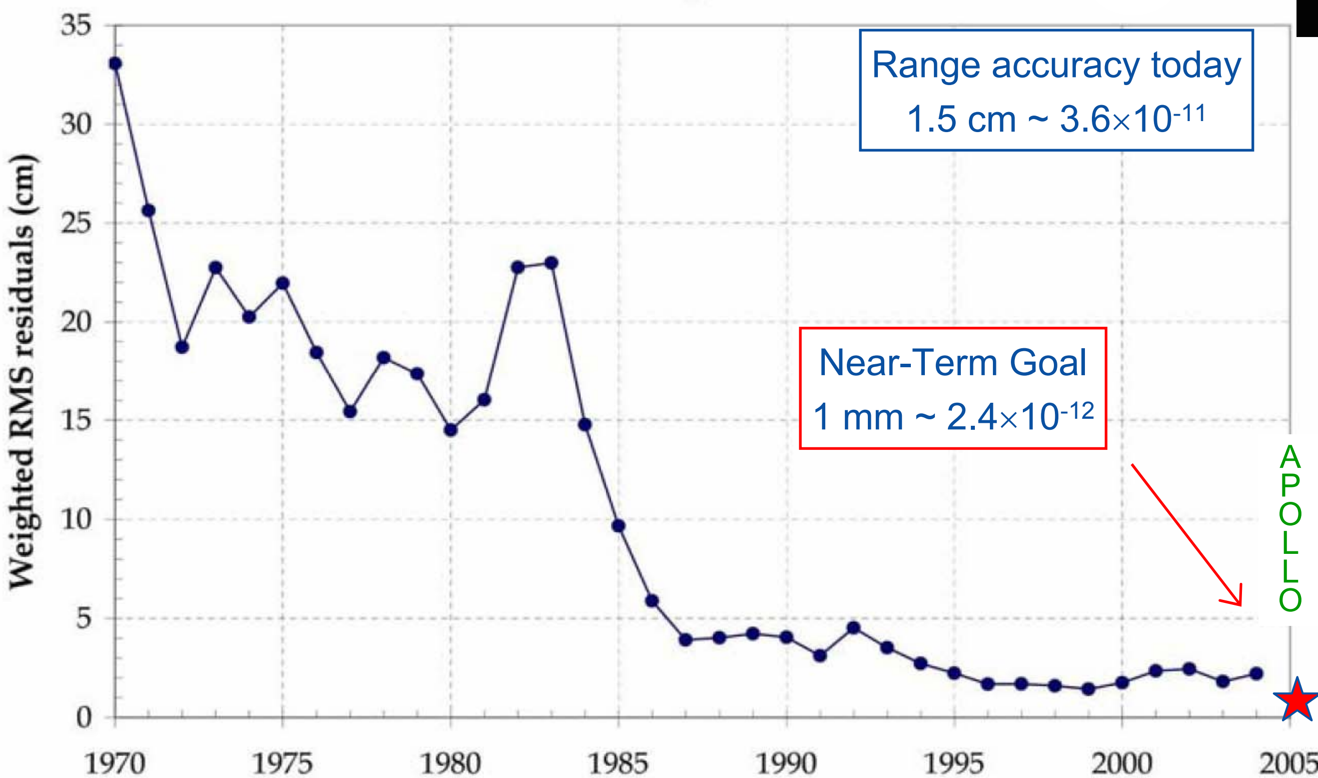
Historical Accuracy of LLR

Schematics of the LLR experiment





Historical Accuracy of LLR Data



- Raw ranges vary by ~1,000s km
- Present range accuracy ~1.5cm
- APOLLO will operate at ~1mm (now 4 mm)

LLR contributes to astrometry, geodesy, geophysics, lunar planetology, gravitational physics

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

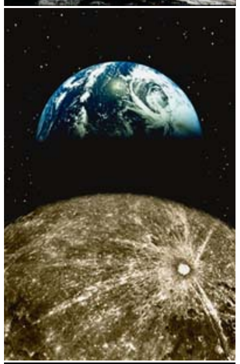
Φ = return beam divergence (diffraction from cubes)

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

Lunar Laser Ranging Science

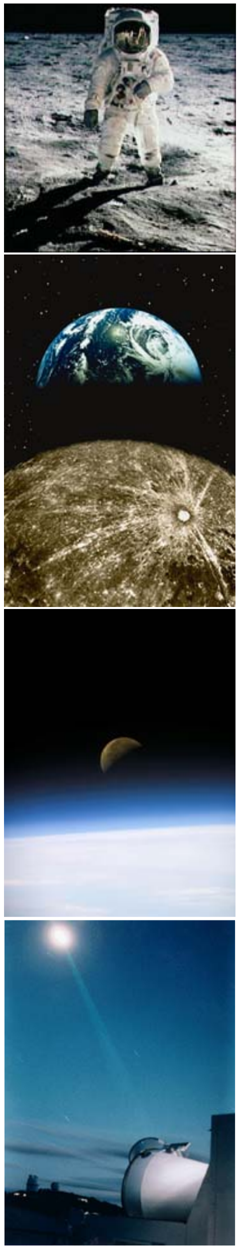


Lunar Science:

- LLR measurements are sensitive to:
  - Lunar rotation & orientation variations, tidal displacements
- Lunar rotation variations sensitive to:
  - Interior structure, physical properties and energy dissipation;
- Weaker sensitivity to:
  - Flattening of the core-mantle boundary (CMB)
  - Moment of inertia of the fluid core

- The second-degree tidal lunar Love numbers are detected:
  - k_2 has an accuracy of 11%
- Lunar tidal dissipation is strong:
  - Its Q has a weak dependence on tidal frequency;
  - A fluid core of ~20% the moon's radius is indicated by the dissipation data;
  - Evidence for the oblateness of the lunar fluid-core/solid-mantle boundary is getting stronger;
  - This would be independent evidence for a fluid lunar core.
- Moon-centered coordinates of four reflectors are determined

Lunar Laser Ranging Science (continued)



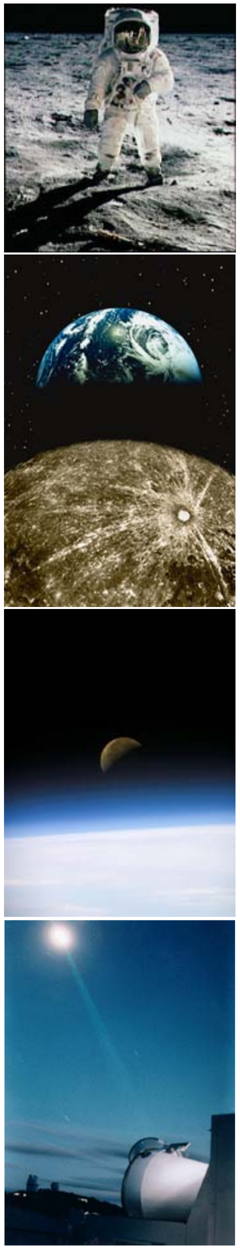
Earth Science:

- LLR data analysis used to determine:
  - LLR station positions and their motion,
  - Earth rotation variations, nutation, and precession

Science from the Orbit:

- Lunar ephemeredes are a product of the LLR analysis that is used by current and future spacecraft missions
- Analysis is sensitive to astronomical parameters such as orbit and mass
- Dissipation-caused acceleration in orbital longitude is –25.7 $''/cy^2$, dominated by tides on Earth with a 1% lunar contribution
- Sensitive tests of gravitational physics include:
  - The Equivalence Principle (also used for an accurate determination of the PPN parameter β),
  - Limits on the time variation of the gravitational constant G,
  - Geodetic precession, frame-dragging, and
  - Gravitational inverse square law

Data Analysis



- Raw Ranges:
  - Starting with ~50,000 km variations and ending up with few centimeter residuals is done with detailed modeling of the range and weighted least-squares fits
  - Spectrum of residuals has a 4 mm maximum and a 1 mm background
- Analysis Concept:
  - For the analysis of angular data, the orbit is the main concern
  - For range data, the center-to-center orbit is only part of the problem. The geocentric ranging station location and the Moon centered retroreflector position must be determined.
- Dynamical Computations:
  - Joint numerical integration of the orbits of the Moon, Earth, and planets + lunar rotation
  - Model includes relativistic Earth-Moon-planet interactions, gravitational harmonic coefficients for Earth (zonal), Moon and Sun (J_2), tides on Earth and Moon, and a fluid lunar core.
- Dynamical Partial Derivatives:
  - Numerical integration of partial of the orbits and lunar Euler angles with respect to solution parameters such as initial conditions, mass ratios, gravity coefficients, and tide, core, and relativity parameters.

LLR Modeling and Related Science

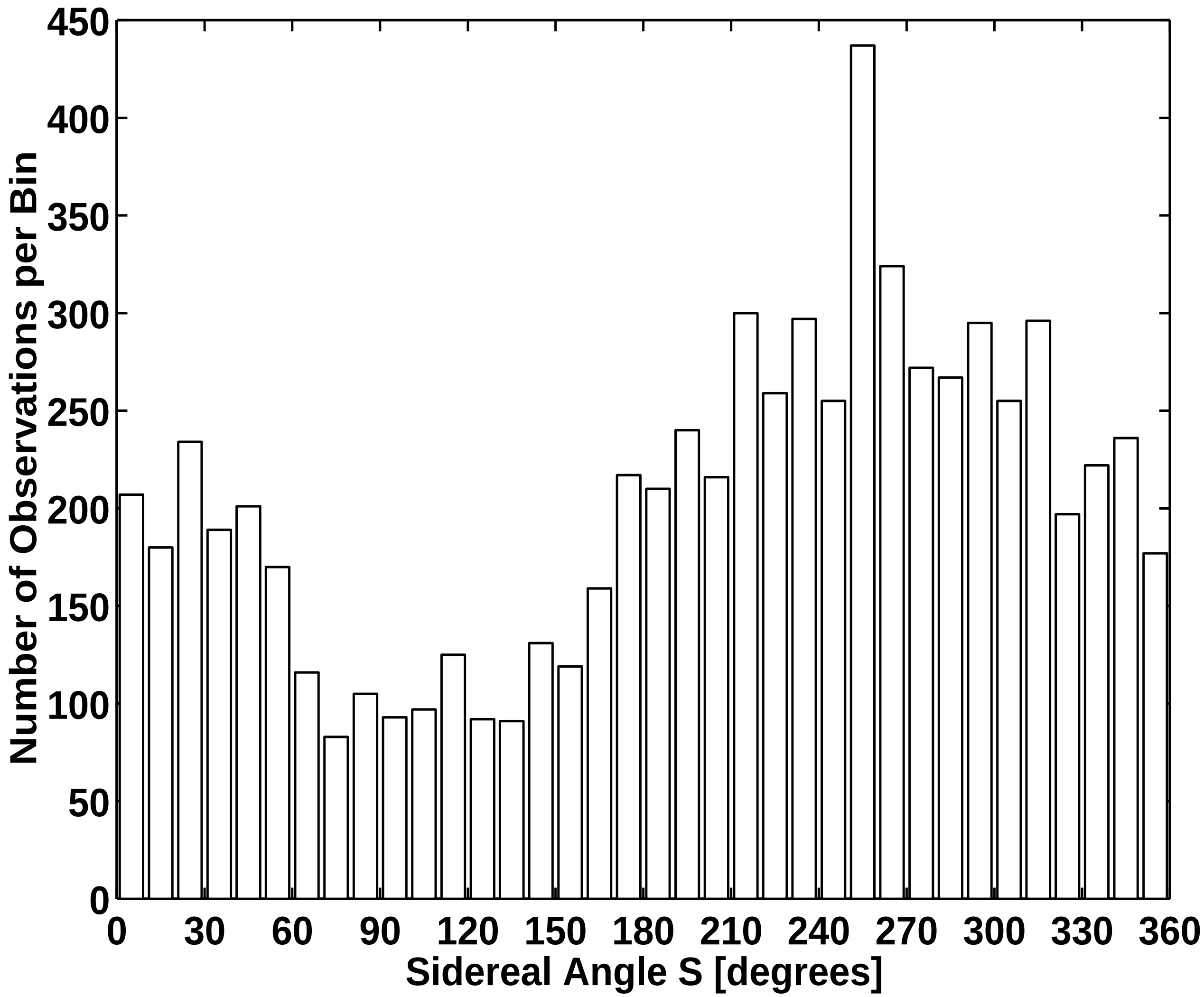
Effects in the Model:

- Modeling orbit dynamics:
  - Grav. interaction between Sun, Moon, Earth, planets. Includes masses and general relativity parameters.
  - Asteroid Newtonian attractions
  - Newtonian attraction between bodies and gravitational harmonics of extended bodies
  - Tidal effects
- Lunar rotation dynamics:
  - Torques from other bodies
  - Dissipative torque from fluid core
  - Core-mantle interaction
- Effects at Earth station:
  - Plate motion
  - Tidal effects
  - Orientation of Earth's rotation axis and rotation
- Effects at lunar reflector:
  - Tidal effects
  - 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:

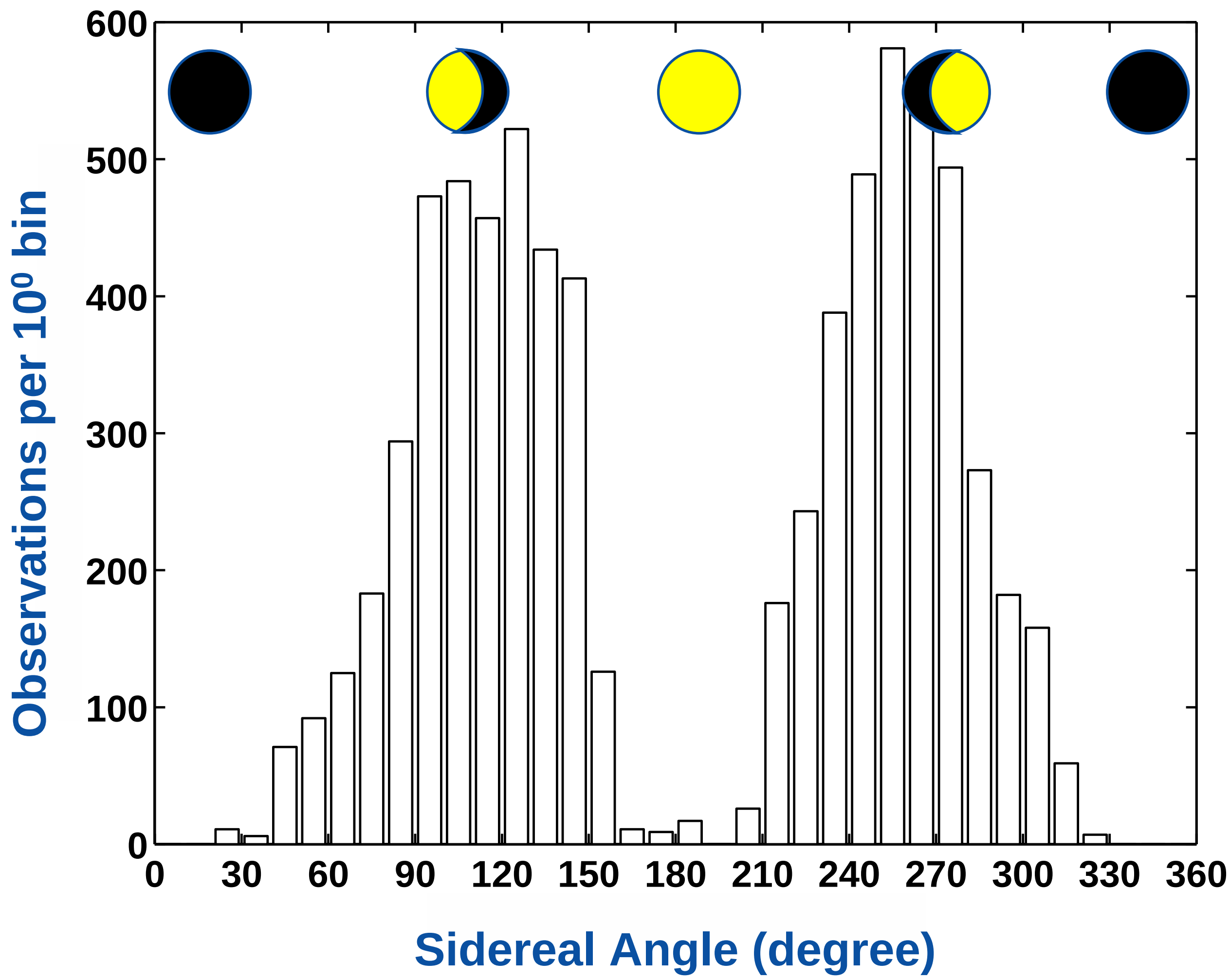
- Lunar ephemerides and orbit:
  - are a product of the LLR analysis used by current and future spacecraft missions.
  - LLR greatly improved knowledge of the Moon's orbit: permits analyses of solar eclipses as far back as 1400 B.C.
- Gravitational physics:
  - Tests of the Equivalence principle
  - 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)
- 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.

Distribution of Observations per Sidereal Month



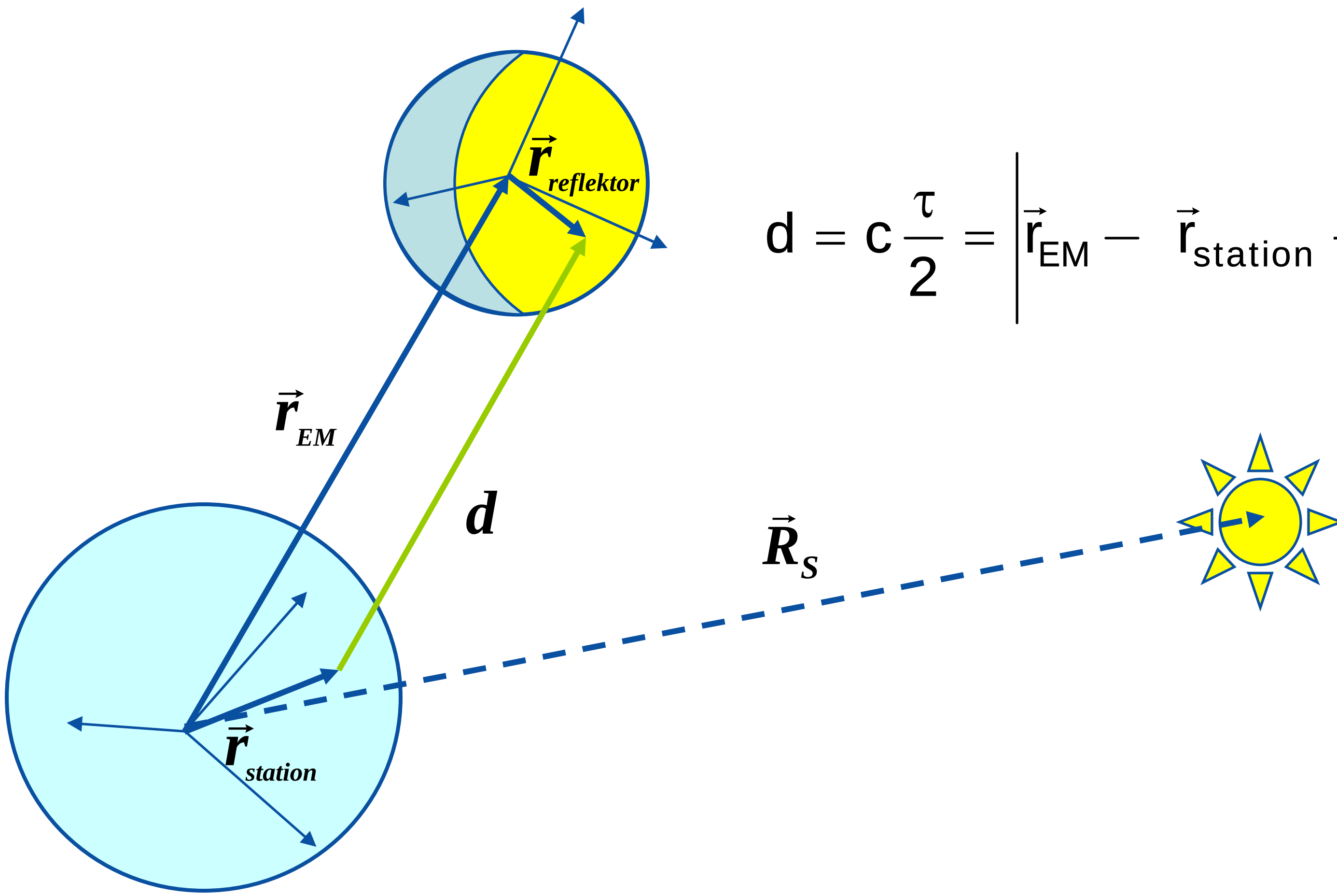
Uneven distribution as no observatory on the Southern Hemisphere

Distribution of Observations per Synodic Month



Large data gaps near Full and New Moon

Observation Equation



$$d = c\,\frac{\tau}{2} = \left| \vec{r}_{EM} - \vec{r}_{station} + \vec{r}_{reflector} \right| + \Delta\tau$$

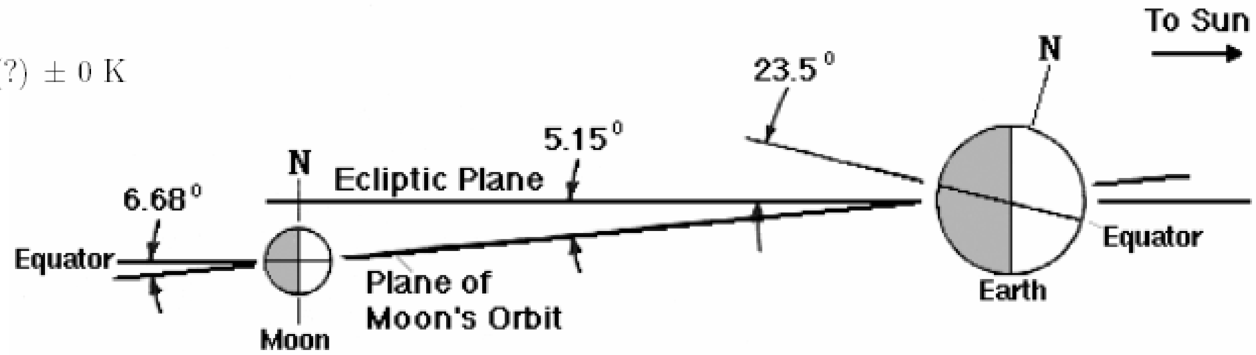
$$\ddot{\vec{r}}_{EM} = -\frac{GM_{E+M}}{r_{EM}^3}\,\vec{r}_{EM} + GM_S \left(\frac{\vec{R}_S - \vec{r}_{EM}}{\left|\vec{R}_S - \vec{r}_{EM}\right|^3} - \frac{\vec{R}_S}{R_S^3} \right) + \vec{b}_{Newtonian} + \vec{b}_{Relativity}$$

