Laser-Enabled Tests of Gravity:

Recent Advances, Technology Demonstrations, and New Ideas

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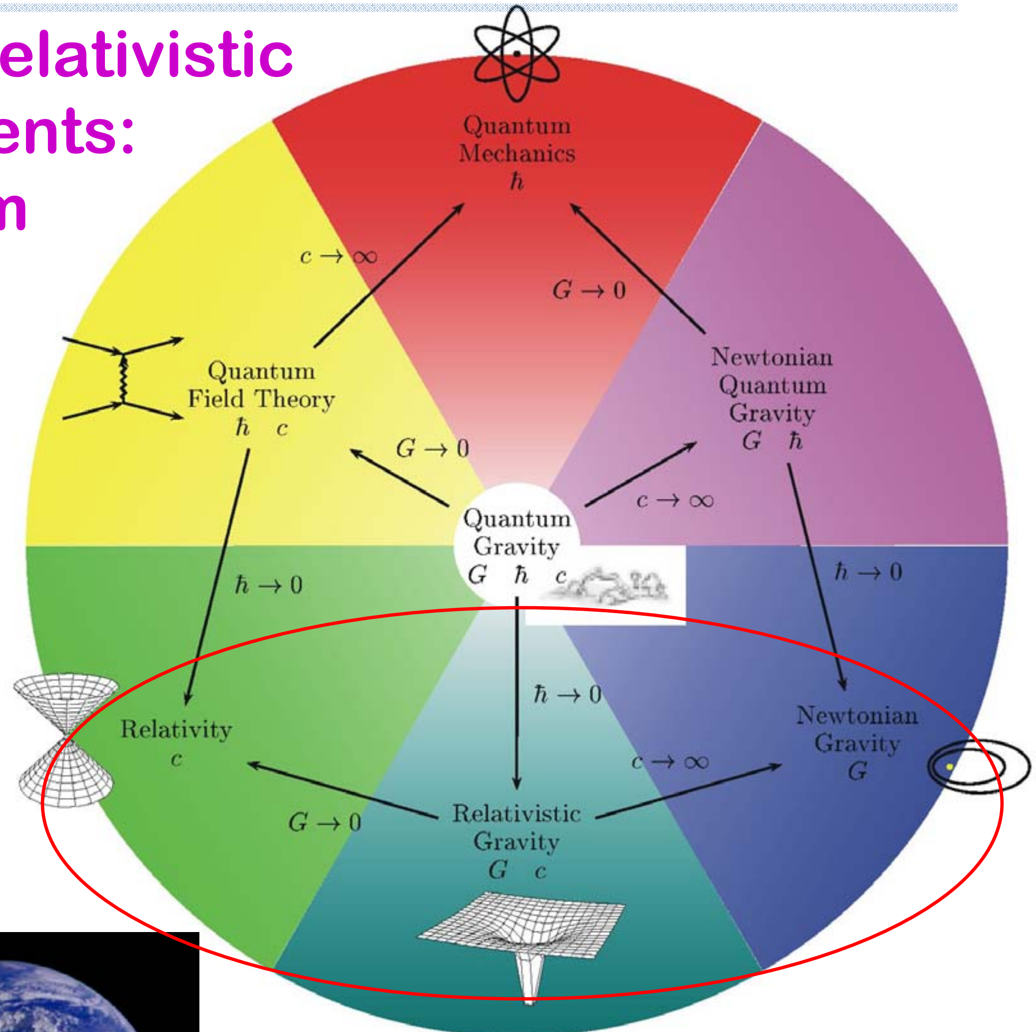
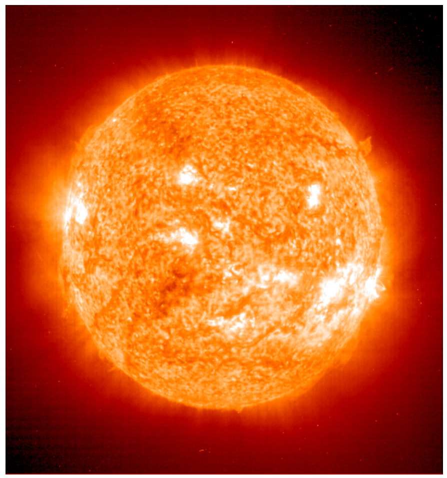
Moscow State University, Moscow, 6 February 2007

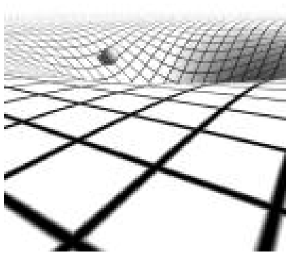
Laboratory for Relativistic Gravity Experiments: Our Solar System





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:

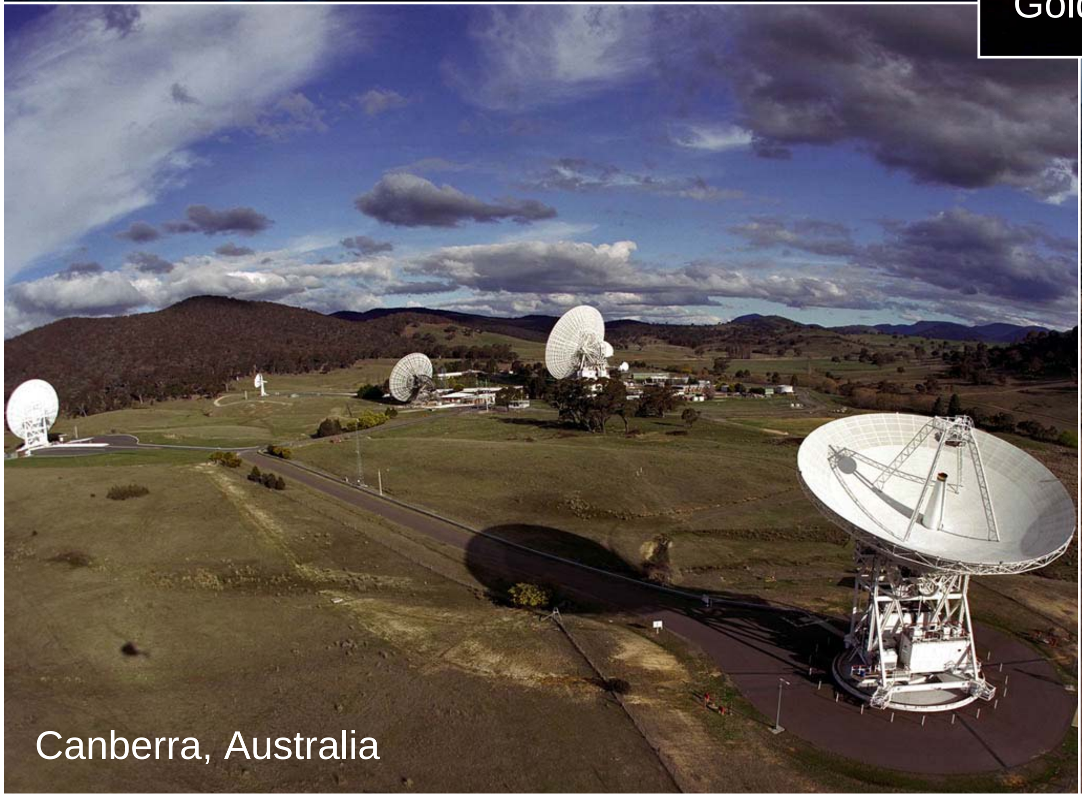
- ISS, LLR, SLR, free-fliers

Technology is available to conduct tests in immediate solar proximity

Deep Space Network


Goldstone, California


Goldstone, California


Canberra, Australia


Madrid, Spain

Navigation Tracking Requirements (2006)

*Based on the current (2006) set of anticipated missions

Tracking Error Source (1σ Accuracy)	Units	current capability	2010 reqt*	2020 reqt*	2030 reqt*
Doppler/random (60s)	μm/s	30	30	30	20
Doppler/systematic (60s)	μm/s	1	3	3	2
Range/random	m	0.3	0.5	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

Interplanetary laser ranging is a very natural step to improve the accuracy

35 Years of Relativistic Gravity Tests

Techniques for Gravity Tests:

Radar Ranging:
- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Cassini, Mars Global Surv., Mars Orbiter
- VLBI, GPS, etc.

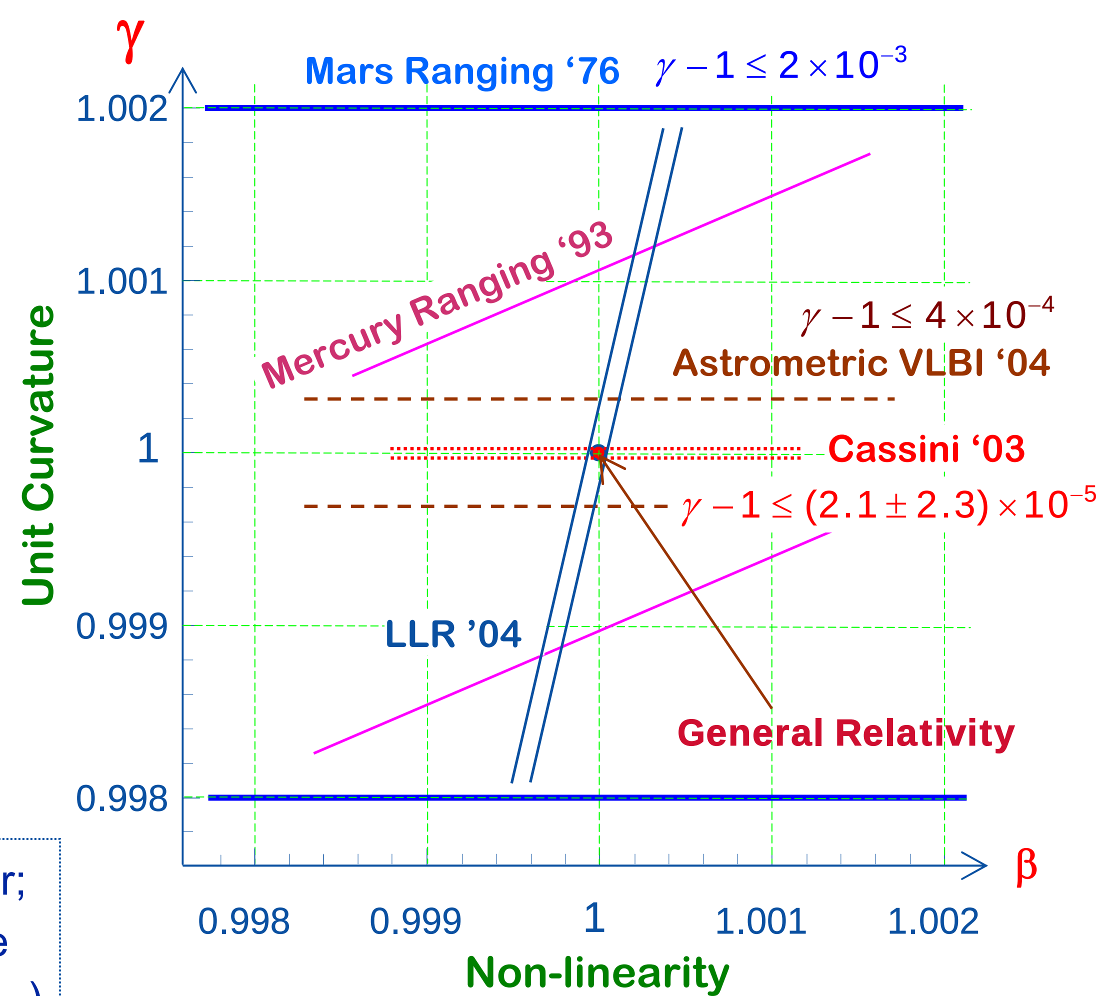
Laser:
- LLR, SLR, etc.