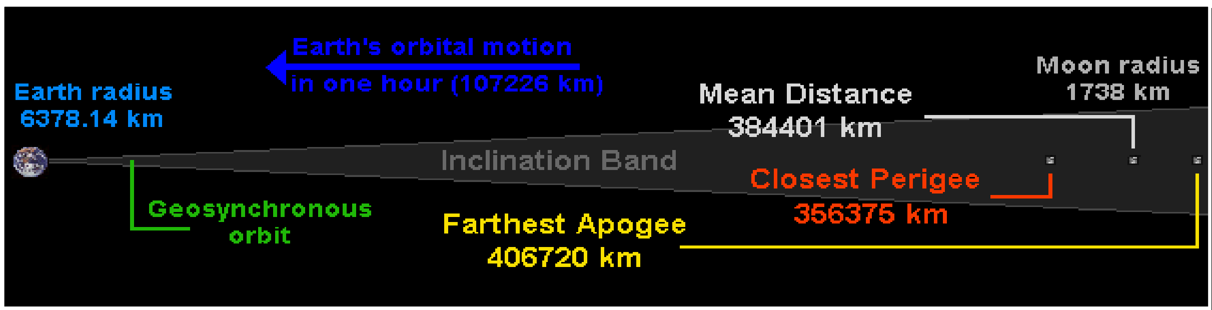
High-Level Overview of Lunar Environments

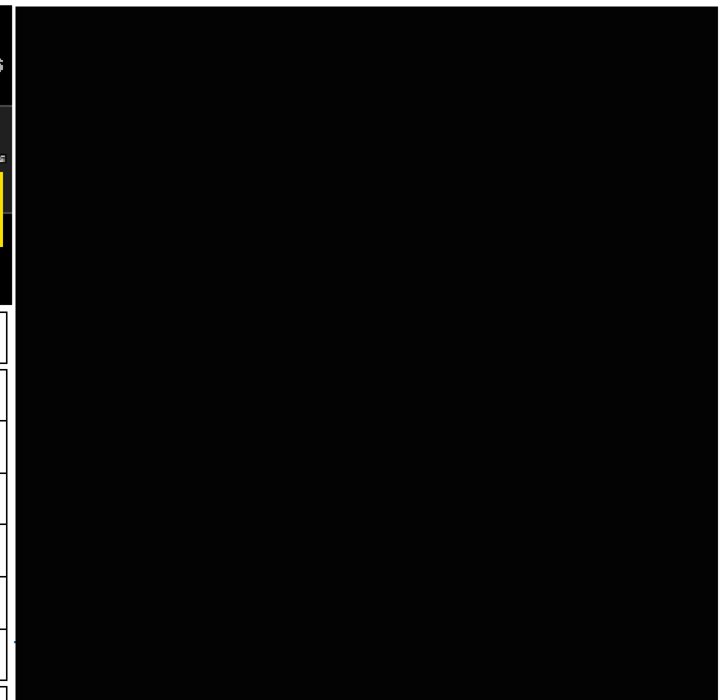
Equator: 255 ± 140 K

Polar: 220 ± 10 K

Shadowed polar craters: 40 (?) ± 0 K

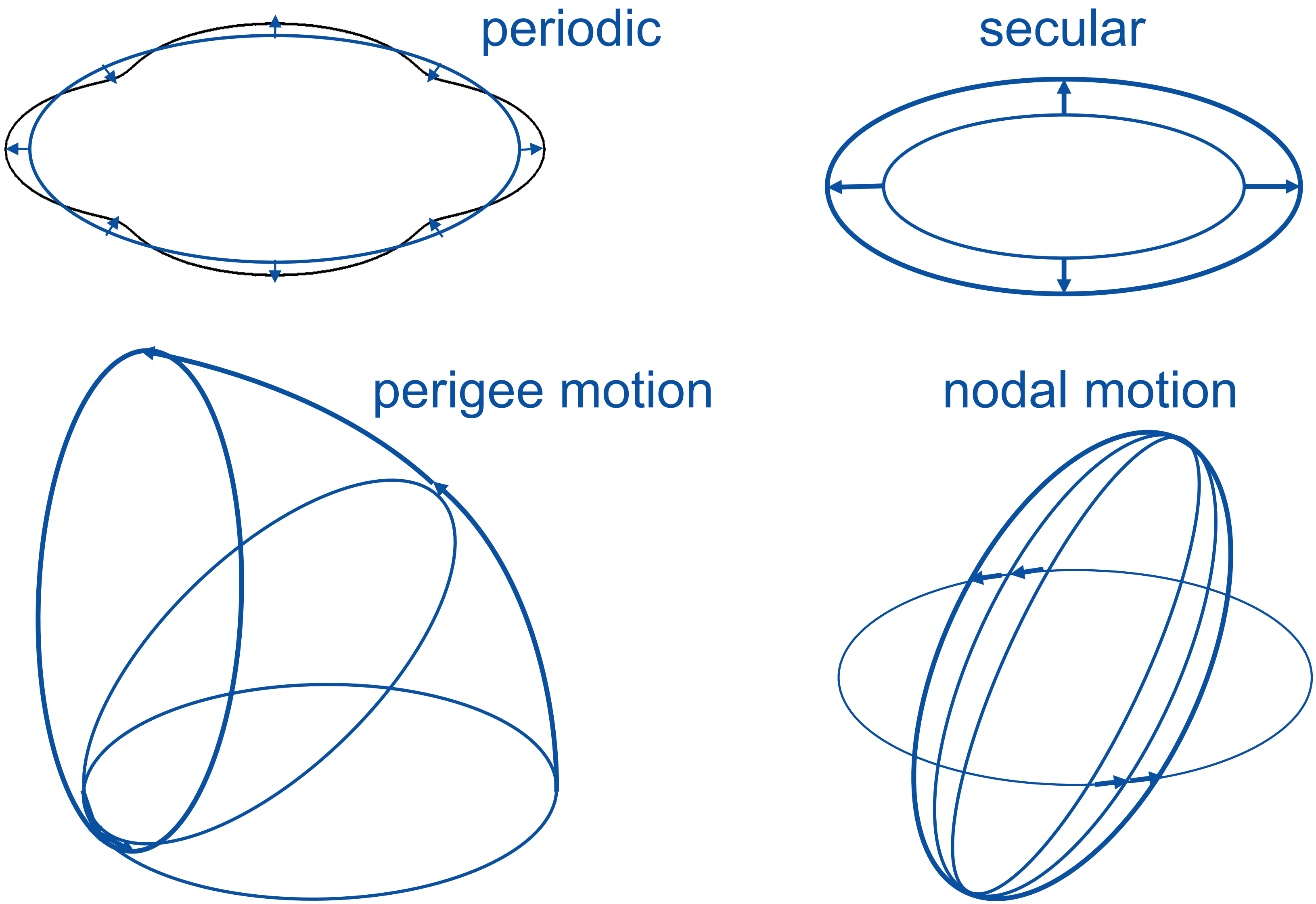




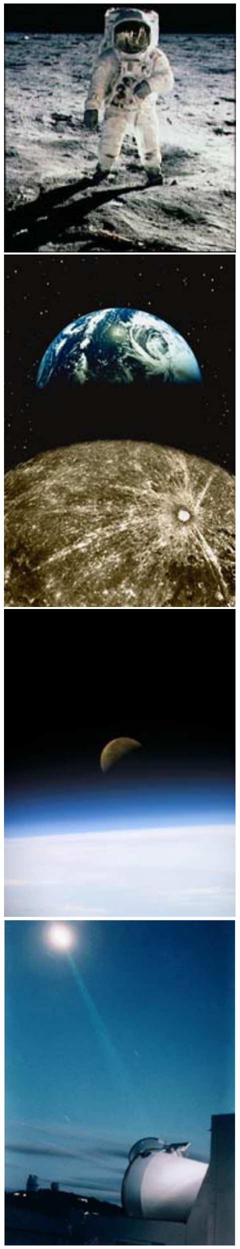


	Moon	Earth	Moon/Earth ratio
Equatorial radius	1738 km	6378 km	27 %
Polar radius	1736 km	6357 km	27 %
Mass	7.35×10^{22} kg	5.97×10^{24}	1/81
Mean density	3.350 g/m^3	5.515 g/m^3	0.6
Surface gravity	1.62 m/s^2	9.80 m/s^2	1/6
Escape velocity	2.38 km/s	11.2 km/s	1/5
Atmosphere	$10^{4\sim5}$ particles / cm^3	10^{19} particles / cm^3	$10^{-14\sim15}$
Seismic energy	$10^{10\sim14}$ J/year	$10^{17\sim18}$ J/year	$10^{-3\sim8}$

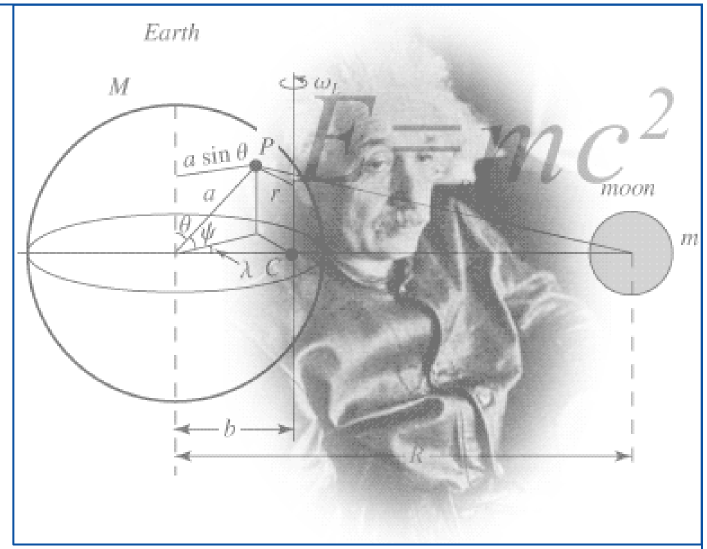
Perturbations of the Lunar Orbit



Mean Lunar Orbit



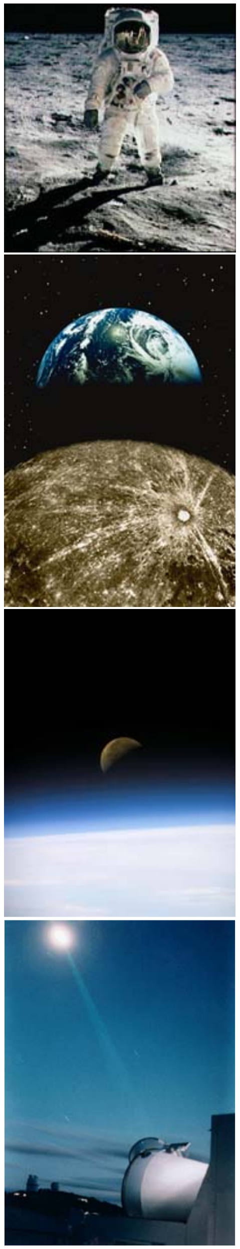
- Mean Lunar Orbit:
  - Semimajor axis 384,399 km
  - Eccentricity 0.0549
  - Inclination 5.145˚
  - Sidereal period 27.322 days
  - Anomalistic period 27.555 days
  - Nodical period 27.212 days



- Perturbed Orbit:
  - Radius series from Chapront-Touzé and Chapront are given as

    385,001 – 20,905 cos l – 3,699 cos(2D- l) – 2,956 cos 2D – 570 cos 2l +… km
  - Mean anomaly *l* has a 27.555 day period..
  - *D* is mean elongation from Sun with a 29.531 day period.
  - Two solar perturbation terms, arguments with *D*, are stronger than the e^2 *(2l)* term.

Causes of Perigee and Node Precessions



Causes of Perigee and Node Precessions

Cause	ϖ rate, "/yr	Ω rate, "/yr
Sun	146,425.38	–69,671.67
Planets	2.47	–1.44
Earth J_2	6.33	–5.93
Moon J_2 & C_{22}	–0.0176	–0.1705
Relativity	0.0180	0.0190

Lunar Orbit — Eccentricity Rate

Source	Value
Tides on Earth	1.3×10^{-11} /yr
Tides on Moon	-0.6×10^{-11} /yr
Anomalous rate	$(1.6 \pm 0.4) \times 10^{-11}$ /yr
Total:	2.3×10^{-11} /yr

The anomalous eccentricity rate amounts to 6 mm/yr in perigee and apogee distance − the cause is unknown.

Largest Effects in Lunar Orbit

Largest Radial Amplitudes by Cause

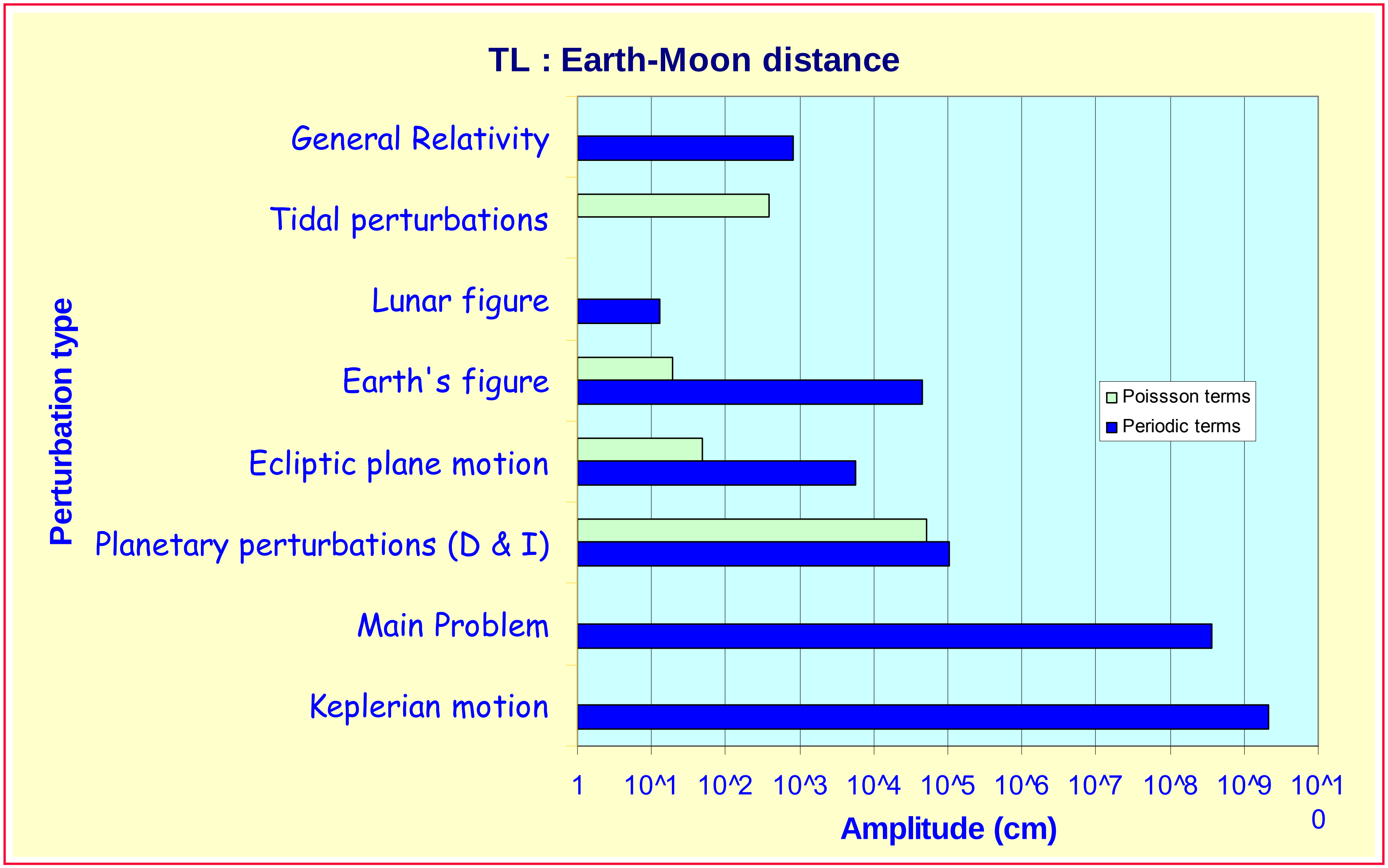
Cause	Amplitude
Ellipticity	20905 & 570 km
Solar perturbations	3699 & 2956 km
Jupiter perturbation	1.06 km
Venus perturbations	0.73, 0.68 & 0.60 km
Earth J_2	0.46 & 0.45 km
Moon J_2 & C_{22}	0.2 m
Earth C_{22}	0.5 mm
Solar radiation pressure	4 mm

Relativistic Effects on Orbit

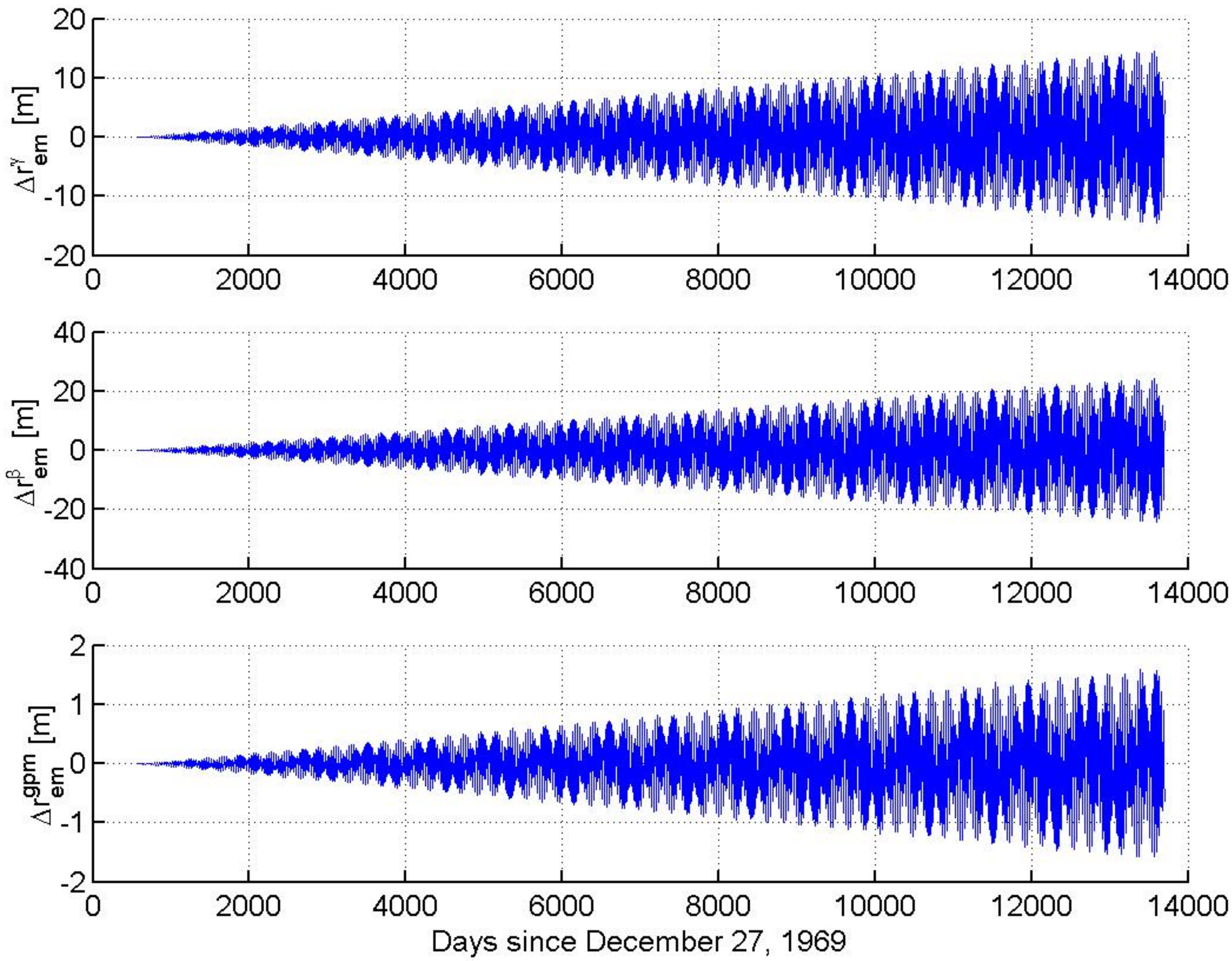
Cause	Amplitude
Lorentz contraction	0.95 m
Solar potential	6 cm
Time transformation	5 & 5 cm
Other relativity	5 cm

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

Largest Perturbations to Lunar Orbit



Sensitivity of Relativistic Parameters (3)

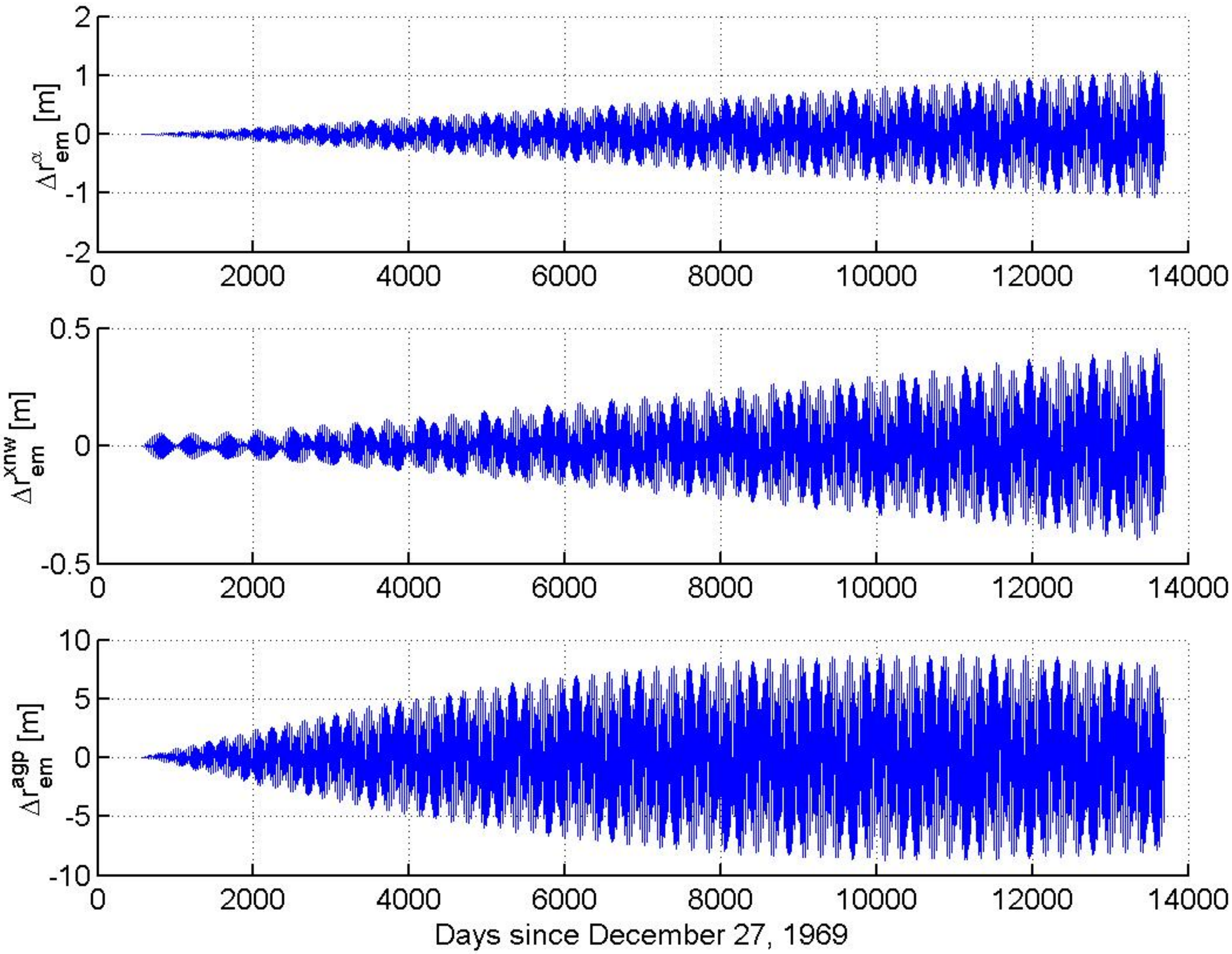


Space curvature γ

Non-linearity β

Geodetic precession

Sensitivity of Relativistic Parameters (4)

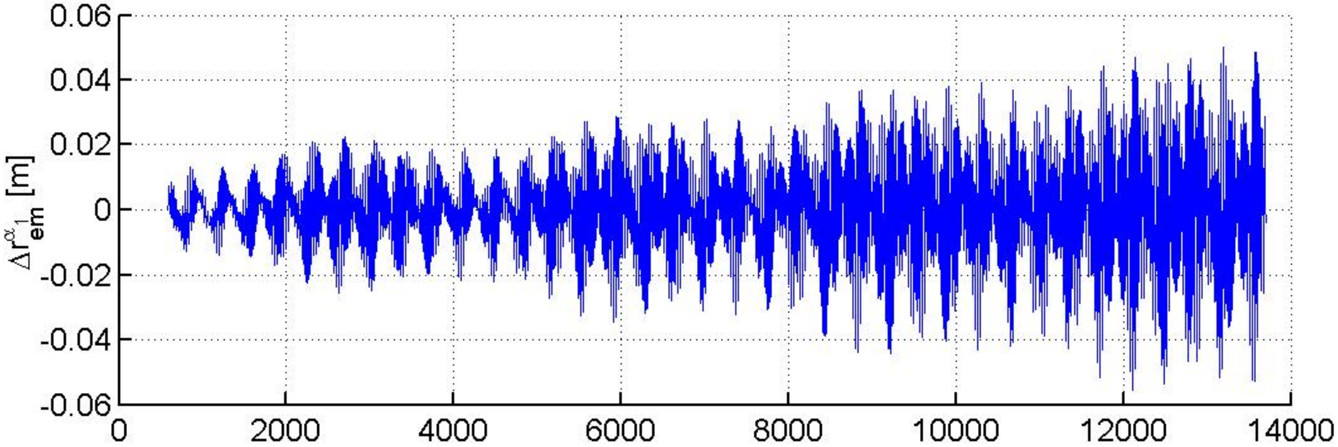


Yukawa α

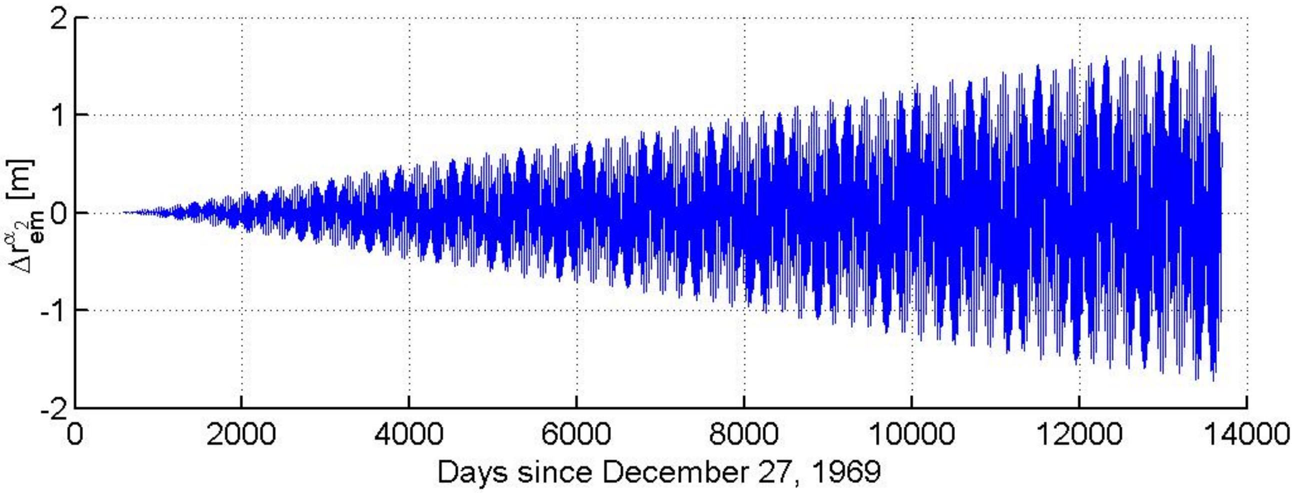
Equivalence principle m_I/m_G

Gravitational constant $\dot{G}/G$

Sensitivity of Relativistic Parameters (5)

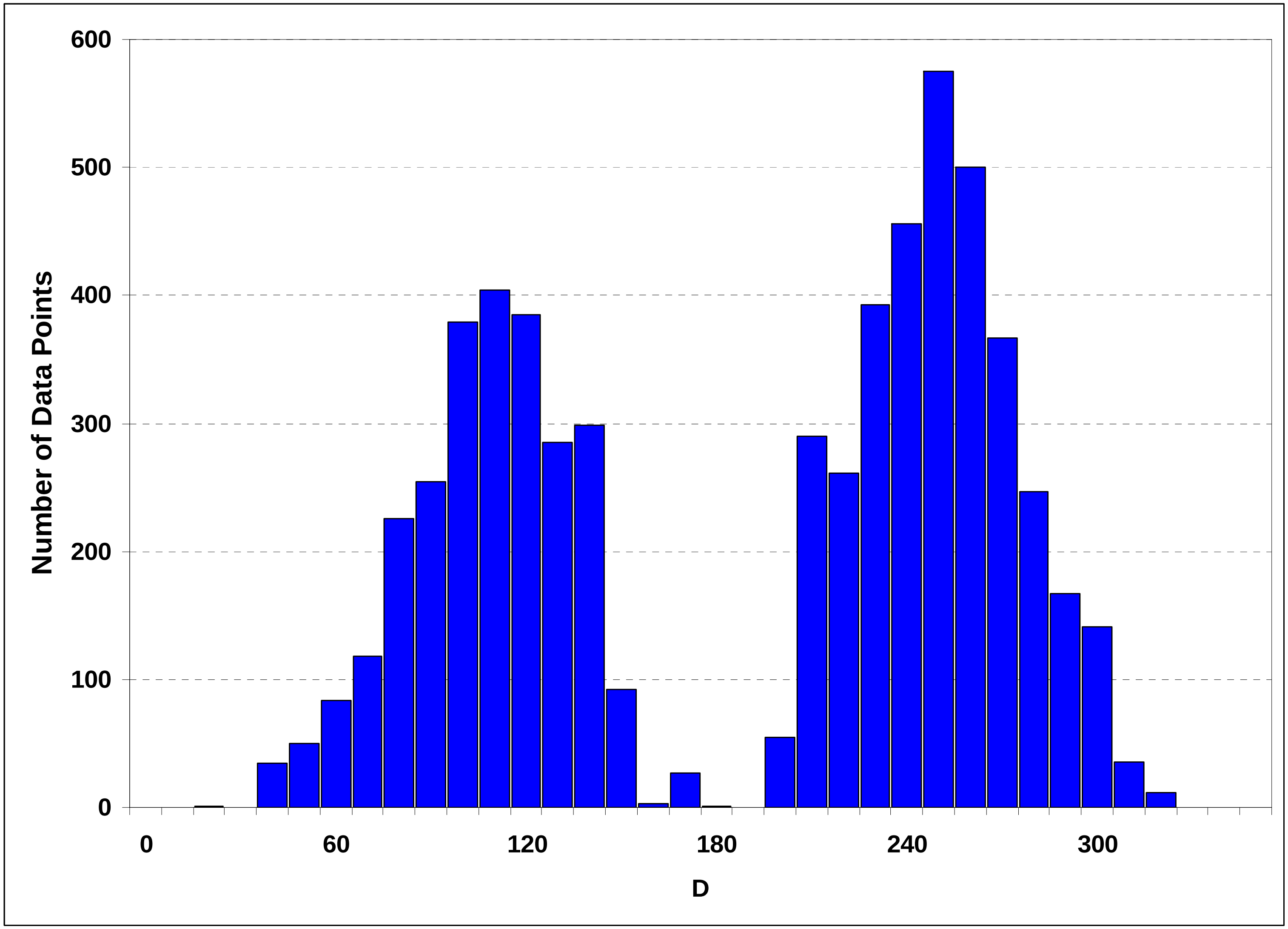


Preferred frames α_1



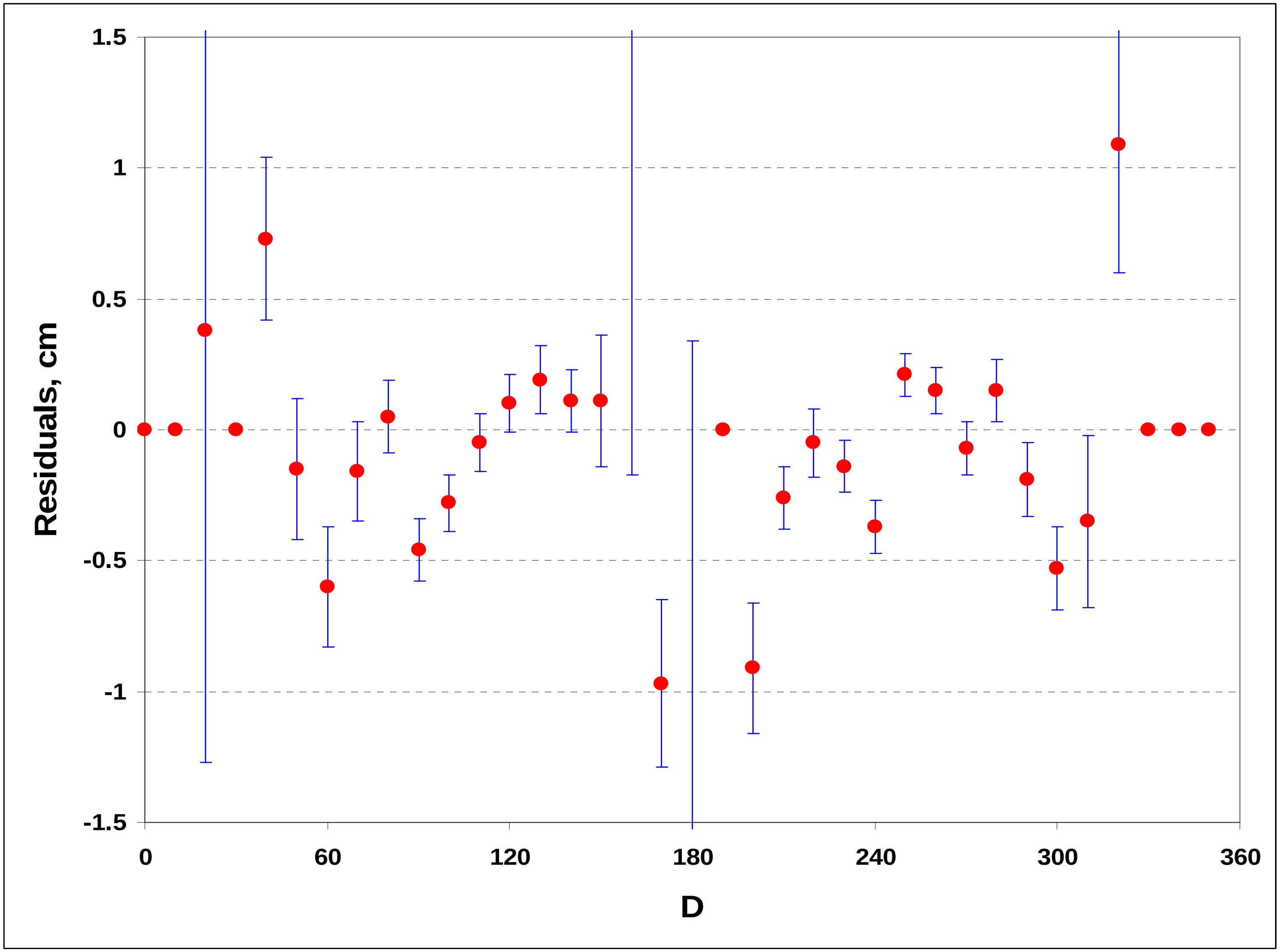
Preferred frames α_2

Synodic Period D-distribution



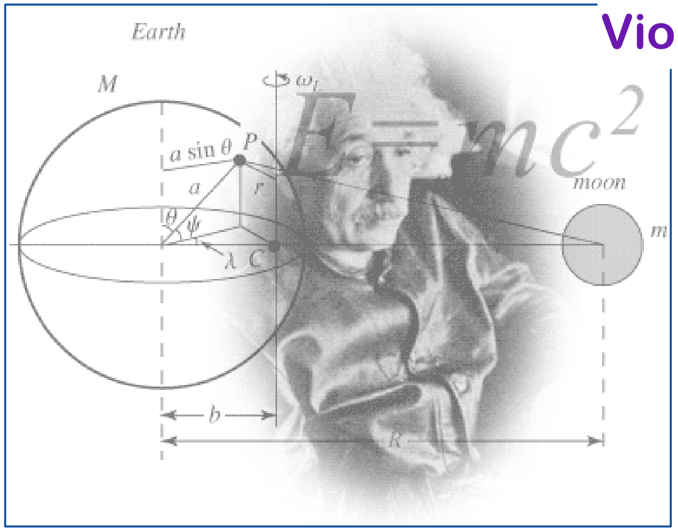
The principal signature for the EP tests has the 29.53 d synodic period between Moon and Sun (the associated argument is called *D*).

Residual vs Angle Distribution



Weighted average residual is distributed well within 1.5 cm

Testing General Relativity with LLR



Violation of the Equivalence Principle in PPN formalism:

$$\frac{\Delta a}{a} \equiv \frac{2(a_1 - a_2)}{(a_1 + a_2)} = \left(\frac{M_G}{M_I}\right)_1 - \left(\frac{M_G}{M_I}\right)_2, \qquad \frac{M_G}{M_I} = 1 + (4\beta - \gamma - 3)\frac{U}{Mc^2}$$

$$\frac{\Delta a}{a} = \eta \cdot \left(\frac{U_e}{M_e c^2} - \frac{U_m}{M_m c^2}\right) = -\eta \cdot 4.45 \times 10^{-10}, \qquad \eta \equiv 4\beta - \gamma - 3.$$

If η =1, this would produce a 13 m displacement of lunar orbit.
By 2007, range accuracy is ~1.5 cm, the effect was not seen.

Recent LLR results (October 2007):

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

$$\Delta\left(\frac{M_G}{M_I}\right) = (-0.95 \pm 1.30) \times 10^{-13}$$ – corrected for solar radiation pressure from Vokrouhlicky (1997).

$$\frac{\Delta a}{a} = (-1.95 \pm 1.91) \times 10^{-13}$$ – test of the Strong Equivalence Principle with Adelberger (2001) results for WEP $\quad \eta = 4\beta - \gamma - 3 = (4.4 \pm 4.3) \times 10^{-4}$

Using Cassini '03 result $\quad \gamma - 1 = (2.1 \pm 2.3) \times 10^{-5} \quad \Rightarrow \quad \beta - 1 = (1.2 \pm 1.1) \times 10^{-4}$

$$K_{\mathrm{GP}} = -0.0007 \pm 0.0047$$ – Geodetic / de Sitter-Fokker precession

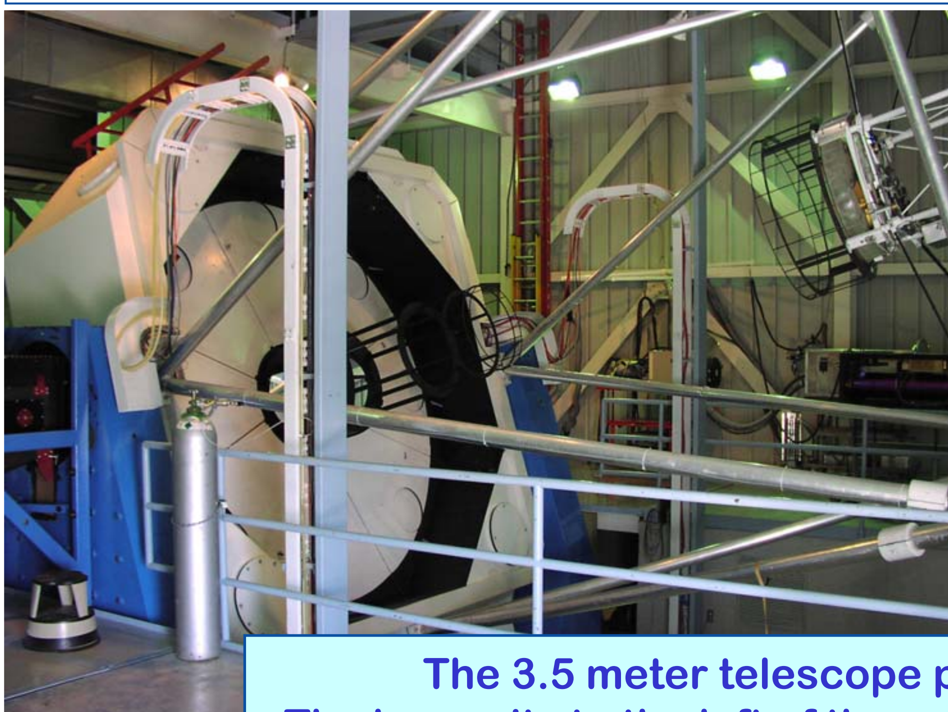
$$\dot{G}/G = (4.9 \pm 5.7) \times 10^{-13} \quad \mathrm{yr}^{-1}$$

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

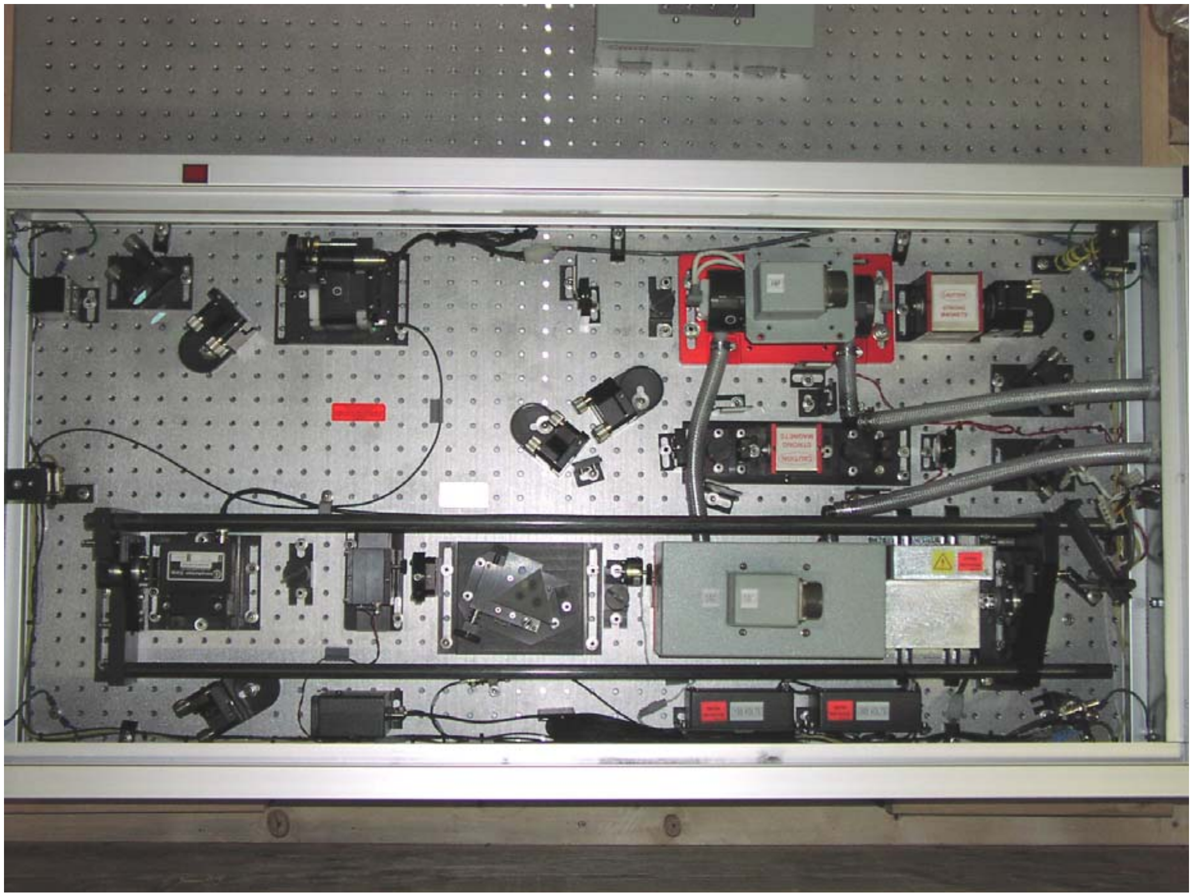
- Uses 3.5-meter telescope at 9200-ft Apache Point, NM
- Excellent atmospheric “seeing”: 1as
- 532 nm Nd:YAG, 100 ps, 115 mJ/pulse, 20 Hz laser
- Integrated avalanche photodiode (APD) arrays
- Multi-photon & daylight/full-moon



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

The APOLLO Laser Layout and Parameters

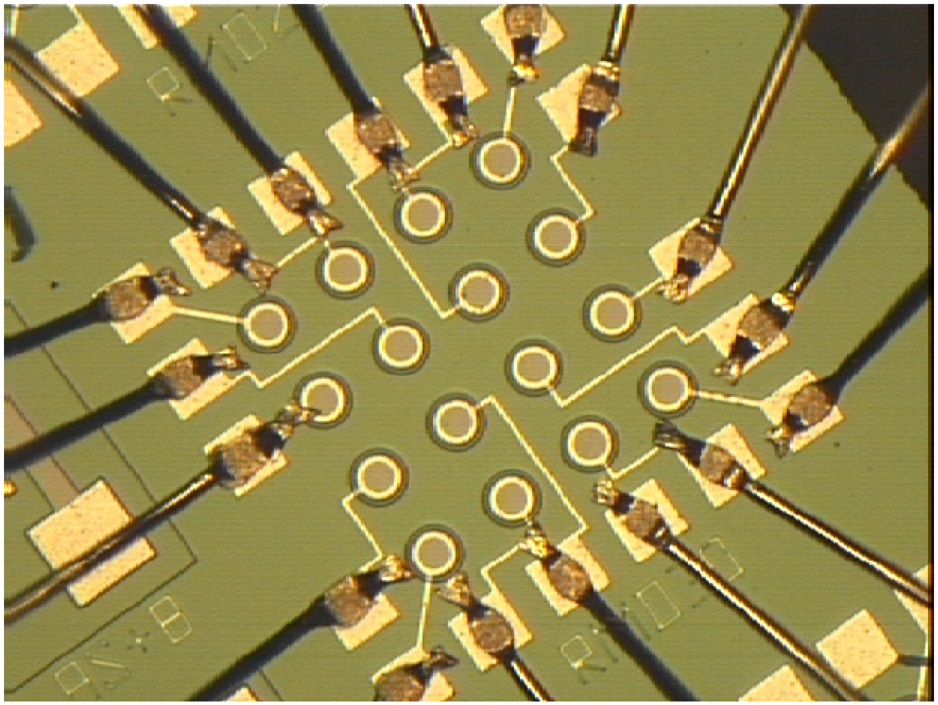


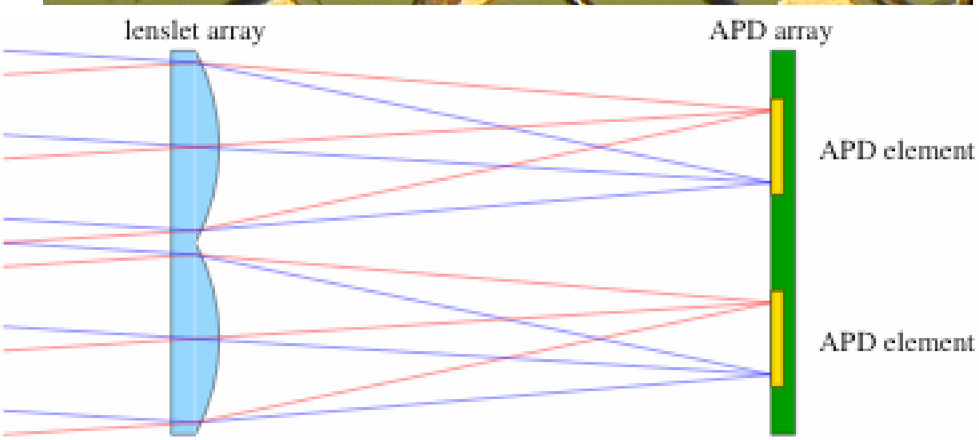
- Nd:YAG mode-locked, cavity-dumped
- Frequency-doubled to 532 nm (green)
- 90 ps pulse width (FWHM)
- 115 mJ per pulse
- 20 Hz repetition rate
- 2.3 Watt average power
- GW peak power!!