Designated Gravity Missions:

- **LLR (1969 - on-going!!)**
- GP-A, '76; LAGEOS, '76,'92; GP-B, '04; LISA, 2014

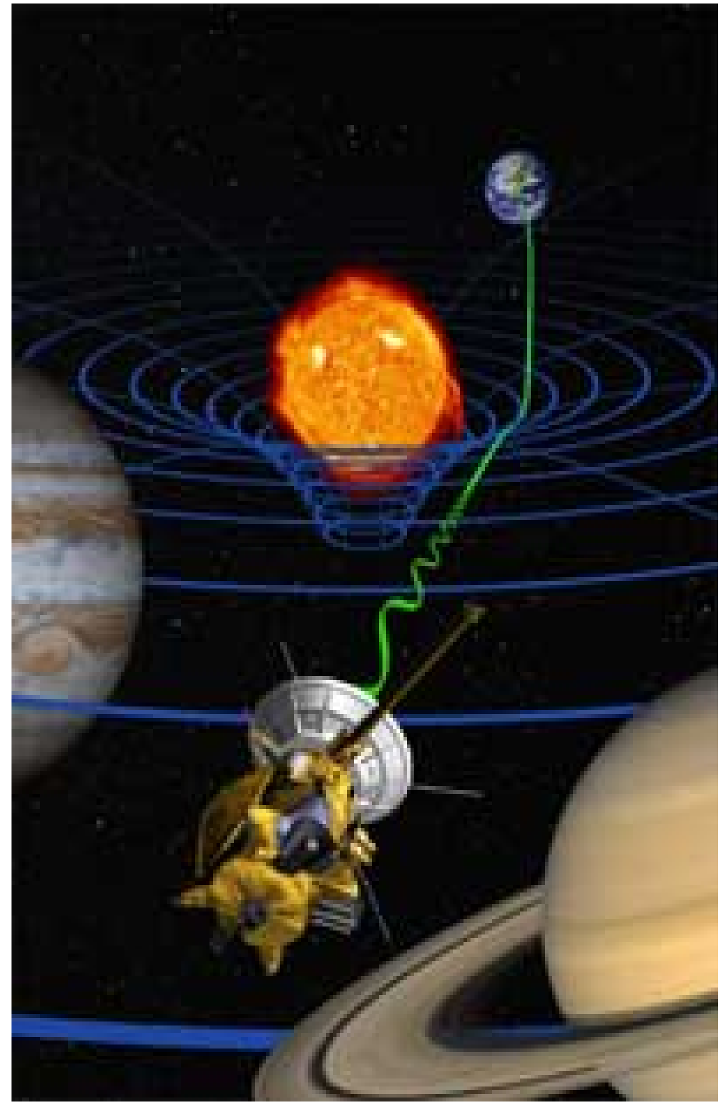
New Engineering Discipline – Applied General Relativity:

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



A factor of 100 in 35 years is impressive, but is not enough for the near future!

Cassini 2003: Where Do We Go From Here?



Cassini Conjunction Experiment 2002:

- Spacecraft—Earth separation > 1 billion km
- Doppler/Range: X~7.14GHz & Ka~34.1GHz
- Result: $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$

Possible with Existing Technologies?!

- VLBI [current $\gamma = 3 \times 10^{-4}$]: in 5 years $\sim 5 \times 10^{-5}$:
  - # of observations (1.6M to 16M → factor of 3)
- LLR [current $\eta = 4 \times 10^{-4}$]: in 5 years $\sim 3 \times 10^{-5}$:
  - mm accuracies [APOLLO] & modeling efforts
- μ-wave ranging to a lander on Mars $\sim 6 \times 10^{-6}$
- tracking of BepiColombo s/c at Mercury $\sim 2 \times 10^{-6}$
- Optical astrometry [current $\gamma = 3 \times 10^{-3}$]:

  SIM & GAIA $\sim 1 \times 10^{-6}$ (2015/16?)