- Beam is expanded to 3.5 meter aperture
  - Less of an eye hazard
  - Less damaging to optics

The laser layout – a lot of gadgetry on the optical table.

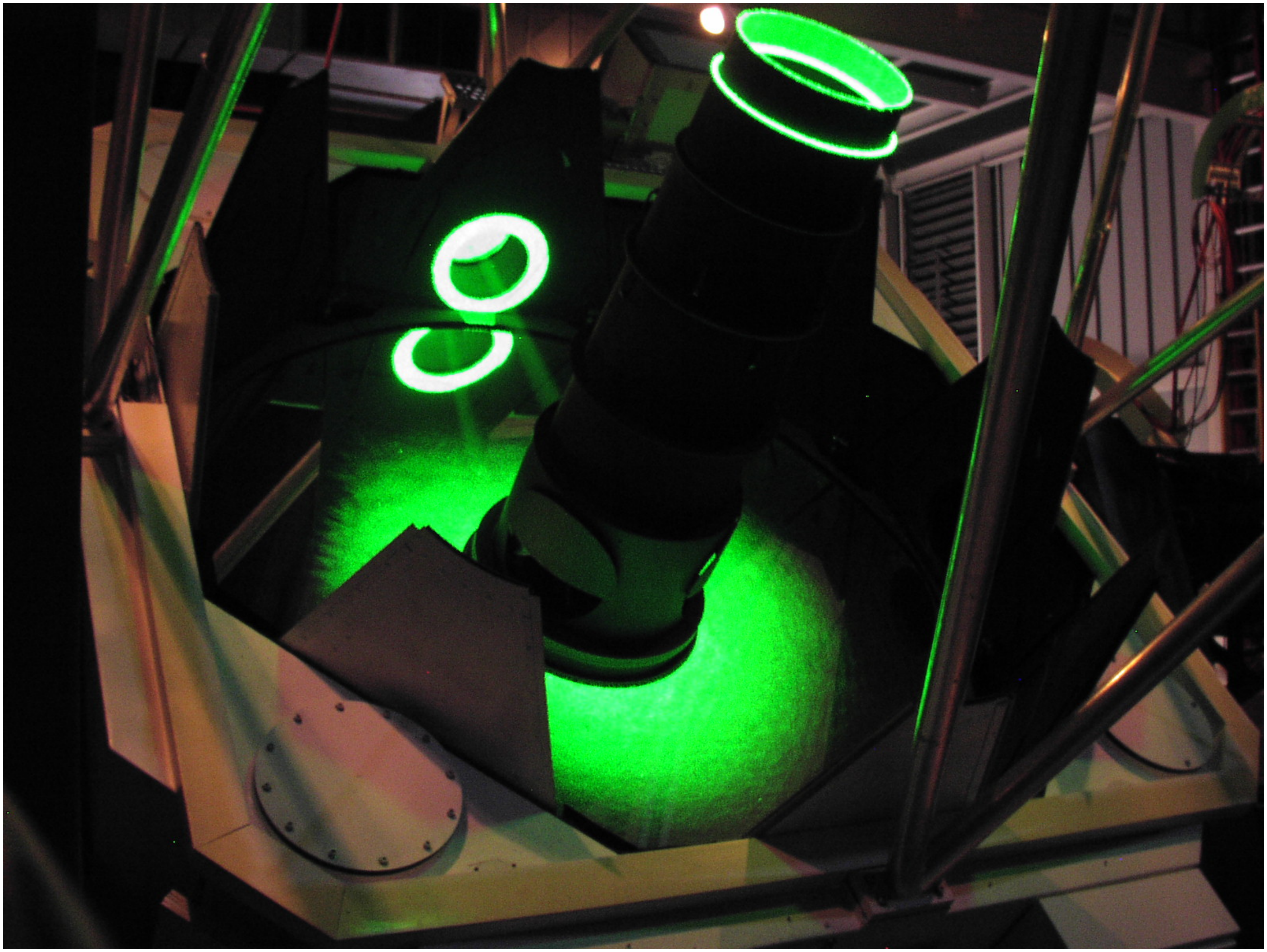
Catching All the Photons





- Several photons per pulse necessitates multiple “buckets” to time-tag each
  - Avalanche Photodiodes (APDs) respond only to *first* photon
- Lincoln Lab prototype APD arrays are perfect for APOLLO
  - 4×4 array of 30 μm elements on 100 μm centers
- Lenslet array in front recovers full fill factor
  - Resultant field is 1.4 arcsec on a side
  - Focused image is formed at lenslet
  - 2-D tracking capability facilitates optimal efficiency

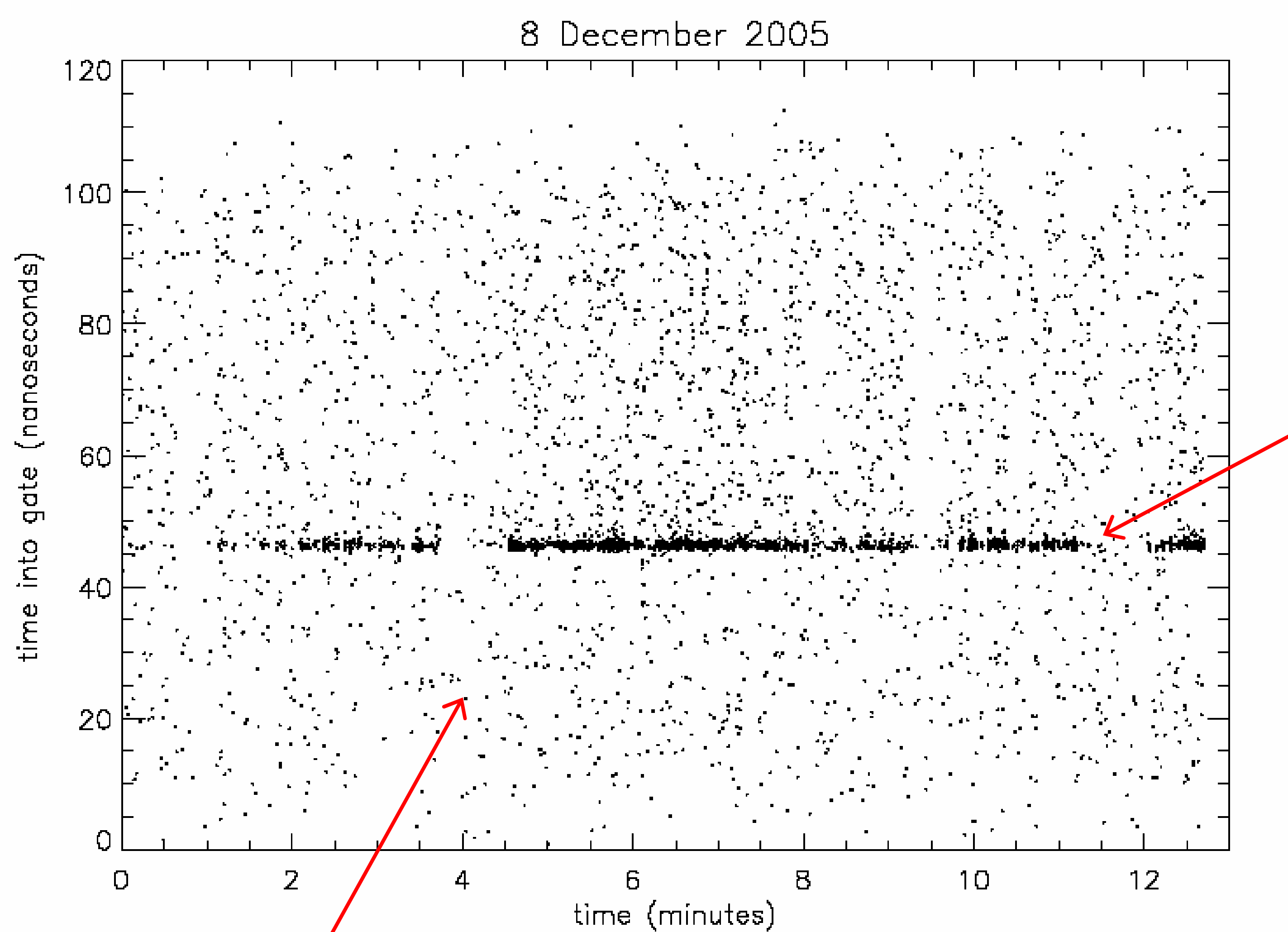
First Light: July 24, 2005



First Light: July 24, 2005

Blasting the Moon

Example Data From Recent Run



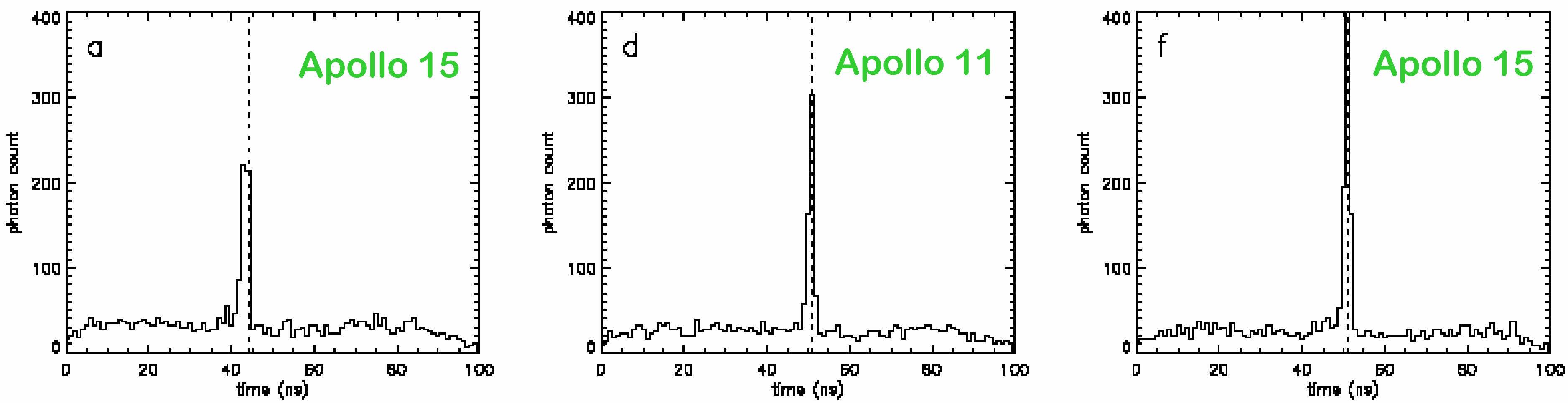
Return photons from reflector

width is < 30 cm

2150 photons in 14,000 shots

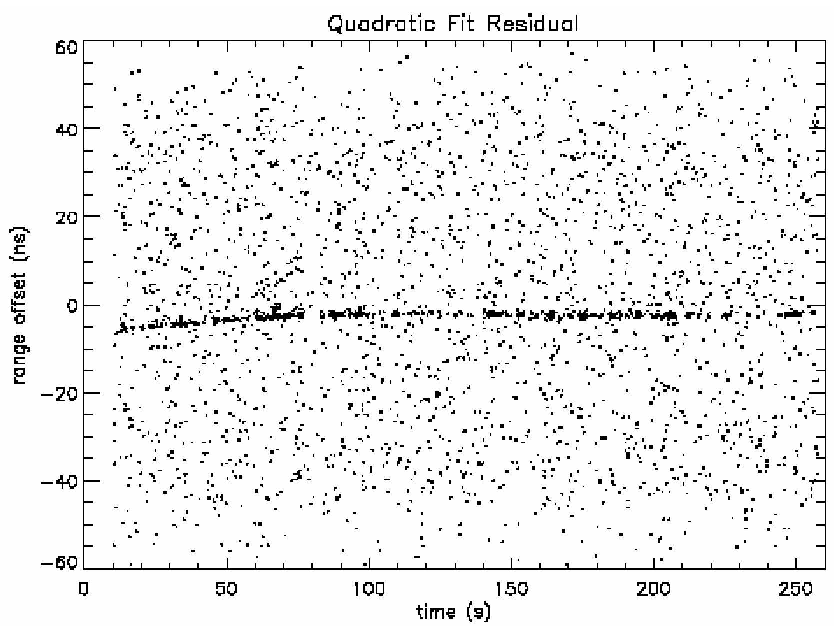
Randomly-timed background photons (bright moon)

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.

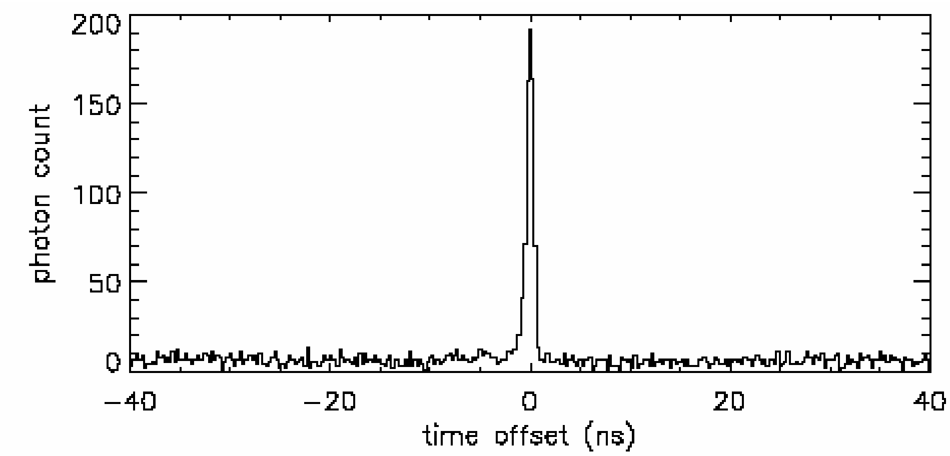


Error Source	Round-Trip Time Uncertainty, [ps]	One-Way Range Error, [mm]
Retro Array Orientation	100–300	15–45
APD Illumination	60	9
APD Intrinsic	<50	< 7
Laser Pulse Width	45	6.5
Timing Electronics	20	3
GPS-slaved Clock	7	1
Total Random Uncert.	136–314	20–47

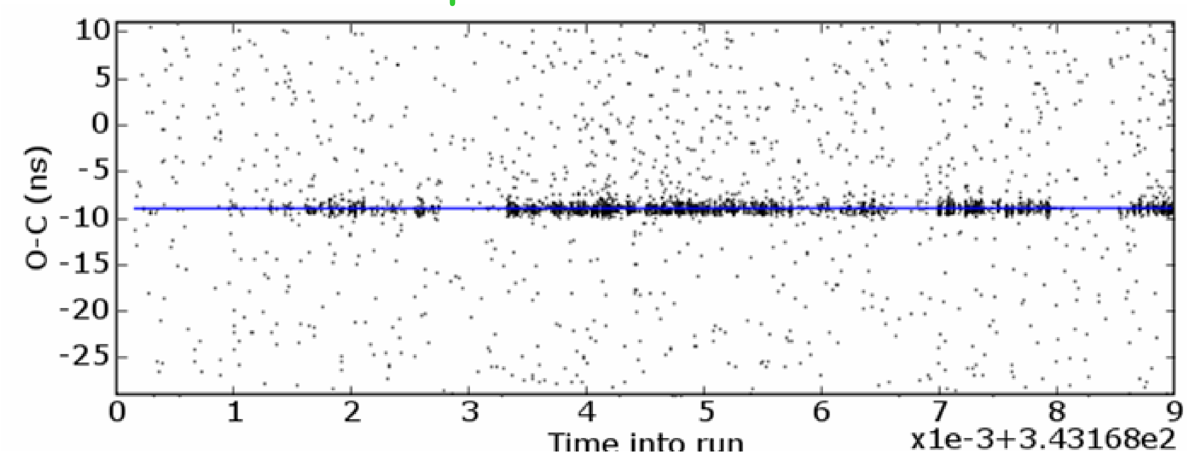
Single-photon random error budget

Good Start for APOLLO

Results of the runs with Apollo 15



Residuals computed with new data



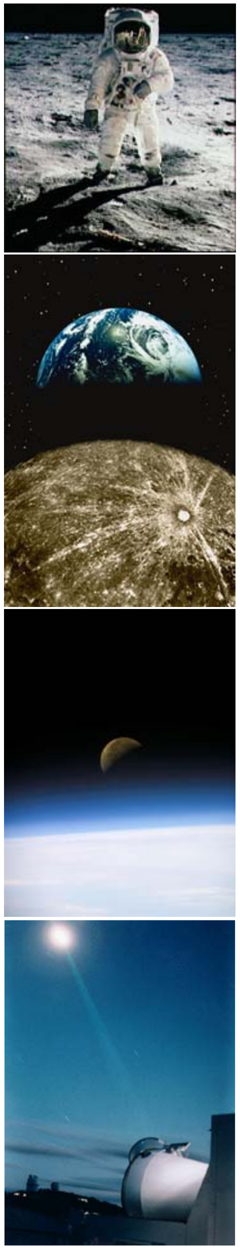
APOLLO Recipe for a mm-range:

- 7 ps round-trip travel time error
- ~0.5 m lunar reflectors at ±7° tilt → up to 35 mm RMS uncertainty per photon
- 95 ps FWHM laser pulse → 6 mm RMS
- Need ~40^2 = 1600 photons to beat error
- Calculate ~5 ph/pulse return for APOLLO
- "Realistic" 1 photon/pulse → 20 ph/sec → mm statistics on few-minute timescales

- 1,500 photons in 13 min
- 1 mm statistical uncertainty

Interplanetary laser ranging is the next logical step

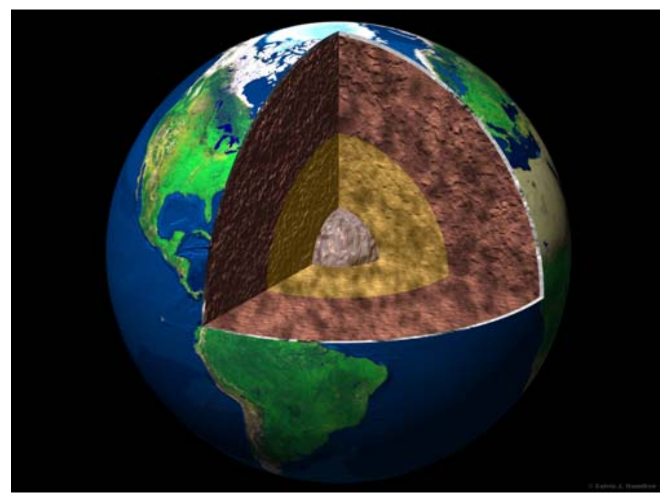
Well-understood Effects: Earth



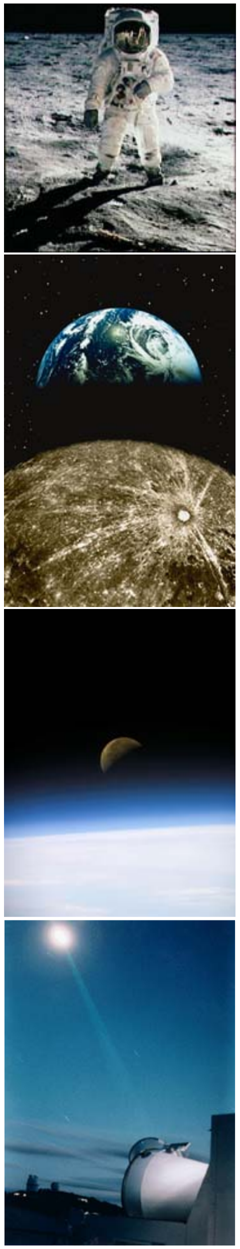
LLR Modeling Challenges:

Effects with analytical formulations are straightforward, but not yet implemented:

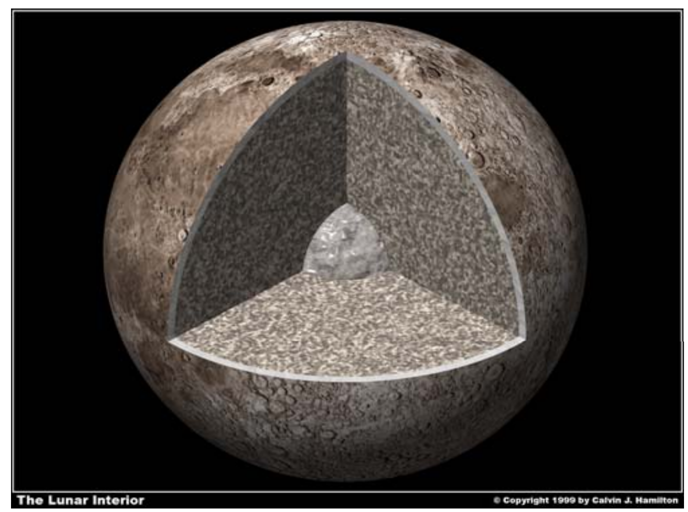
- Several periodic tidal effects on the Earth are noteworthy
- The Earth's surface distorts elastically due to atmospheric pressure variations
- An annual relativity effect on station radius with 1 mm amplitude
- A new algorithm for mapping atmospheric delay vs elevation
- The Earth's J_2 is slowly decreasing
- Dynamical effect of Earth's J_{22} harmonic is ~0.6 mm with a 12.5 hr period