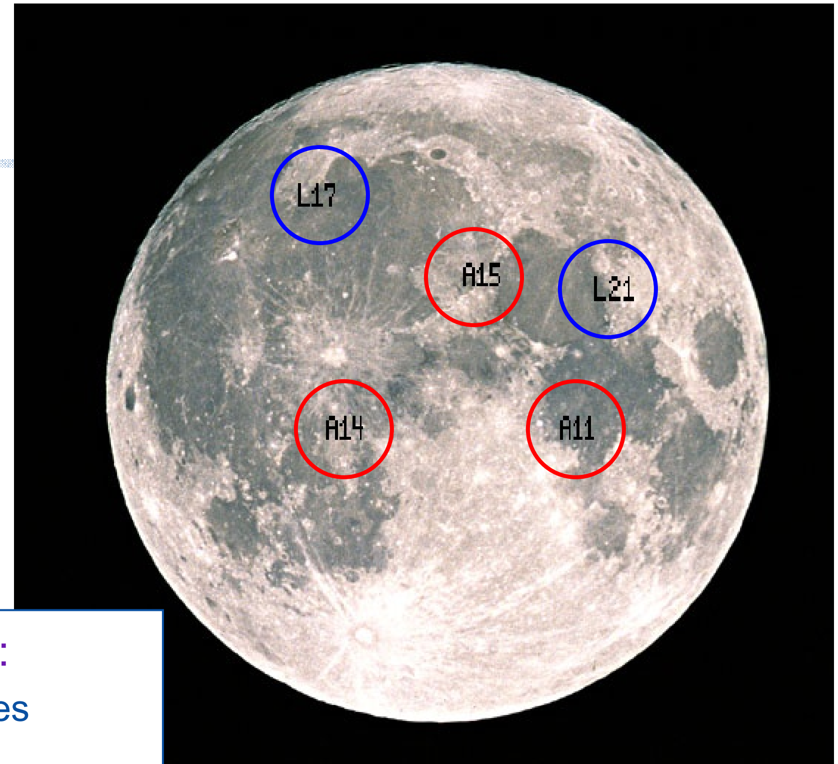
We need a dedicated mission to explore accuracies better then 10^{-6} for both PPN parameters γ (and β). Optical and atom technologies show great promise.

LUNAR LASER RANGING SCEINCE

Lunar Laser Ranging

It is all begun 37 year ago…

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



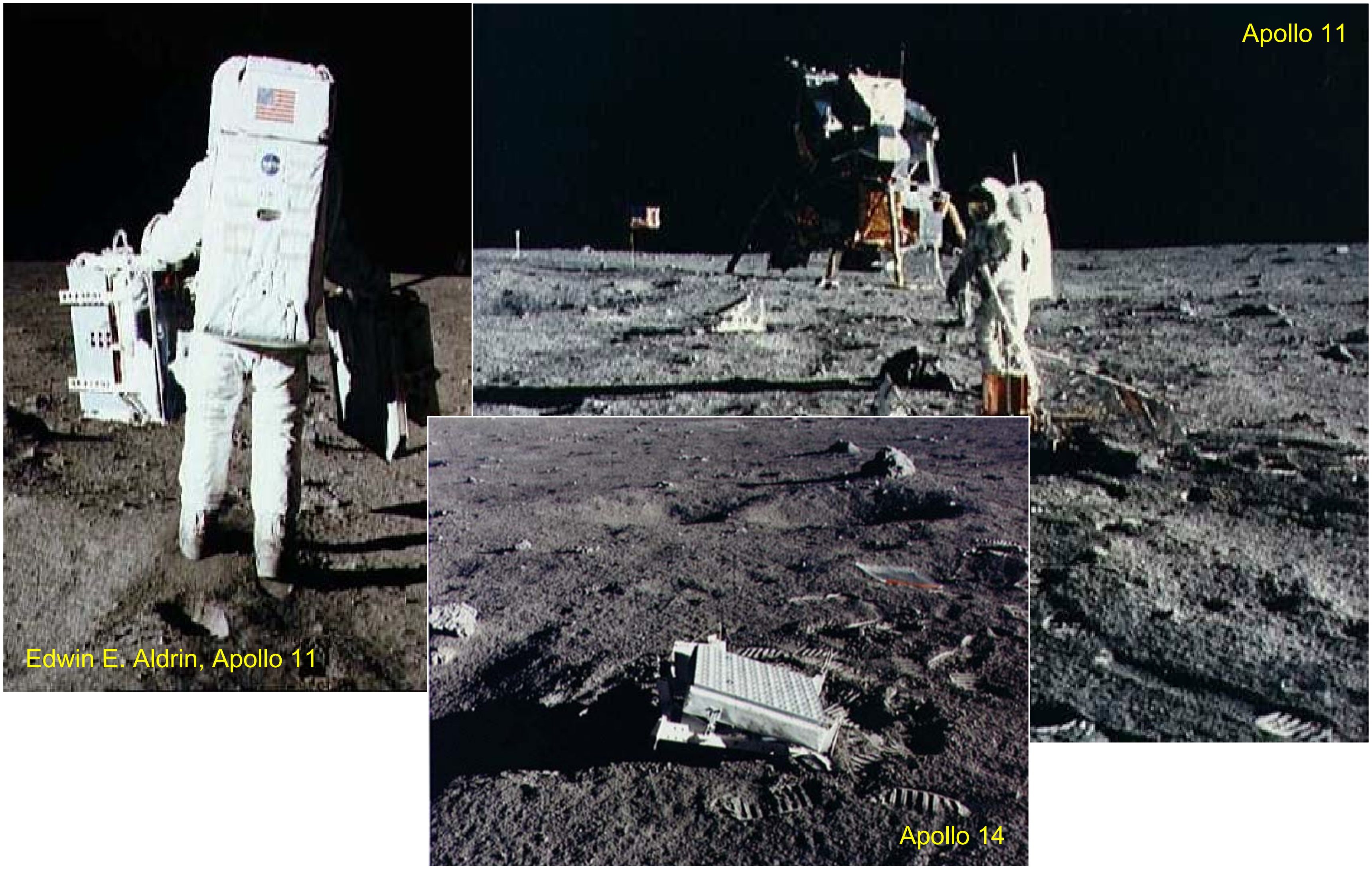
- 4 reflectors are ranged:
  - Apollo 11, 14 & 15 sites
  - Lunakhod 2 Rover