Well-understood Effects: Moon

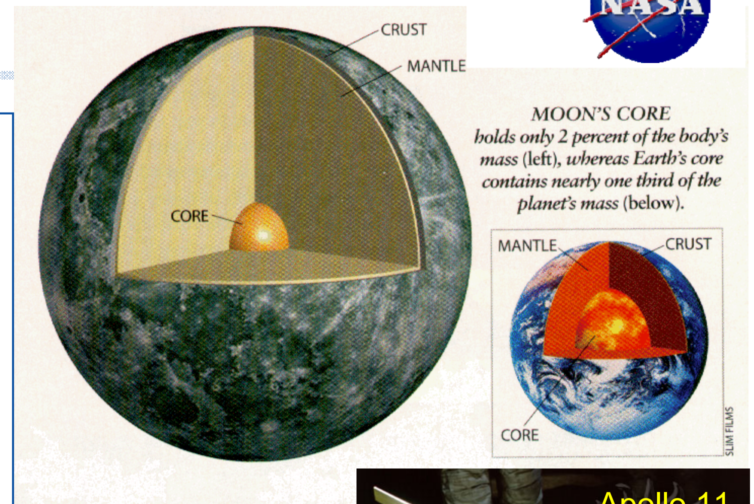


- An annual periodic term of 8 mm amplitude at the equator, due to the time transformation, which projects into ~3 mm in range
- Another relativistic effect on the rotation is geodetic precession
- Solar tides on the Moon cause a 2 mm periodic displacement with 1/2 synodic month period
- From the lunar rotation it is known that the Moon has a sizable tidal dissipation with a bulk monthly tidal Q of 33. This Q should cause a shift of the tidal displacement of about 2 mm. Solar tides also influence the rotation
- Time delay due to refraction in CCs exceeds 1 cm, but is mostly constant

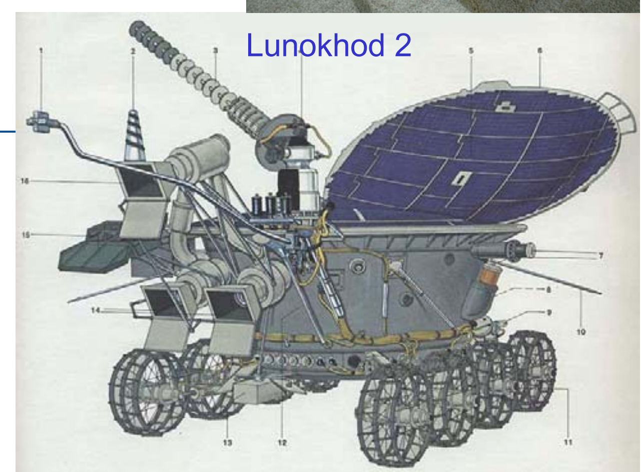


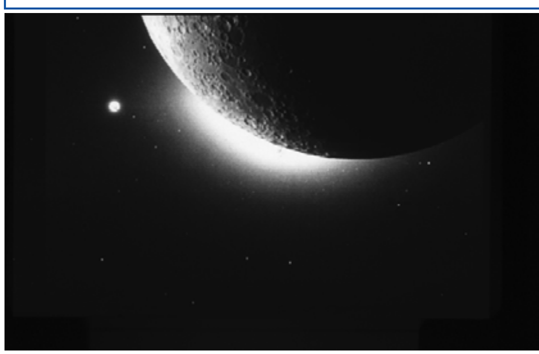
Effects to be Investigated

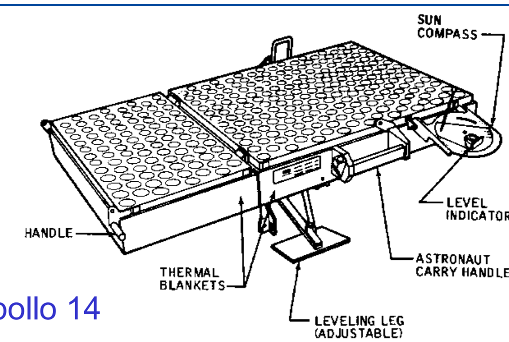
- Torque due to the flow at an oblate boundary between a fluid core and a solid mantle
- If the Moon has an inner solid core, there can be gravitational torques between the inner core & the mantle



- Monthly thermal expansion of retroreflector heights are 1-2 mm for the Apollo, but is ~5 mm for the Lunokhod reflectors
- The dynamical sensitivity to the higher degree gravity harmonics of the Earth and Moon should be reconsidered
- The relativistic transformation effects, particularly the time transformation
- Temperature effects on the telescope must be considered
- The Earth's atmosphere tilts with respect to the surface.

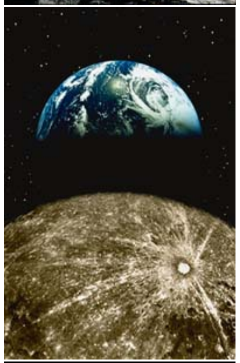






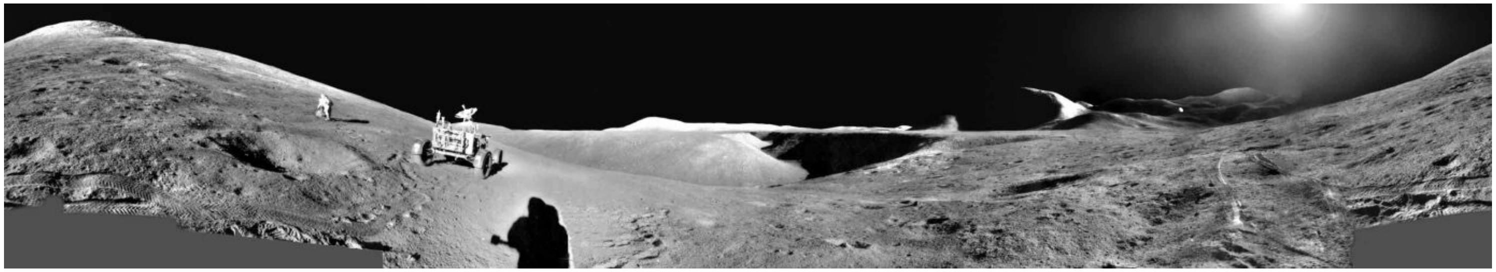
Apollo 14

Effects Poorly Understood

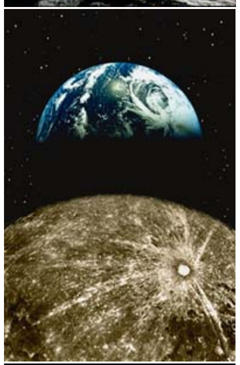



- Solutions for the orbital eccentricity rate give an anomalous value after accounting for tidal dissipation on Earth and Moon
- Changes in local ground water cause small motions of the surface at the ranging site. <u>An on-site gravimeter should help.</u>
- The atmospheric delay model assumes a static atmosphere, but the atmosphere is not static and there are horizontal pressure gradients. <u>An extended array of pressure gauges.</u>
- Part of atmospheric loading that depends on pressure surrounding the site. <u>An on-site gravimeter should help.</u>
- Other effects: solar radiation pressure, lunar thermal expansion, solar tides on the moon, etc.

Both size and signature determine the priority of on-going modeling effort



A Next Generation of Lunar Laser Ranging

- A next-generation of the lunar laser ranging (LLR) experiment:
  - Would rely on either the new sets of laser retroreflector arrays on the Moon or
  - Laser transponders pointed at Earth (or both of these instruments).
- Improving the efficiently of LLR science:
  - Since 1969, LLR has strongly contributed to our understanding of the Moon's internal structure and the dynamics of the Earth-Moon system. However, the current distribution of the retroreflectors is not optimal, other weaknesses exist.
  - A geographic distribution of new instruments on the lunar surface wider than the current distribution would be a great benefit; the accuracy of the lunar science parameters would increase several times.
  - A bright transponder source on the Moon would open LLR to dozens of SLR stations which cannot detect the current weak signals from the Moon.
- Science Outcome:
  - Properties of the lunar interior, including liquid core and solid inner core can be determined from lunar rotation, orientation, and tidal response.
  - Anticipated improvements in Earth geophysics and geodesy would include the positions and rates for the Earth stations, Earth rotation, precession rate, nutation, and tidal influences on the orbit.
  - Improvements are also expected in several tests of general relativity.
  - Science investigations with optical transponders on the Moon can also be used as a prototype demonstration for later laser ranging to Mars; a lunar installation would provide valuable early feedback on their operational characteristics.

Expected Benefits from Next Generation of LLR

Lunar science effects that will benefit from a wider distribution of LLR arrays

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

Earth geodesy and geophysics effects that would benefit from a bright lunar target (i.e., laser transponder).

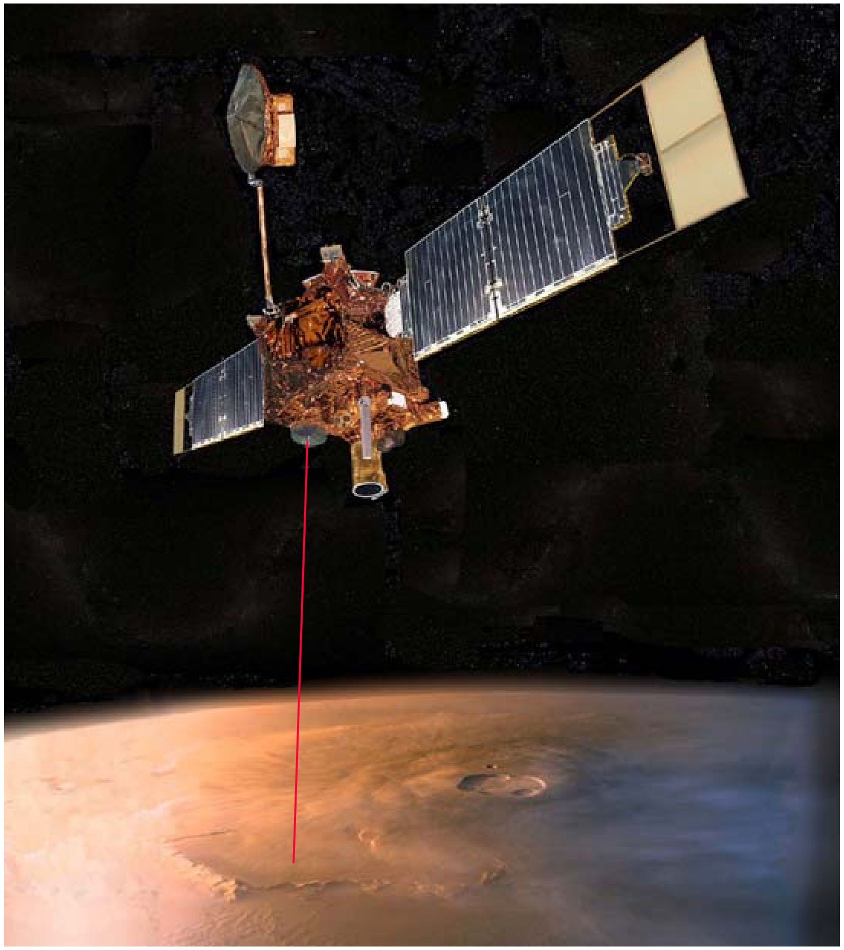
Effect	Current	Future Goals
Station positions & motions	yes	More stations on more plates
UT and polar motion	yes	More stations, improved UT1 and polar motion accuracy including diurnal and semidiurnal variations
Precession and nutation	yes	Improved accuracy
Obliquity and equinox	yes	Improved accuracy

Pulsed Lidar Space Missions: History

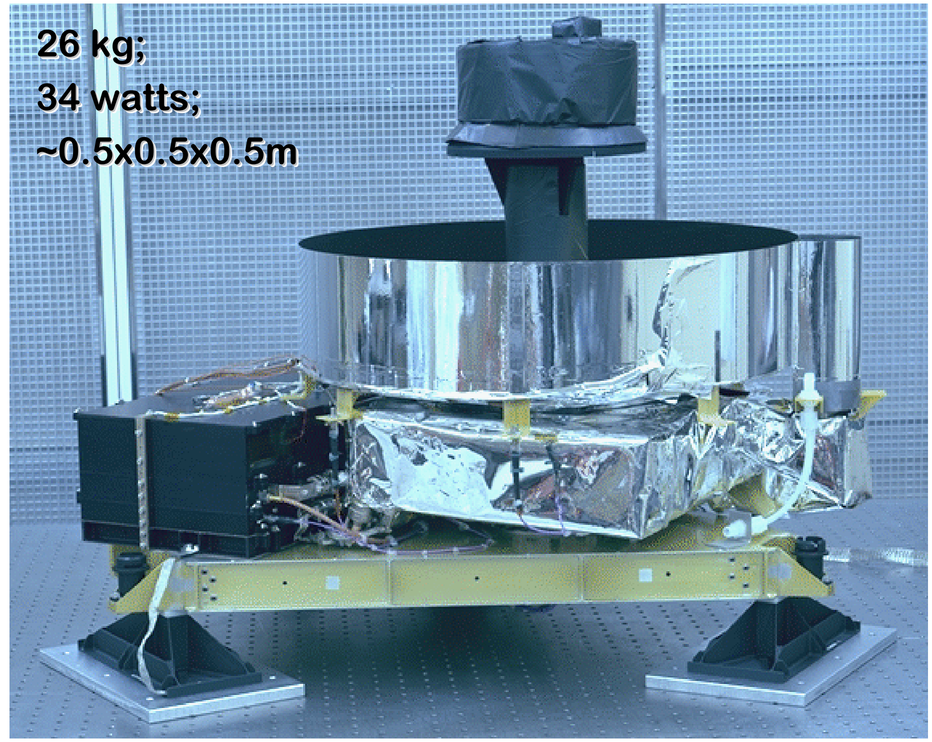
Mission	Launch	Objective	Performance
– Apollo 11, 14, 15	1969-72	Ranging, Moon	Success [passive LLR targets]
– MOLA I	1992	Ranging, Mars	S/C Lost (Contamination)
– Clementine	1994	Ranging, Moon	Success (BDMO/NASA)
– LITE	1994	Profiling, Shuttle	Success (Energy Decline by 30%)
– *Balkan*	*1995*	*Profiling*	*Success (Russia)*
– NEAR	1996	Ranging	Success
– SLA-01	1996	Ranging, Shuttle	Success
– MOLA II / MGS	1996	Ranging, Altimeter	Success (Bar dropouts)
– SLA-02	1997	Ranging, Shuttle	Success
– MPL/DS2	1999	Ranging	S/C Lost
– VCL	2000	Ranging	Cancelled
– SPARCLE/EO-2	2001	Profiling, Shuttle	Cancelled
– Icesat/GLAS	2003	Ranging + Profiling	Laser 1, 2, 3 Anomalies
– Messenger/MLA	2004	Profiling, Mercury	Success; at Mercury on 3/18/11
– Calipso	2006	Profiling	Success [NASA/CNES]
– *T2L2/Jason 2*	*2008*	*TT, Altimeter, Ranging*	*Healthy program (CNES)*
– LOLA/LRO	2008	Altimeter, Moon	Instrument assembly
– MLCD/MTO	2009	Lasercomm	Cancelled
– Mars Science Lab	2009	Altimeter, Ranging	Design / assembly
– *ADM*	*2009*	*Wind Demo.*	*ESA (delayed, was 2006)*
– *BepiColombo*	*2013*	*Altimeter, Ranging*	*ESA (delayed, was 2011)*
– LISA	2017 ?	CW Ranging	*TBD,* NASA/ESA

Laser-enabled instruments becoming major components of space missions

Mars Orbiter Laser Altimeter (MOLA)

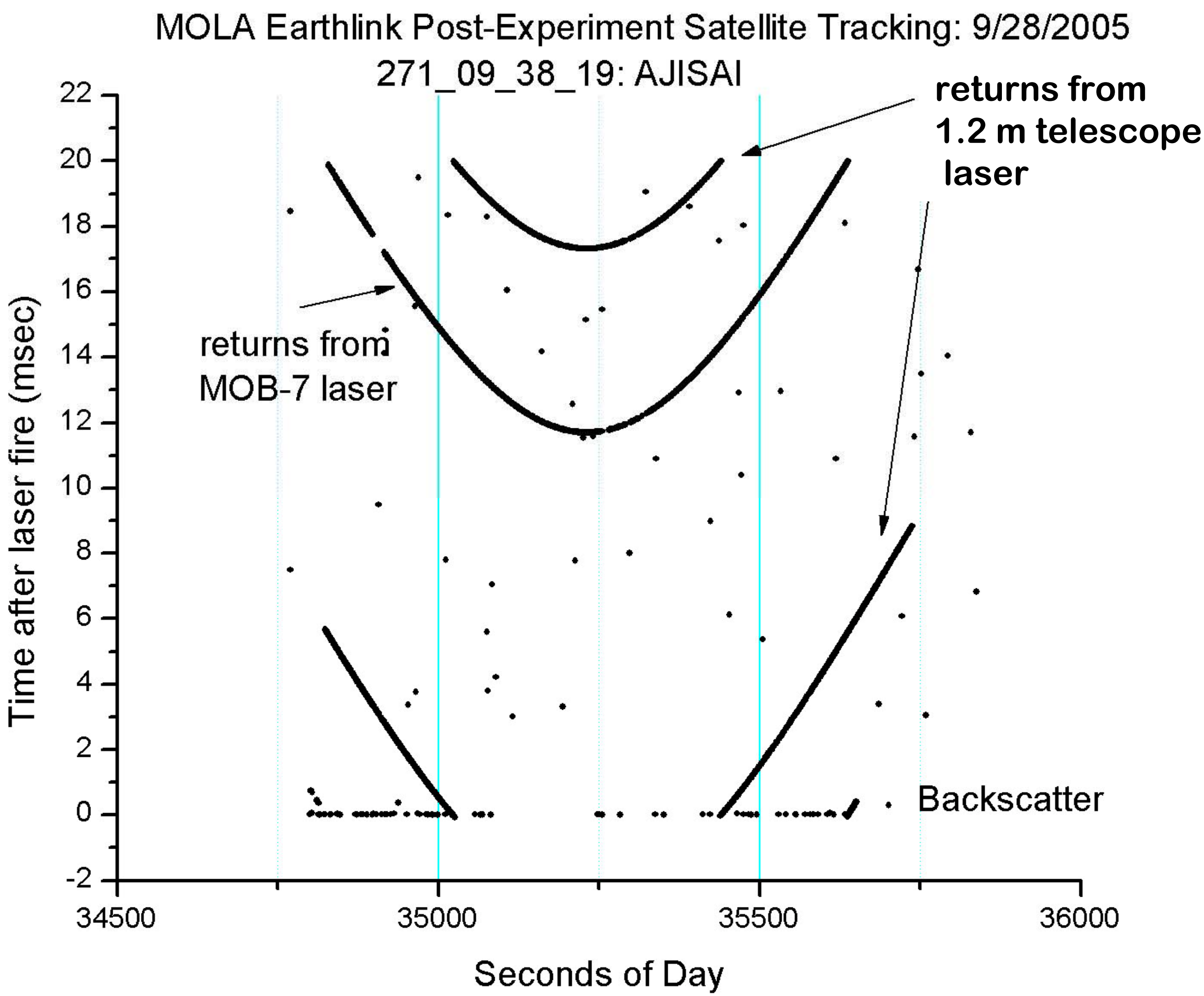


Lunch: Nov. 7, 1996.
Was in circular orbits around Mars at 400km altitude and 2 hour orbit period.
(Last communication on Nov. 2, 2006.)



- One of the science payload instruments on Mars Global Surveyor (MGS)
  - PI: David E. Smith, GSFC;
  - DPI: Maria T. Zuber, MIT
- Receiver field of view: 0.85 mrad
- Minimum detectable signal at telescope: ~ 0.1 fJ/pulse at >90% detection probability

MOLA-Earthlink Experiment

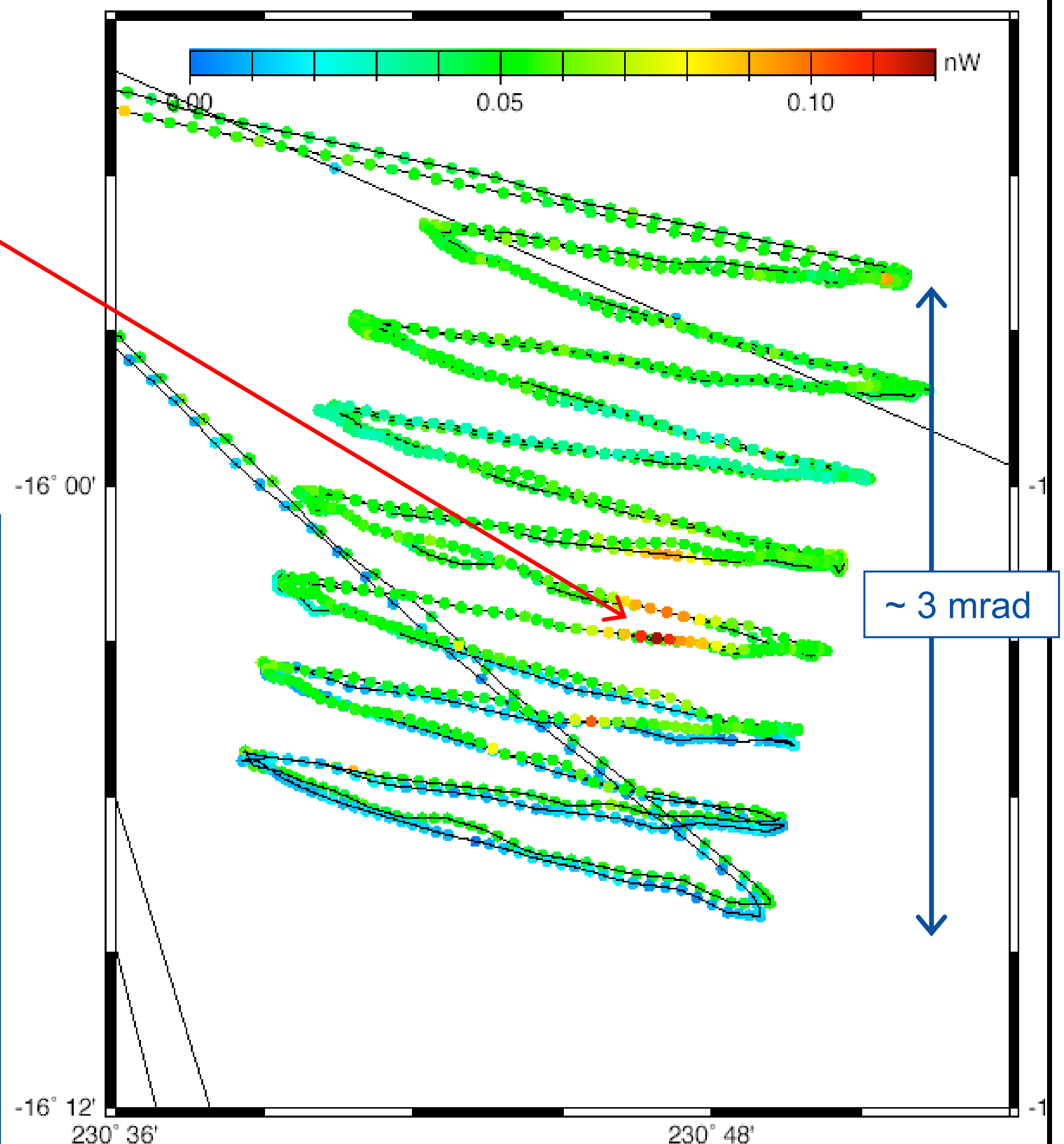


MOLA Earth Scan (2005)

MGS scans about Earth: Earthshine is seen in MOLA receiver ch#2 as red-orange-yellow in plot from 9/21/2005.