- 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



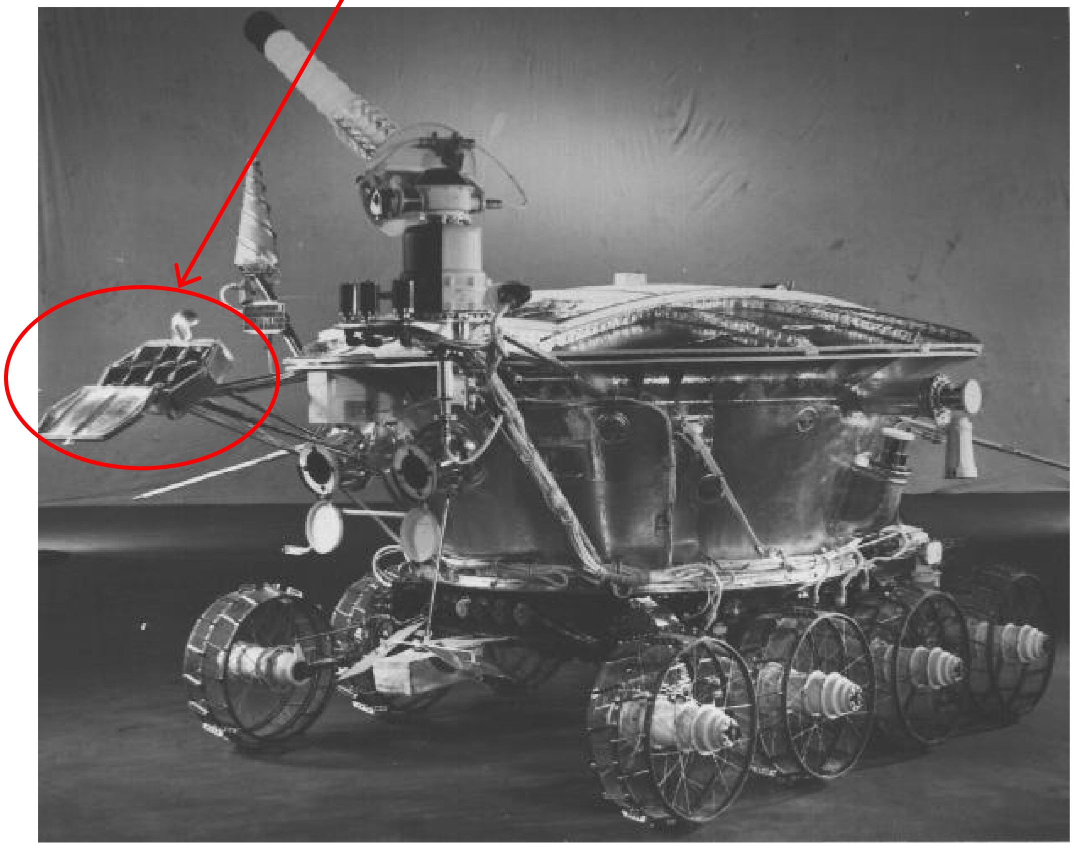
Edwin E. Aldrin, Apollo 11

Apollo 11

Apollo 14

Lunar Retroreflectors

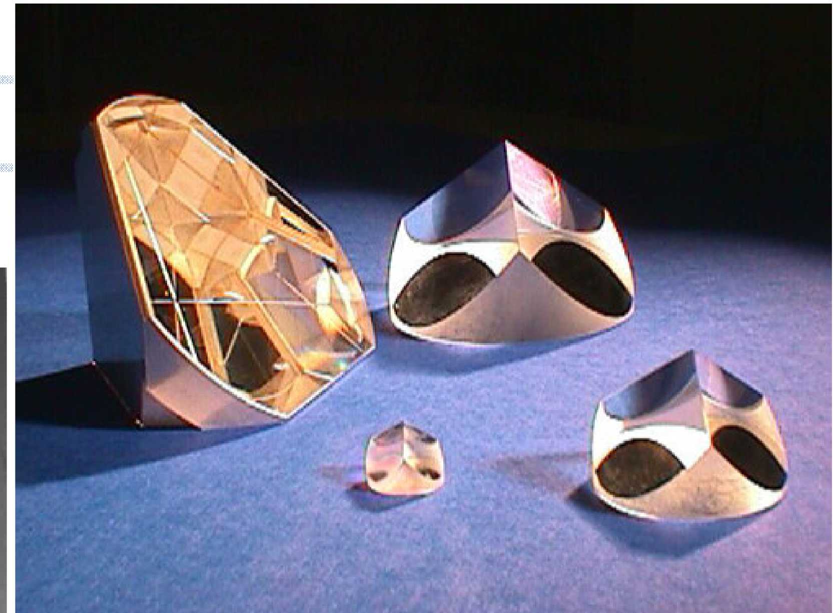
French-built retroreflector array

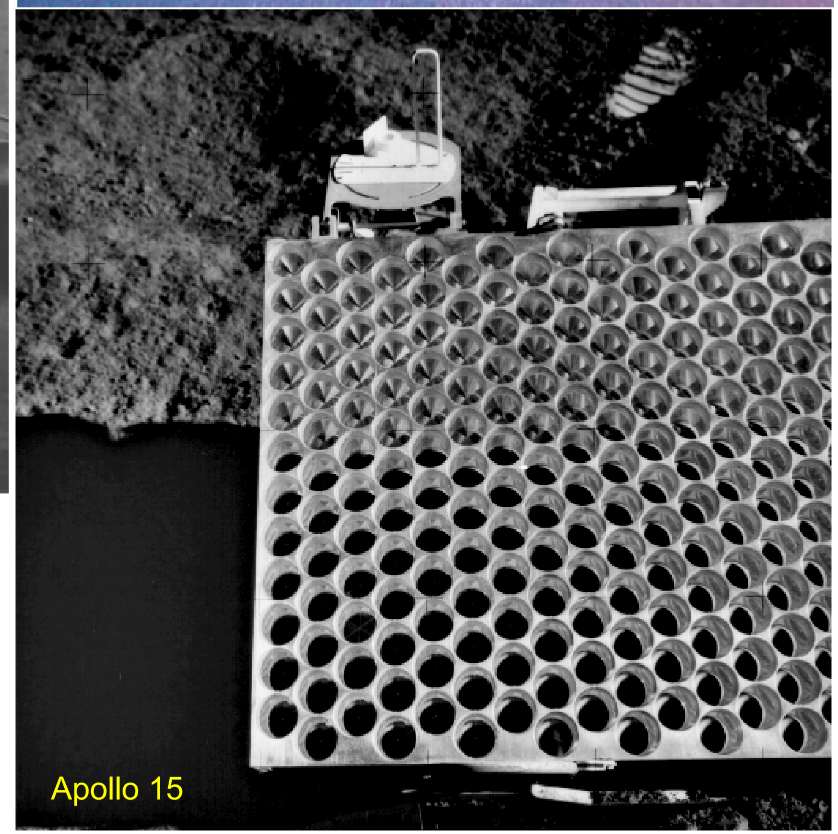


Lunokhod Rover (USSR, 1972)

Beginning of the laser ranging technology.
Today, laser ranging has many applications:

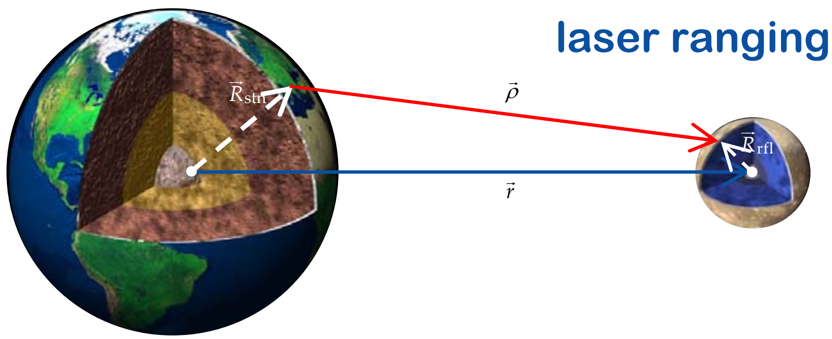
- Satellite laser ranging, communication systems, metrology, 3-D scanning, altimetry, etc.