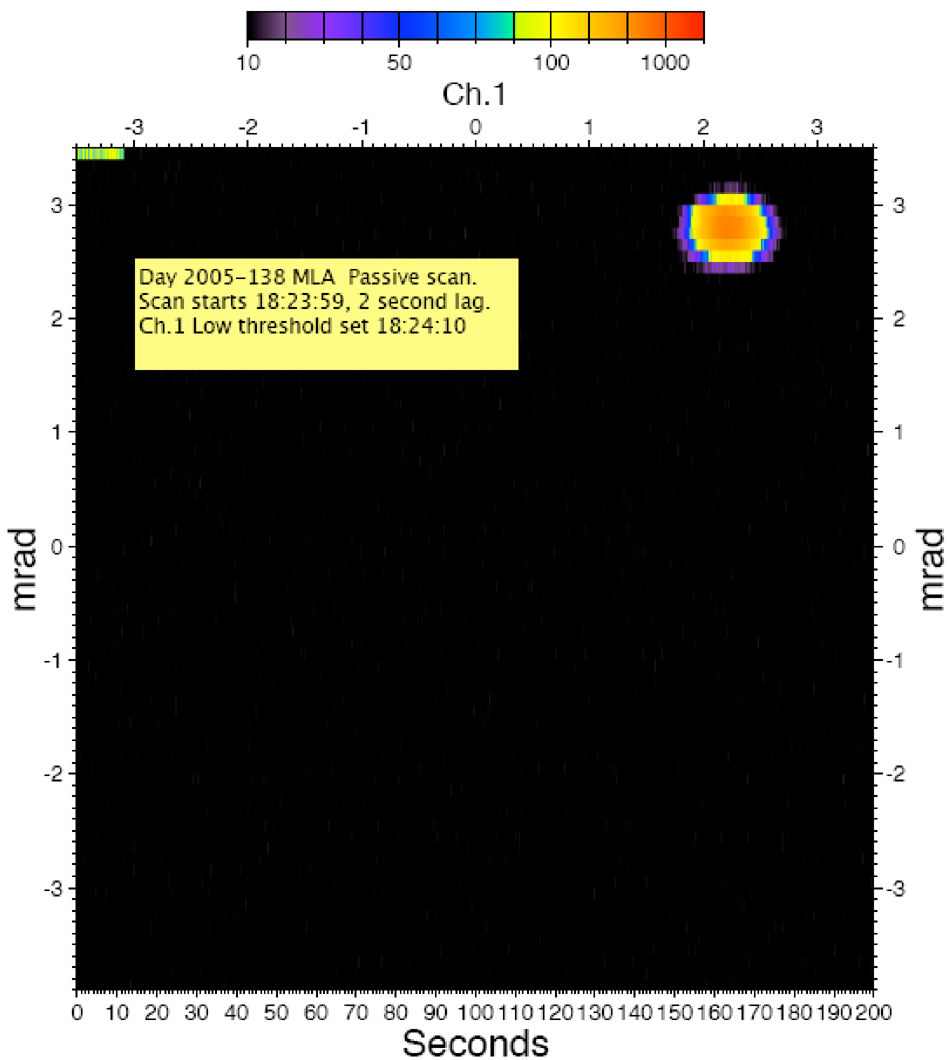
Each day's experiment consisted of two back-to-back scans.

Scans were very repeatable.



- Performed tests on 3 scheduled dates with spacecraft (9/21, 9/24, 9/28): at ~ 08:00 UTC.
- Each lasted ~45 min & involved 2 spacecraft scans of Earth.
- Maximum time Earth laser in MOLA FOV per scan line: ~8 sec
- MOLA saw earthshine in channel 2 detector on all 3 dates – very repeatable.

MLA-Earthlink Experiment Results:



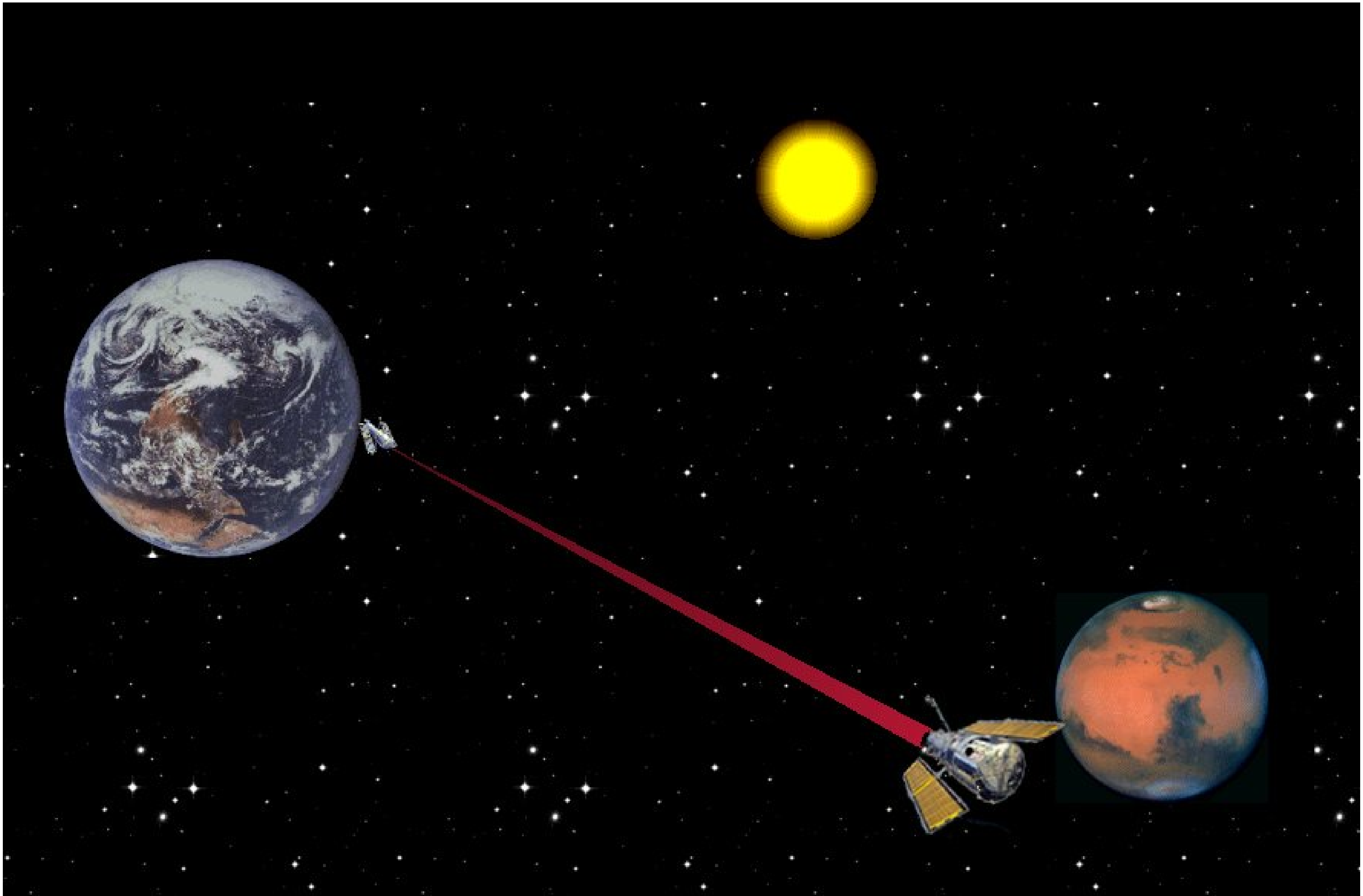
- Performed on 3 scheduled dates with spacecraft in May 2005 (5/26, 5/26, 5/31) at ~ 17:00 UTC
- Each test lasted ~ 5 hours and involved spacecraft scan of Earth over 7 x 7 mrad area.
- Maximum time earth laser in MLA FOV: ~ 5 seconds.
- Passive radiometry scan of Earth by MESSENGER was performed earlier in the month & verified s/c pointing.
- MLA laser pulses were detected at the ground. MLA also detected laser pulses from ground laser.

First successful 2-way lasercomm at interplanetary distances 24 mln km (acc ± 12 cm).

Summary of Recent Transponder Experiments

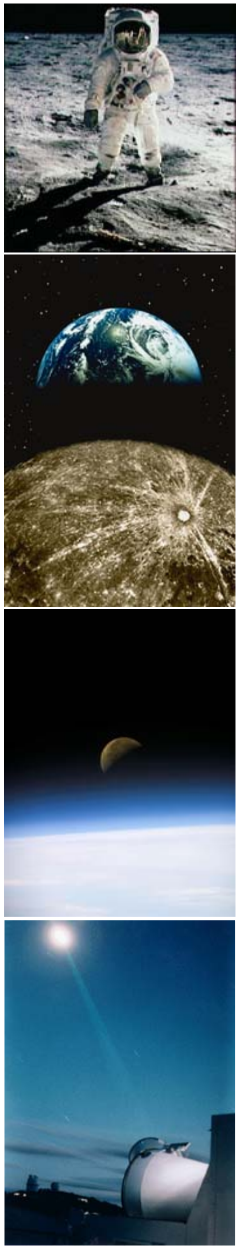
Experiment	MLA (cruise)		MOLA (Mars)
Range (10^6 km)	24.3		~80.0
Wavelength, nm	1064		1064
	Uplink	Downlink	Uplink
Pulsewidth, nsec	10	6	5
Pulse Energy, mJ	16	20	150
Repetition Rate, Hz	240	8	56
Laser Power, W	3.84	0.16	8.4
Full Divergence, μrad	60	100	50
Receive Area, m^2	0.042	1.003	0.196
EA-Product,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

- Key instrument parameters for recent deep space transponder experiments at 1064 nm
- 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)



Next Step – Interplanetary Laser Ranging

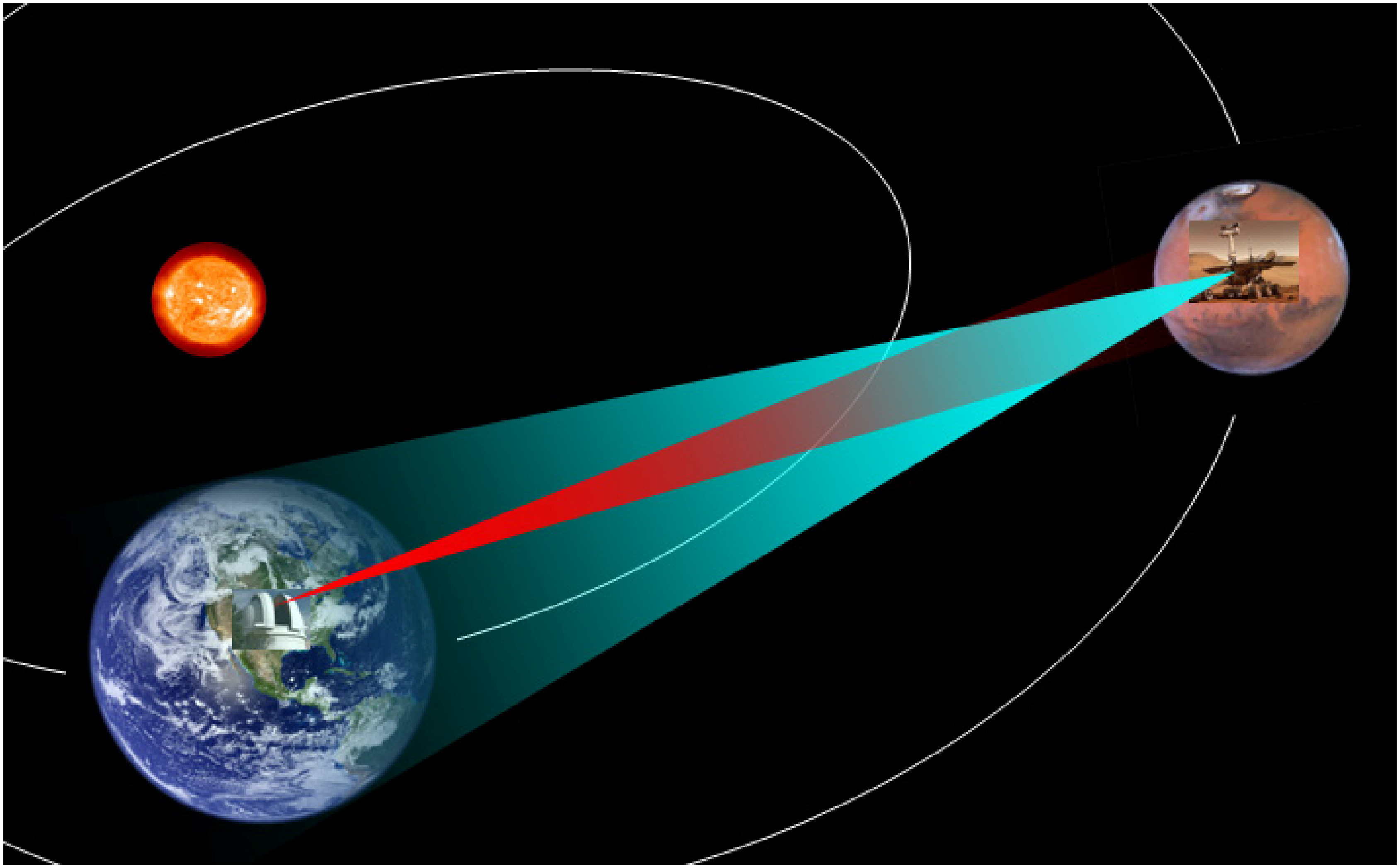
A Case for Laser Ranging to Mars



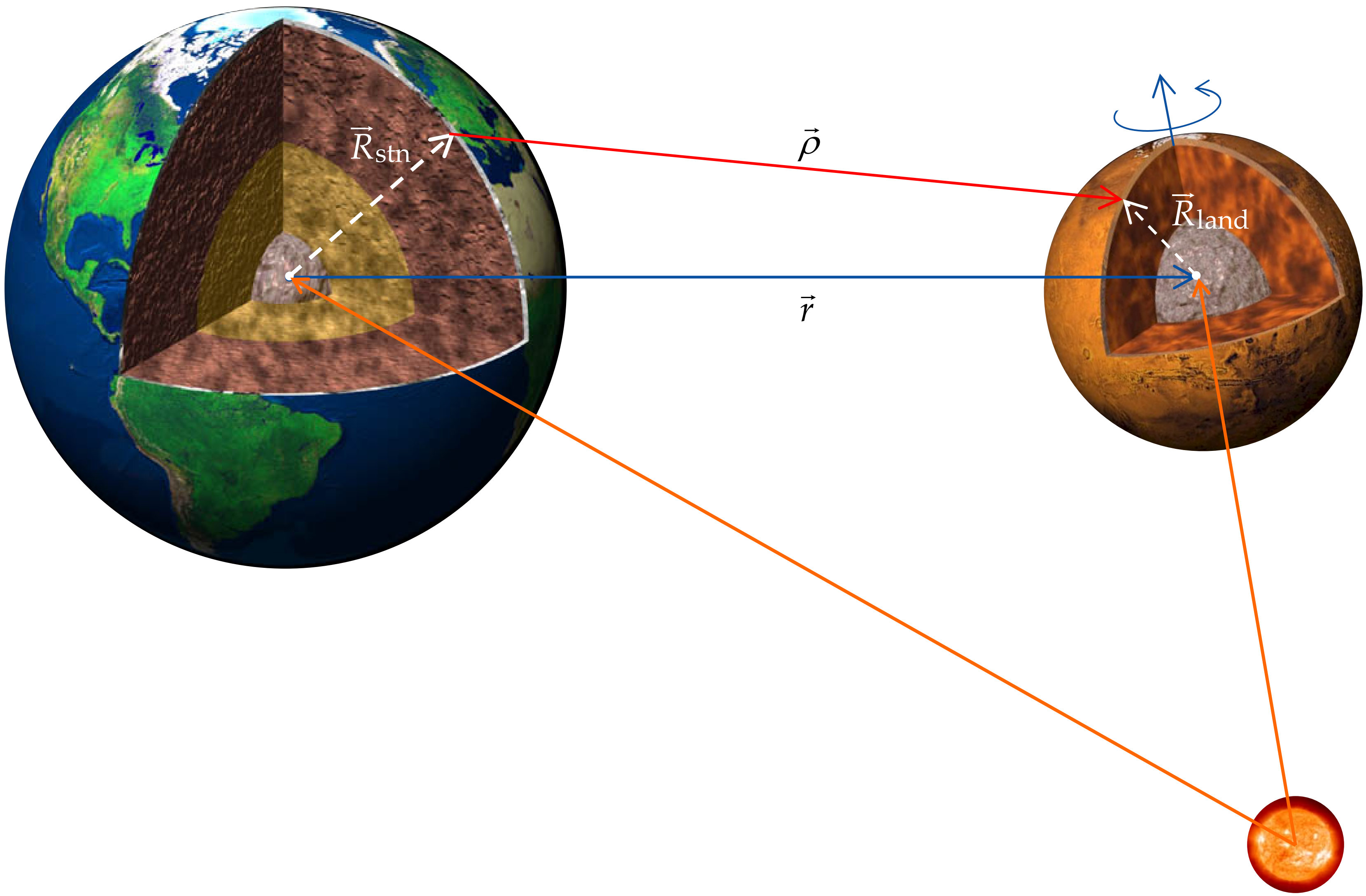
- Solar-system Ranging
  - Radar
    - Topography mapping (10 km) – for Mars (2km)
    - Fine structure (craters, etc. 1 km) – for Mars (200 m)
    - Closure points (imperfect)
  - Spacecraft ranging to Mars
    - Viking landers (5m)
    - Mars Pathfinder (10m)
    - Present day (2007) accuracy for Mars (2m)
  - Laser Ranging to Mars
    - Could be done with 1 to 100 mm range precision

- Science Questions to be investigated:
  - At what level and in what respects will general relativity fail?
  - Is there new theory of matter, space and time needed?
  - Are there new forces of nature acting at long distances?
  - Does the strength of gravity change with time?
  - Is there is new physics beyond the Standard Model?

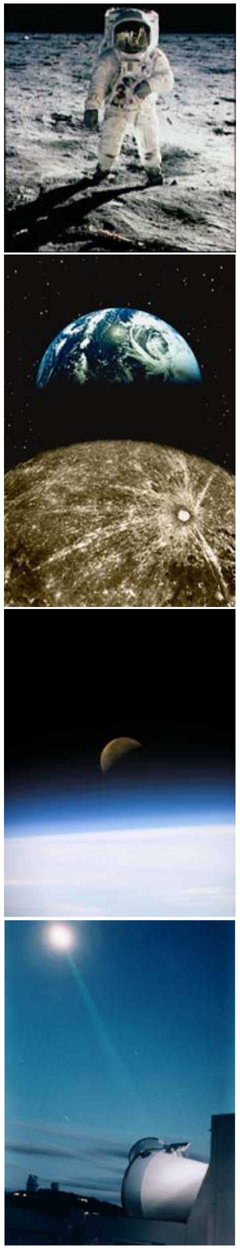
Mars Laser Ranging: Architecture



Mars Laser Ranging: Principle

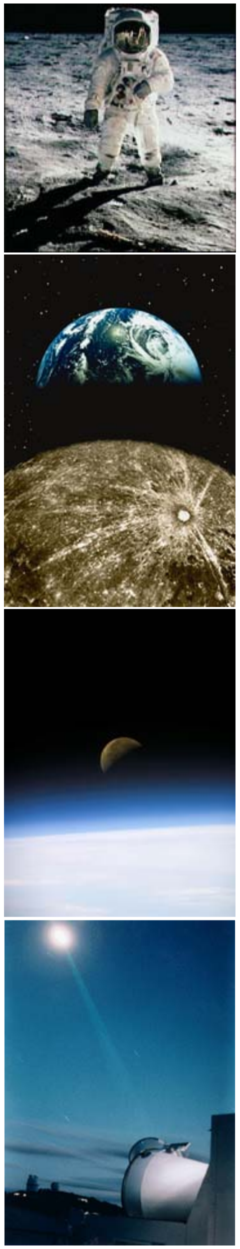


Tests of General Relativity with Mars Ranging



- Independent measurement of the PPN parameter γ:
  - Using Mars' conjunctions one can perform the Shapiro time delay experiments. (Current Mars ranging achieves only ~2 meter level accuracy).
  - With 1 cm precision ranging, the PPN parameter γ can be measured to about 1×10^{-6} or twenty times better than the currently best Cassini result (i.e., 2×10^{-5}).
  - LLR can not provide competitive measurement of this PPN parameter.
- Interplanetary test of the Strong Equivalence Principle (SEP):
  - Sun-Earth-Mars-Jupiter system tests SEP qualitatively different from LLR. SEP polarization effect is ~100 times larger for Earth-Mars orbits than for lunar orbit.
  - A weak EP test is possible with accuracy of 5×10^{-15} or better (current 1×10^{-13})
  - With 1 cm precision ranging, from combination of perihelion precession and EP violating polarizations toward Jupiter, the SEP violating parameter η can be measured to 2×10^{-6} for observations ranging up to six years (current 4×10^{-4}).
  - Combined with the time delay measurements (PPN parameter γ, below) this leads to a measurement of PPN parameter β to the 1×10^{-6} level.
- Testing possible variation in the Newtonian gravitational constant:
  - With improved ranging accuracy and a combination of LLR and Mars ranging data sets the Gdot/G accuracy is possible at the level of to about 1×10^{-14} yr^{-1} in about 6 years (current 7×10^{-13} yr^{-1}) – likely to be severely limited by the asteroids.
- Test of the gravitational inverse square law (at distances of 2 AU):
  - 2 orders of magnitude improvements will be possible compared to the currently published limits (of about 1×10^{-10} of the gravity strength) at ranges of 2 AU.

Mars Ranging Science Possibilities



- Relativistic time transfer and clock synchronization:
  - Should a high-accuracy clock will be present on the surface of Mars, a picosecond accuracy for the time transfer is possible between the active laser ranging terminals separated by 2 AU
- Mars interior science:
  - A lander on Mars with ranging capability (radio or laser) is sensitive to Mars precession, nutation, polar motion and UT1.
  - From the precession one gets moment of inertia. Nutation has sensitivity to interior structure. Better measurements of Mars' rotational dynamics could provide estimates of the size of the core. The atmospheric pressure and polar caps change seasonally which affects UT1 and polar motion.
- Planetary science:
  - The inputs into the EP signal are gravitational to inertial mass ratios for Sun, Earth, and Mars (Sun minus Earth, Sun minus Mars), with Jupiter supplying just an overall proportionality constant --- its active mass --- to the possible effect. Therefore, incidentally the fit of the Earth-Mars data determines GM(jup) better than we know it with Pioneers 10/11, Voyagers 1/2, and Galileo data combined.
  - Some of the basic dynamical model parameters for the solar system will be improved – like GM/c^3 of various bodies starting with the Sun, the basic size unit such as R(earth)/c, ratios such as R(mars)/R(earth), or the same expressed in orbital frequencies, depending on how the model is organized, etc.

Comparison of Laser-Enabled Gravity Tests

Relativistic Effect	LLR current	APOLLO	1 cm range to Mars	Combined LLR & Mars
Tests of the Equivalence Principle				
Weak Equivalence Principle, $\Delta a/a$	1.9×10^{-13}	1×10^{-14}	3×10^{-15}	3×10^{-15}
Strong Equivalence Principle, η	4.3×10^{-4}	2×10^{-5}	2×10^{-6}	2×10^{-6}
Determination of the PPN parameter β	1.1×10^{-4}	7×10^{-6}	1×10^{-6}	1×10^{-6}
Determination of the PPN parameter γ	2×10^{-3}	1×10^{-3}	1×10^{-6}	1×10^{-6}
Limits on the time variation of the gravitational constant G, $\dot{G}/G$	6×10^{-13} yr^{-1}	1×10^{-14} yr^{-1}	1×10^{-14} yr^{-1} asteroids…	7×10^{-15} yr^{-1} asteroids…
Gravitational inverse square law (testing for new long range forces)	3×10^{-10} at 4×10^{6} km	3×10^{-11} at 4×10^{6} km	3×10^{-11} at 2 AU	1×10^{-11} at 0.1-2 AU
Relativistic geodetic precession	4.7×10^{-3} lunar orbit	3×10^{-4} lunar orbit	3×10^{-4} Martian orbit	3×10^{-4} both lunar & Martian orbits

Numbers extrapolated from references below (we need a detailed covariance study):

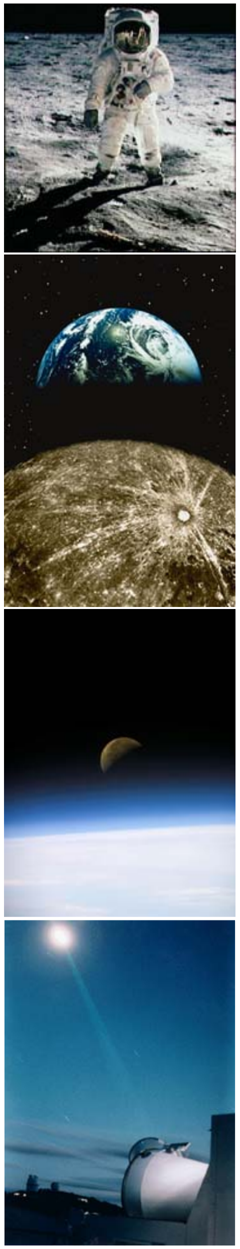
J.D. Anderson, M. Gross, K.L. Nordtvedt, S.G. Turyshev, ApJ, 459 (1996) 365-370 [arXiv:gr-qc/9510029]

J.G. Williams, S.G Turyshev, D.H. Boggs, Phys.Rev.Lett.93:261101 (2004) [arXiv:gr-qc/0411113]

J.F. Chandler, M.R. Pearlman, R.D. Reasenberg, J.J. Degnan, in Proc. 14th LSRS Meeting, 2004

S.G Turyshev, J.G. Williams, [arXiv:gr-qc/0611095]

Mars Ranging Science Issues & Conclusions



- "Grand Fits" are the best strategy to achieve highest accuracy:
  - Grand fits of both the interplanetary and the lunar ranging data (including both laser and radar) will be the most productive way to fit the science.
- Modeling asteroids:
  - Needs a modeling campaign for the asteroids in order to fully utilize the anticipated Martian ranging data
  - Modeling to 1 cm contributions to certain frequency signals may be possible for Earth-Mars range (would lead to an improvement to the theory for relativistic reference frames and time scales)
  - The integrated model error across the frequency spectrum will probably be significantly larger, but most of that modeling error will be orthogonal to our science signals of interest.
  - Solar system barycenter and solar dynamics are part of the analytic input to deriving the EP violating polarizations toward Jupiter, Saturn, etc.
- Laser ranging to Mercury:
  - One of the excellent future science opportunities would be to do transponded laser ranging to a Mercury lander or orbiter, to reduce the asteroid problem and enter a more relativistic regime…
- **Conclusions**:
  - Laser Ranging to Mars offers significant potential for improving tests of gravity.
  - More extensive studies are needed to address the issues identified.

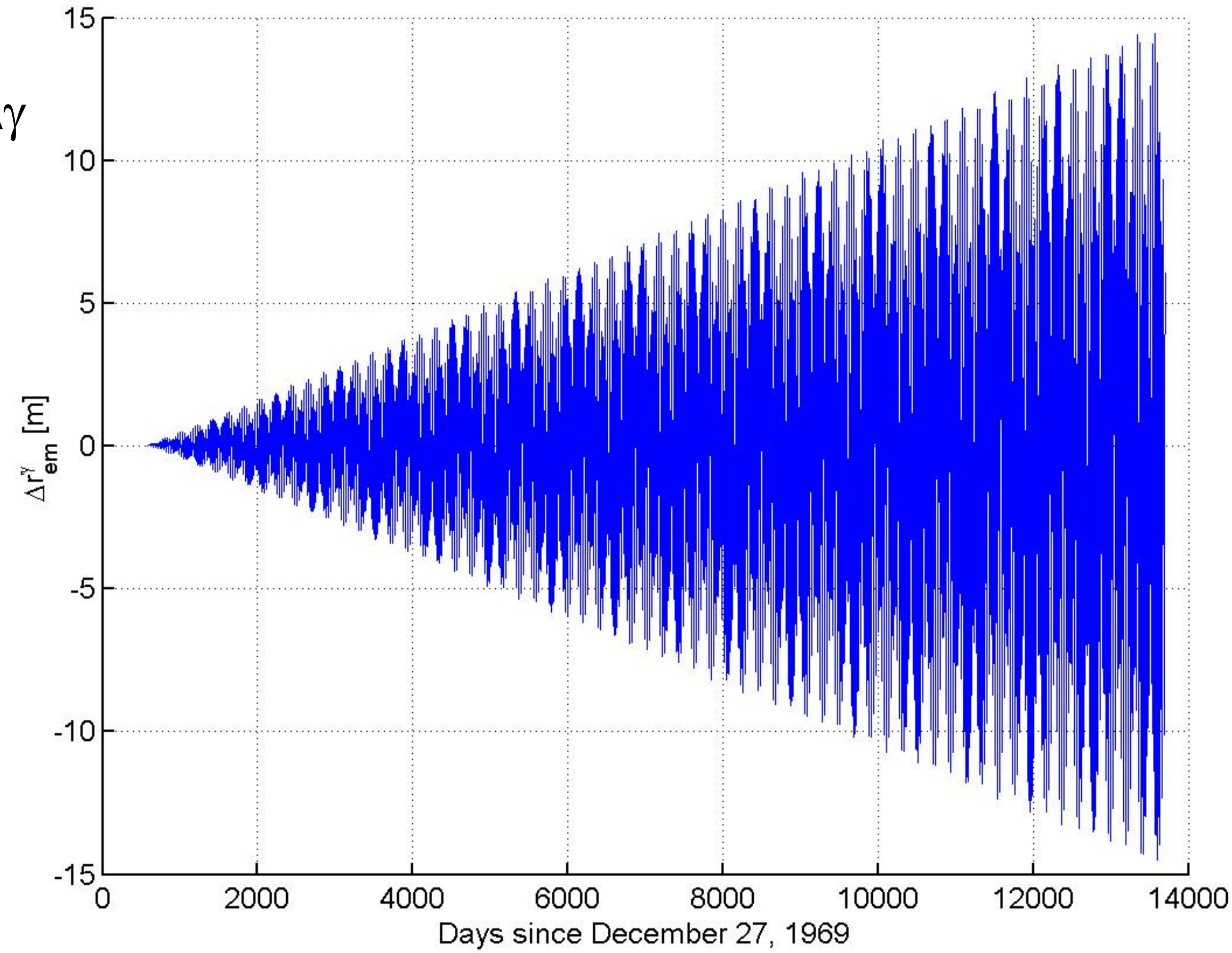

Thank You!
Mars
Venus
Earth

Sensitivity of Relativistic Parameters (1)

Space curvature γ

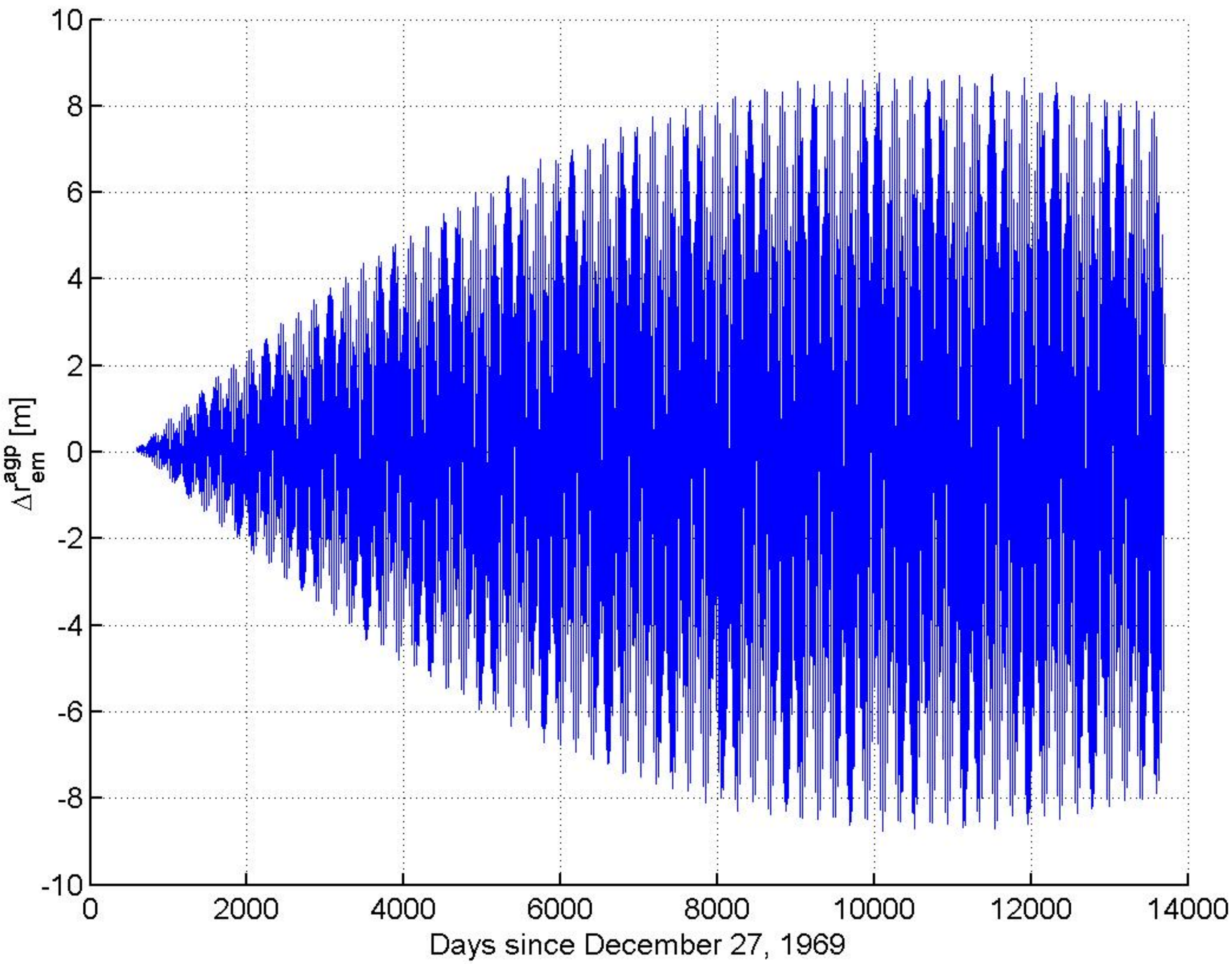
$\Delta r_{em}(\gamma) =$

$\delta r_{em} / \delta\gamma * \Delta\gamma$

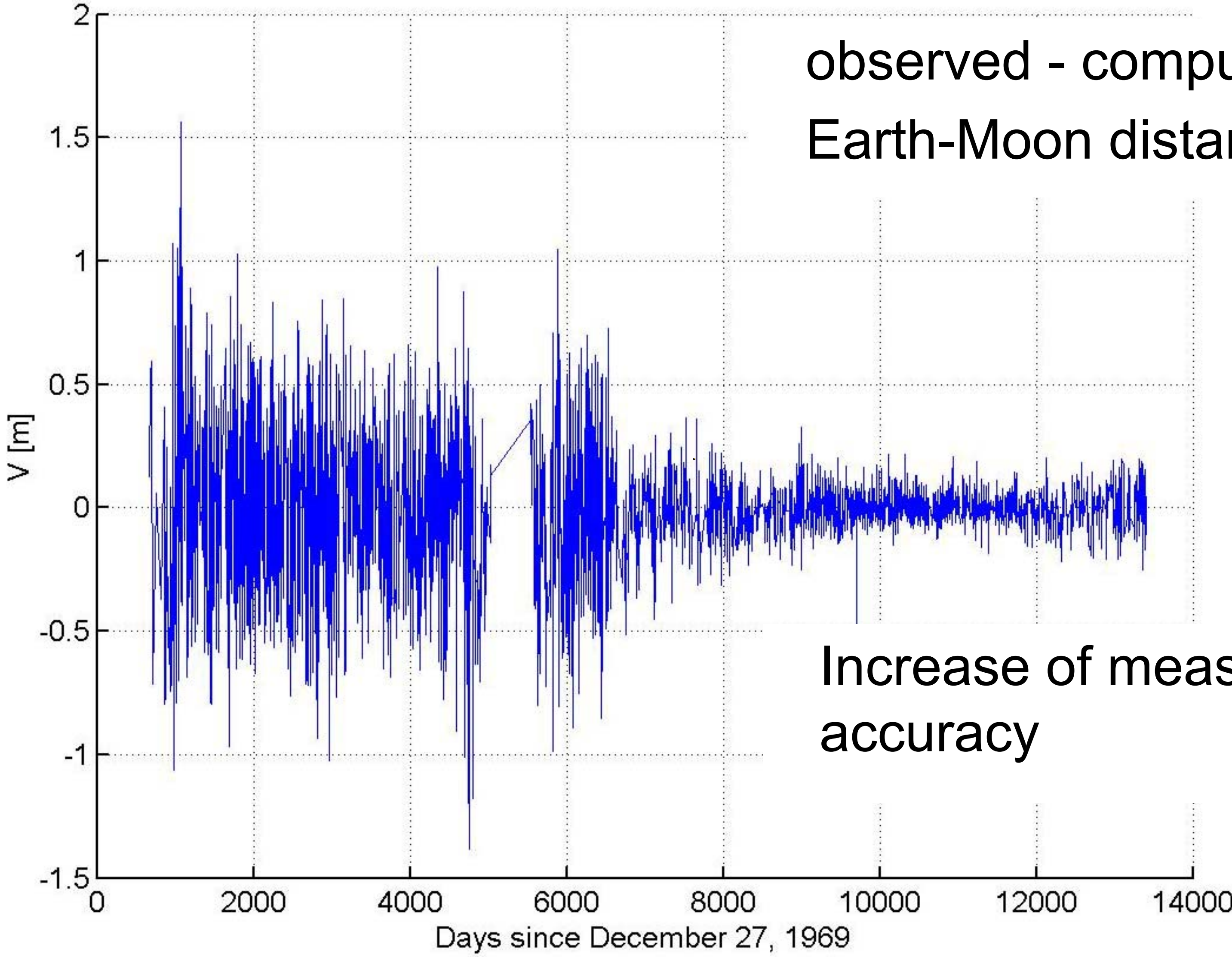


Sensitivity of Relativistic Parameters (2)

Time-variable Gravitational Constant $\dot{G}/G$



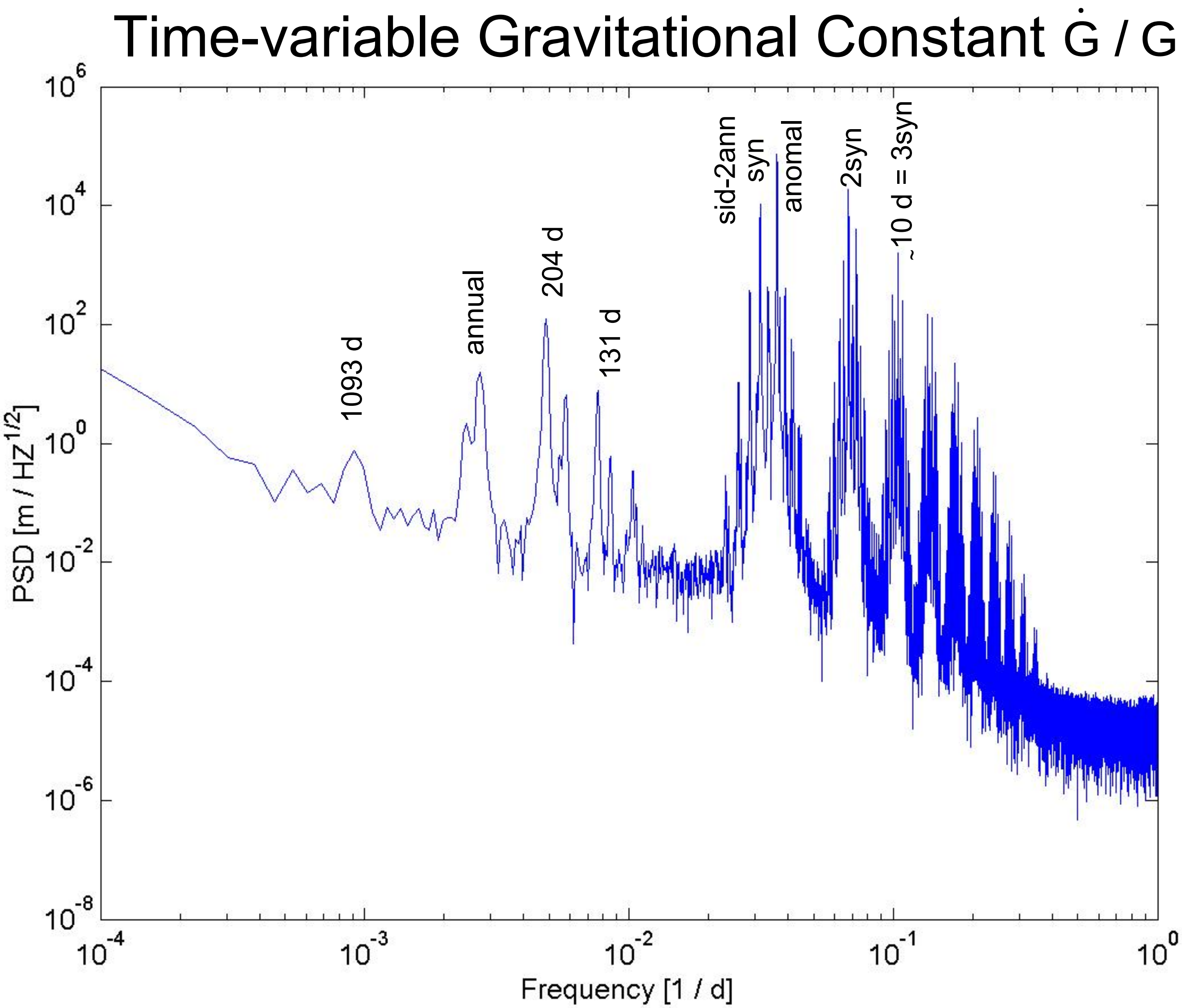
LLR Residuals



observed - computed Earth-Moon distance;

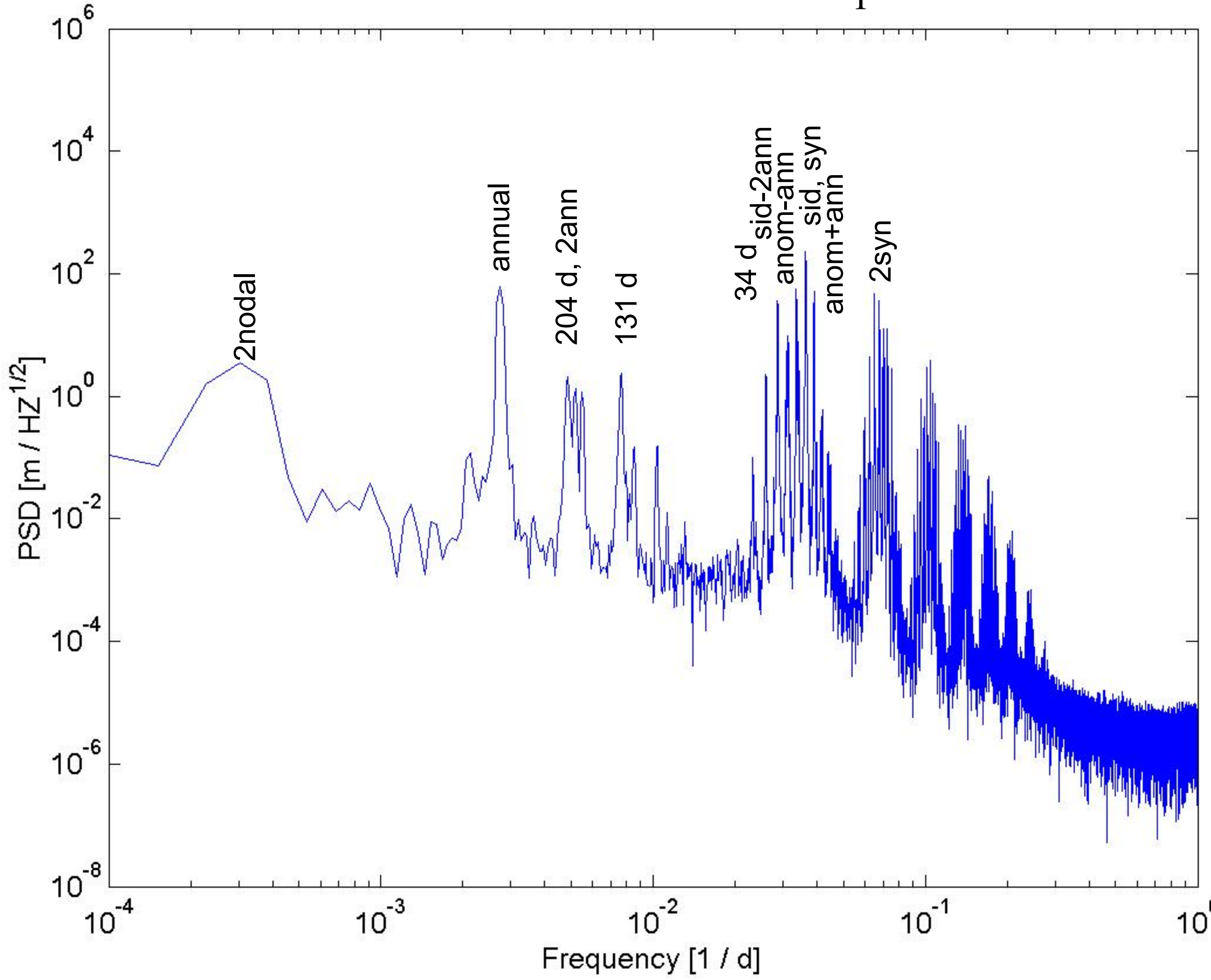
Increase of measurement accuracy

Relativistic Parameters – Power Spectra (1)