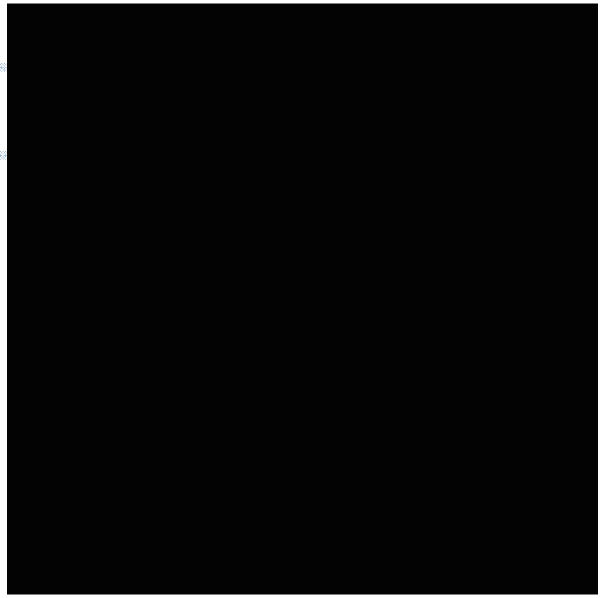




Historical Accuracy of LLR

Schematics of the lunar laser ranging experiment

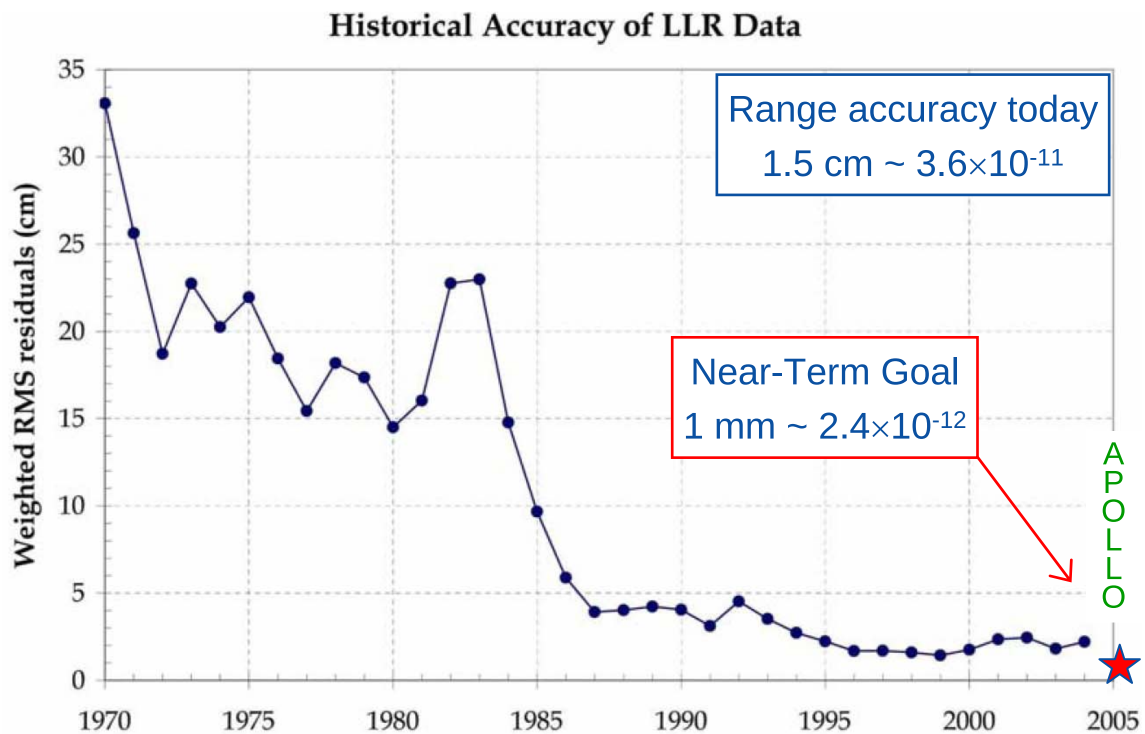




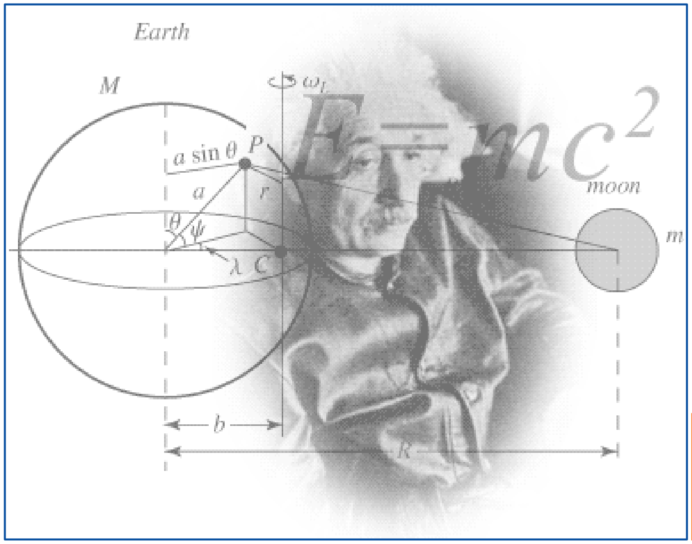
- Raw ranges vary by ~1,000s km
- Present range accuracy ~1.5cm

Solution parameters include:

- Dissipation: tidal and solid / fluid core mantle boundary (CMB);
- Dissipation related coefficients for rotation & orientation terms;
- Love numbers k_2, h_2, l_2;
- Correction to tilt of equator to the ecliptic – approximates influence of CMB flattening;
- Number of relativity parameters.



Testing General Relativity with LLR



The EEP violation effect in PPN formalism:

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

$$\frac{\Delta a}{a} = \eta\cdot\left(\frac{U_e}{M_e c^2}-\frac{U_m}{M_m c^2}\right) = -\eta\cdot 4.45\times10^{-10}, \qquad \eta \equiv 4\beta-\gamma-3.$$

If η =1, this would produce a 13 m displacement of lunar orbit. By 2006, range accuracy is ~1.5 cm, the effect was not seen.

Recent LLR results (September 2006):

16,250 normal points through Jan 11, 2006, including 3 days of APOLLO data (2005)

$$\Delta\left(\frac{M_G}{M_I}\right) = (-0.8\pm1.3)\times10^{-13}$$ – corrected for solar radiation pressure.

$$\boxed{\frac{\Delta a}{a} = (-1.8\pm1.9)\times10^{-13}}$$ – Strong Equivalence Principle $\eta = 4\beta-\gamma-3 = (4.0\pm4.3)\times10^{-4}$

Using Cassini '03 result $\gamma-1 = (2.1\pm2.3)\times10^{-5} \;\Rightarrow\; \beta-1 = (1.0\pm1.1)\times10^{-4}$

$$\boxed{\dot{G}/G = (6\pm7)\times10^{-13}\ \ \mathrm{yr}^{-1}}$$ Geodetic precession $K_{gp} = -0.0005\pm0.0047$