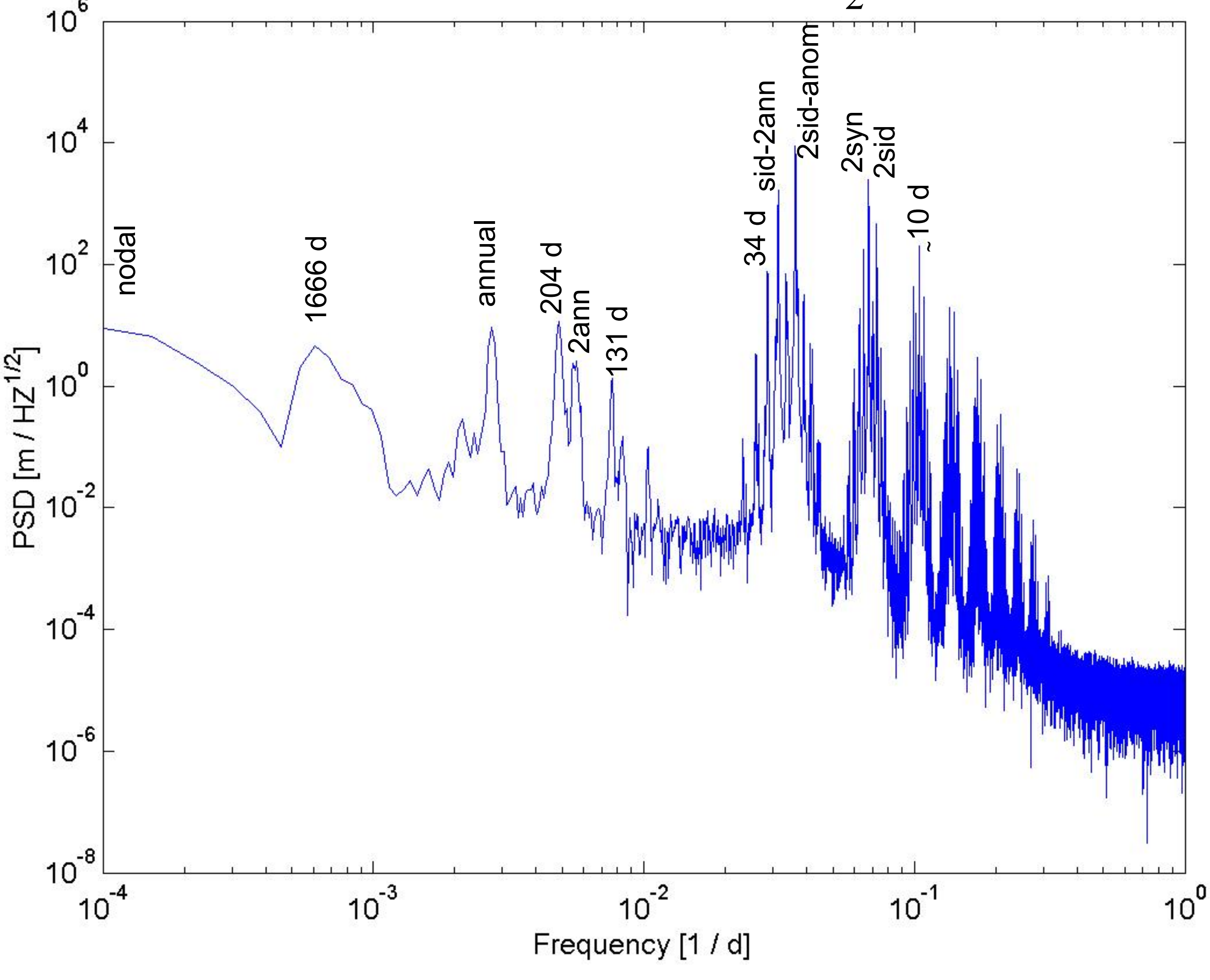
Relativistic Parameters – Power Spectra (2)

Preferred frames α_1



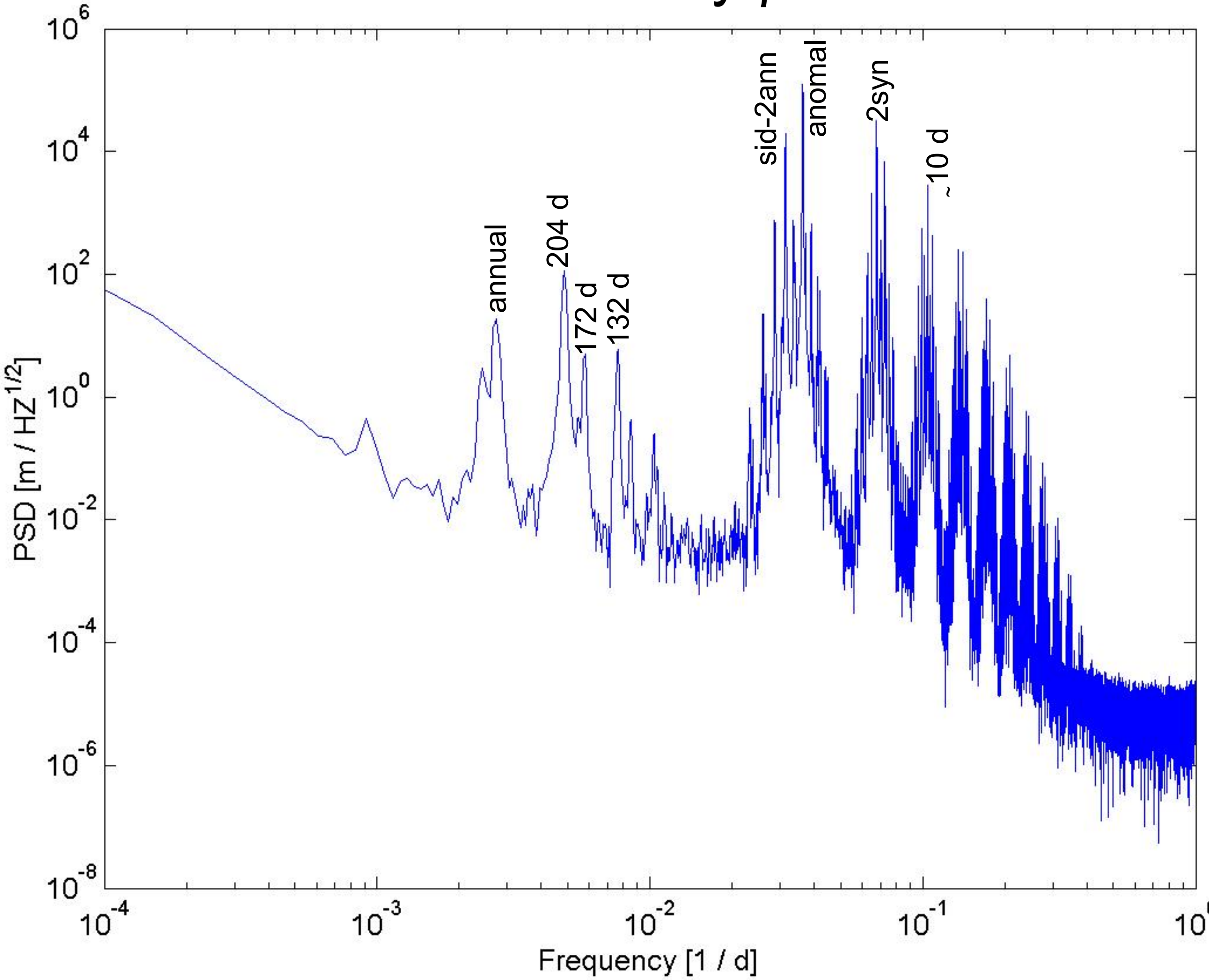
Relativistic Parameters – Power Spectra (3)

Preferred frames α_2



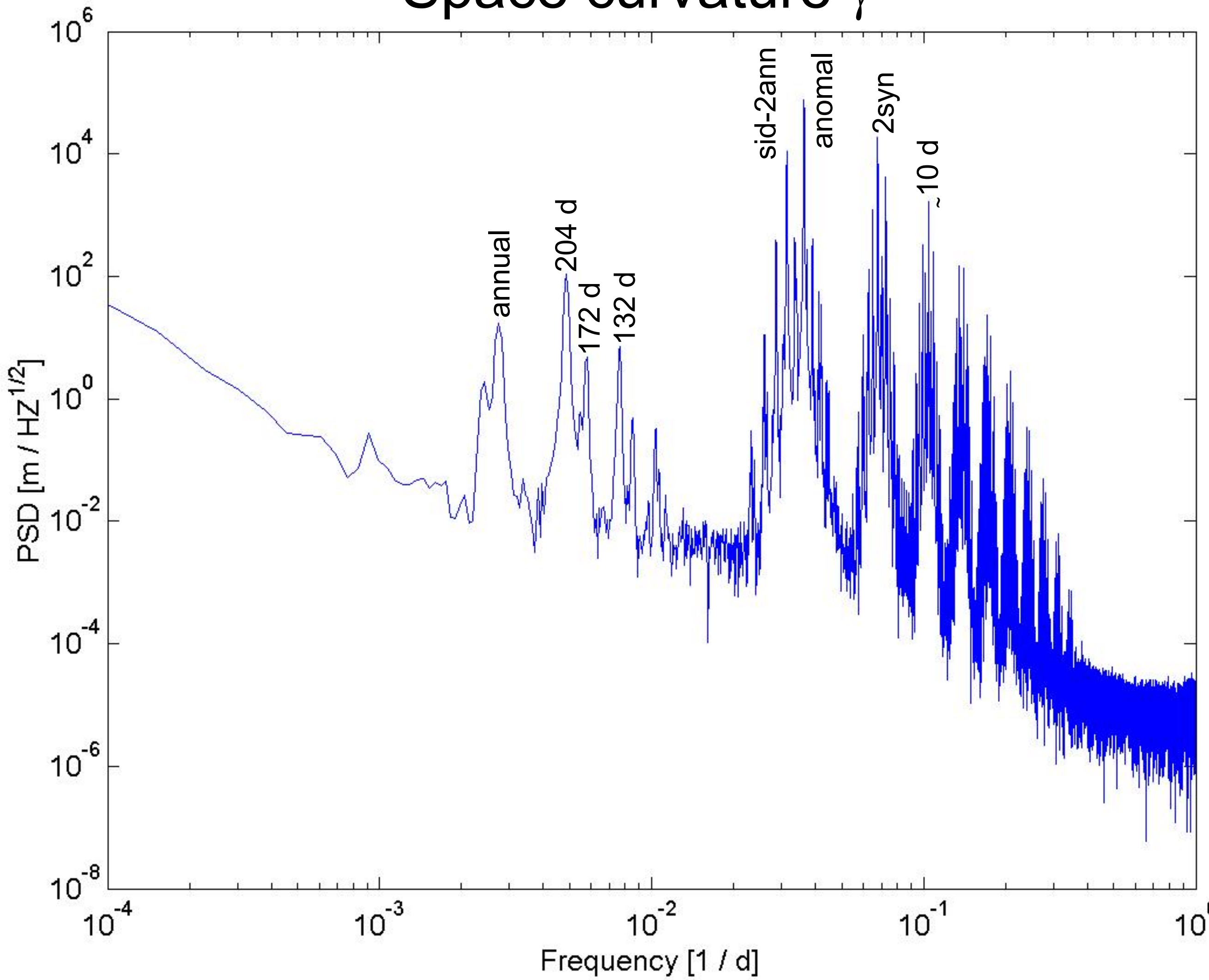
Relativistic Parameters – Power Spectra (4)

Non-linearity β



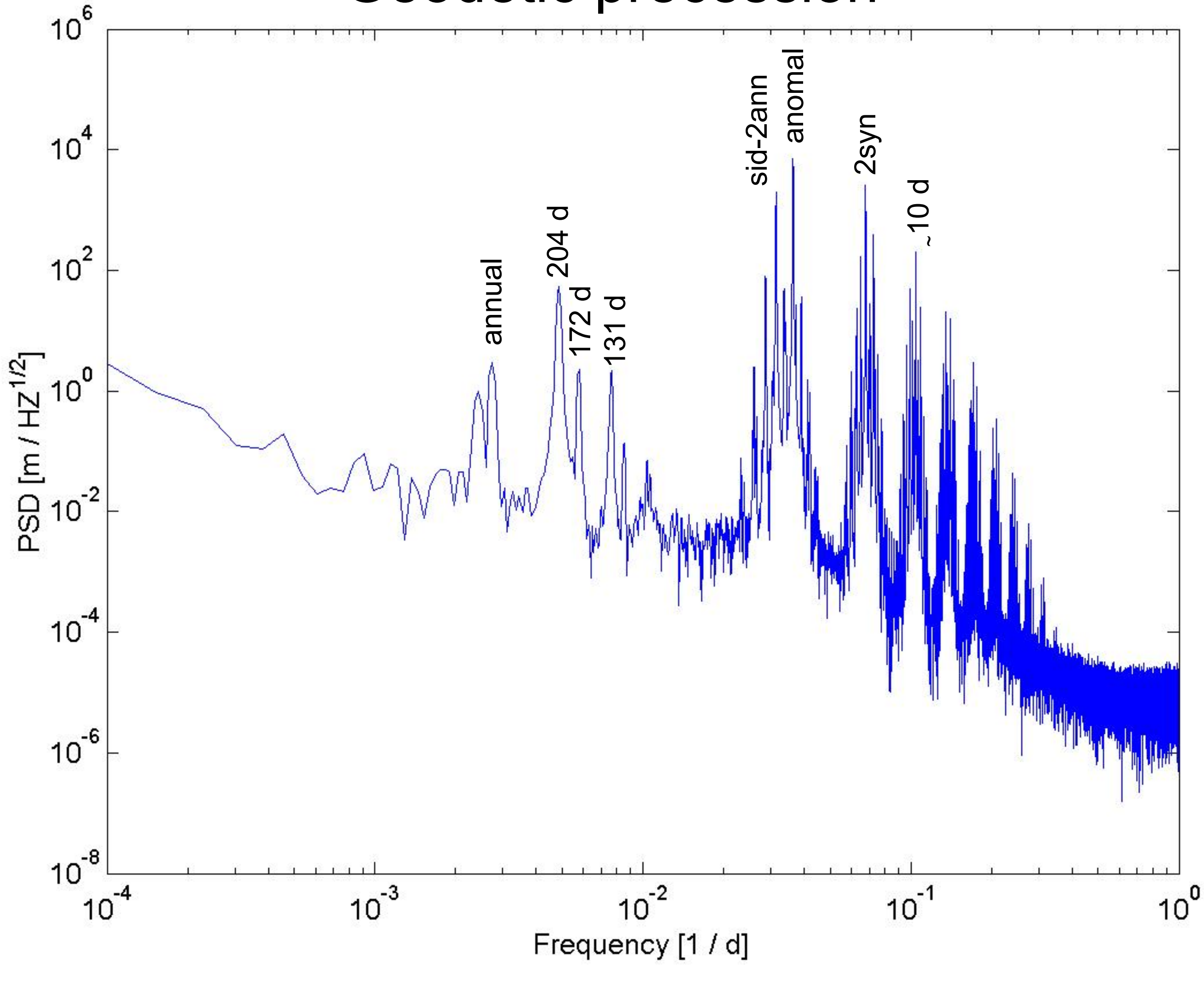
Relativistic Parameters – Power Spectra (5)

Space curvature γ



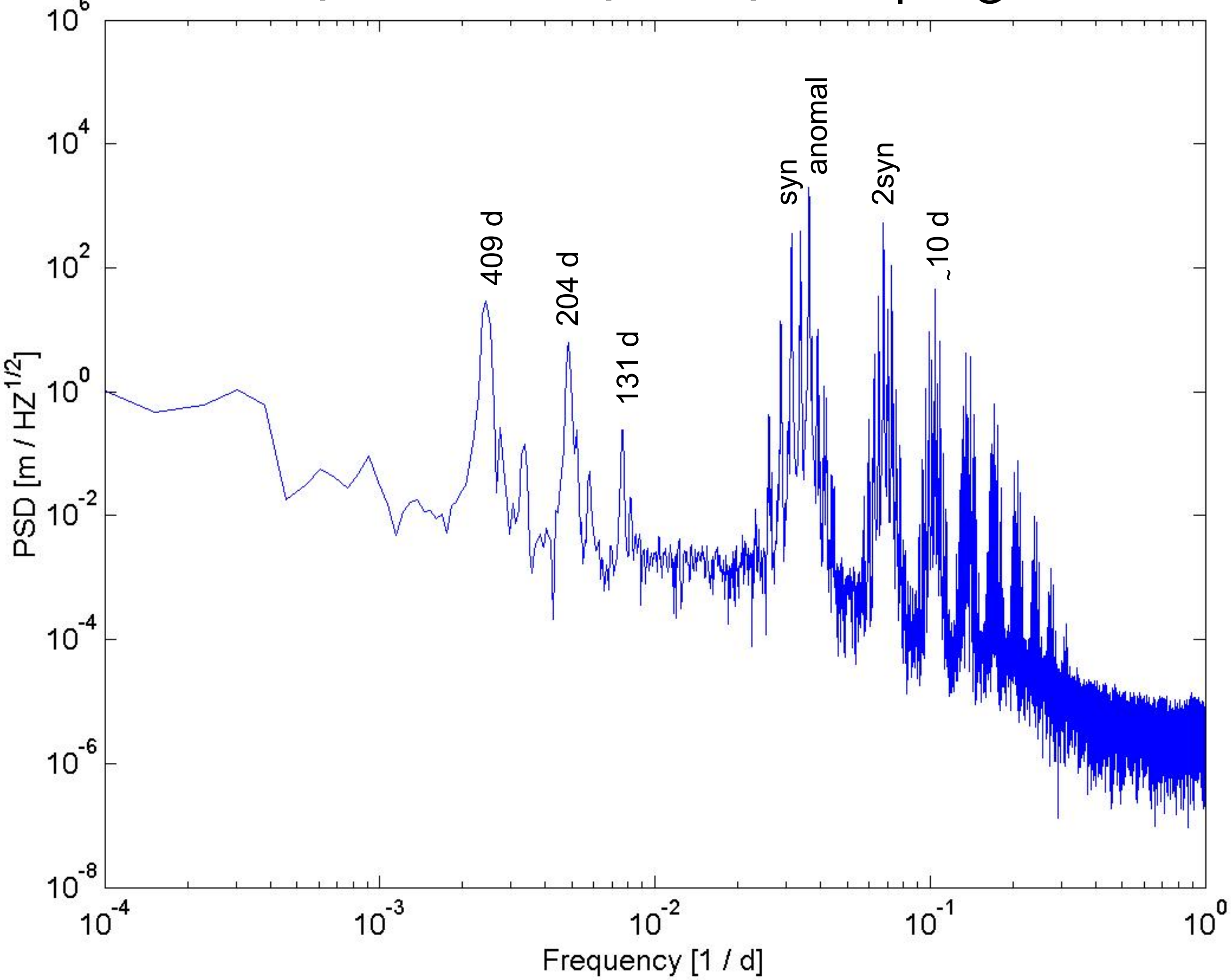
Relativistic Parameters – Power Spectra (6)

Geodetic precession

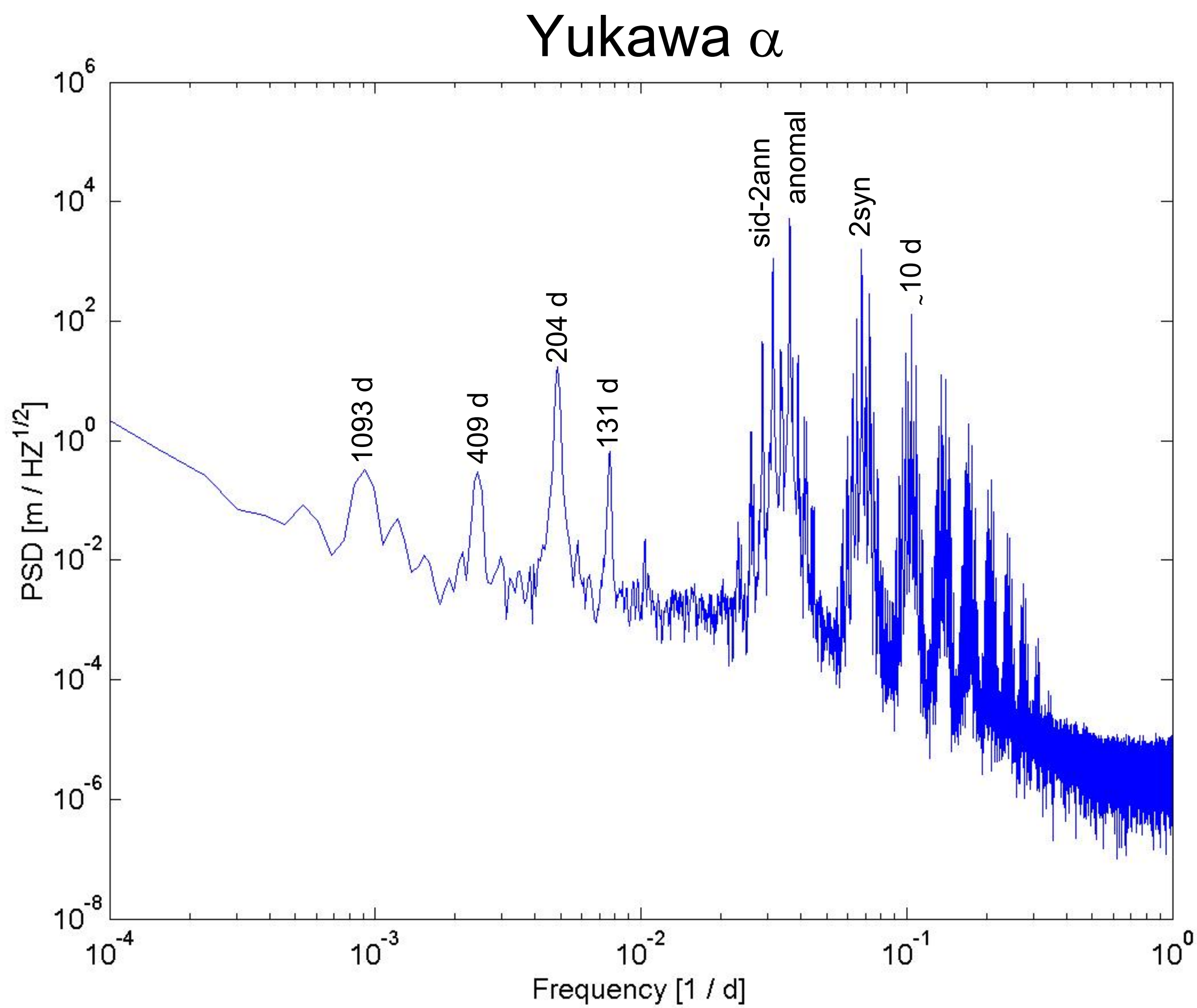


Relativistic Parameters – Power Spectra (7)

Equivalence principle m_I/m_G



Relativistic Parameters – Power Spectra (8)



Mars Laser Ranging: Instruments