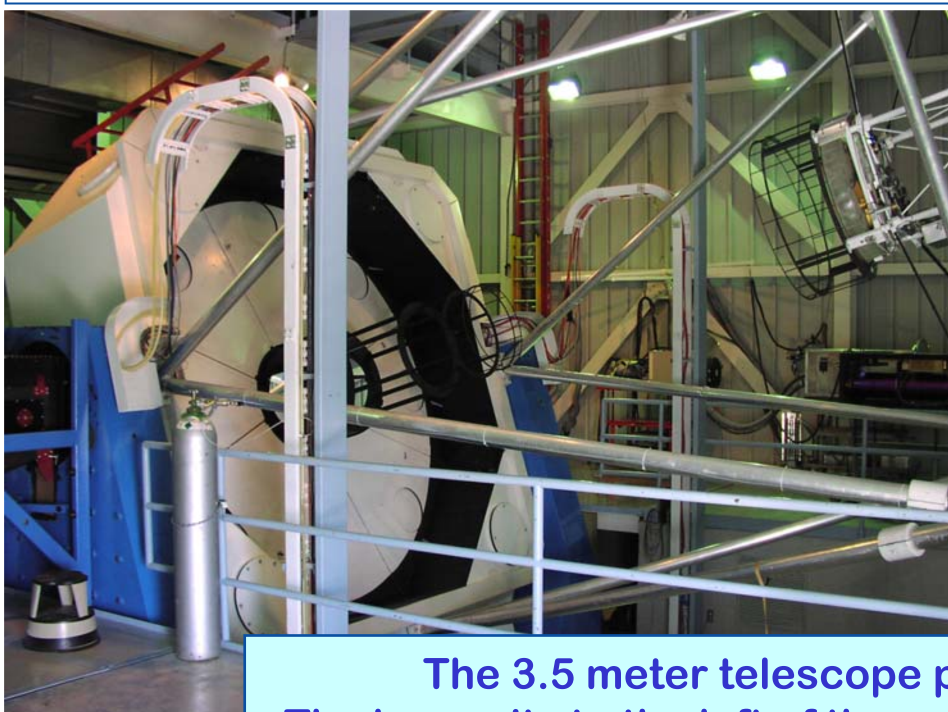
$1/r^2$ force law: 10^{-10} times force of gravity; Gravitomagnetism (frame-dragging): 0.1%

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

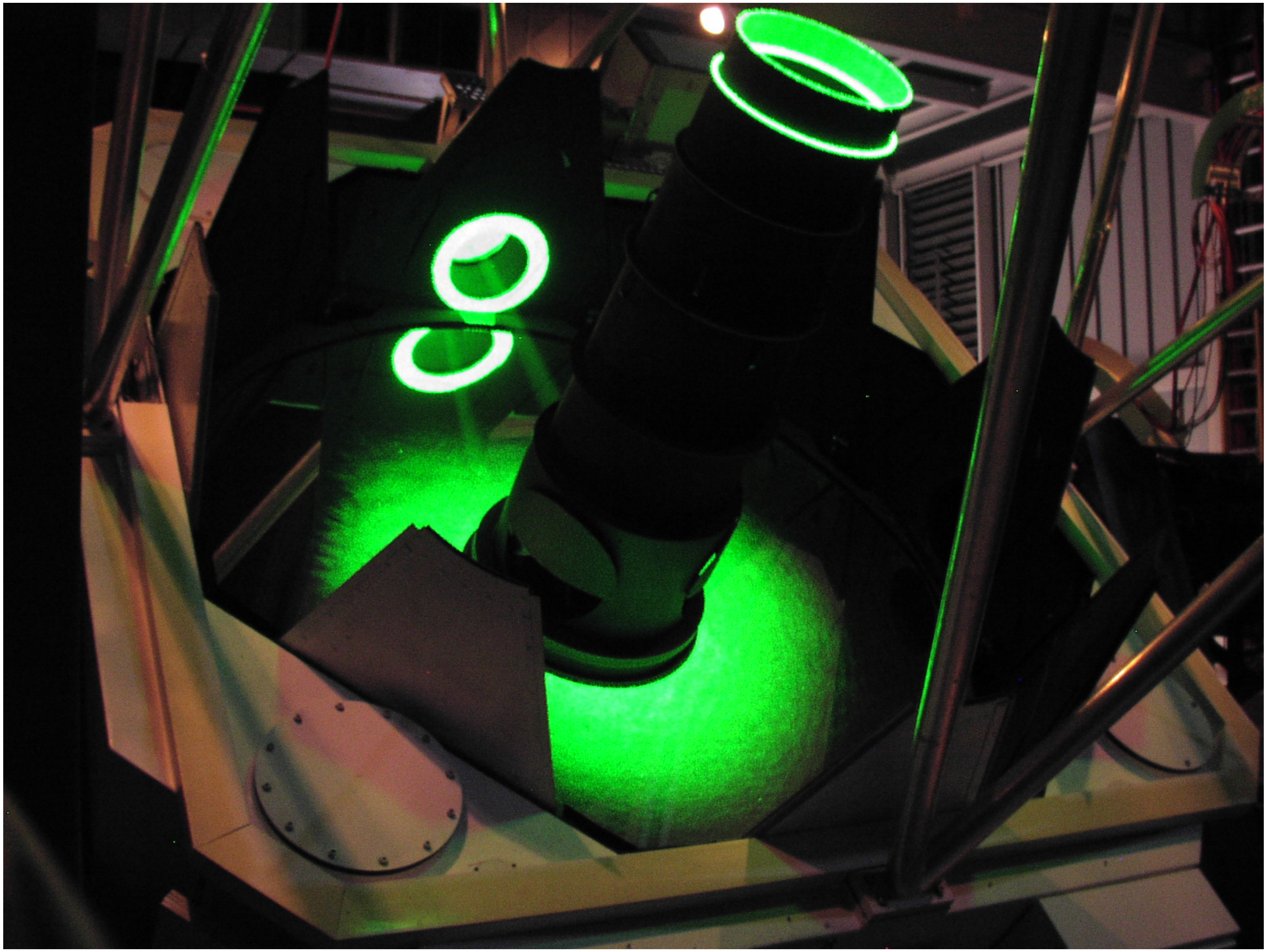
- Uses 3.5-meter telescope at 9200-ft Apache Point, NM
- Excellent atmospheric "seeing": 1as
- 532 nm Nd:YAG, 100 ps, 115 mJ/pulse, 20 Hz laser
- Integrated avalanche photodiode (APD) arrays
- Multi-photon & daylight/full-moon



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

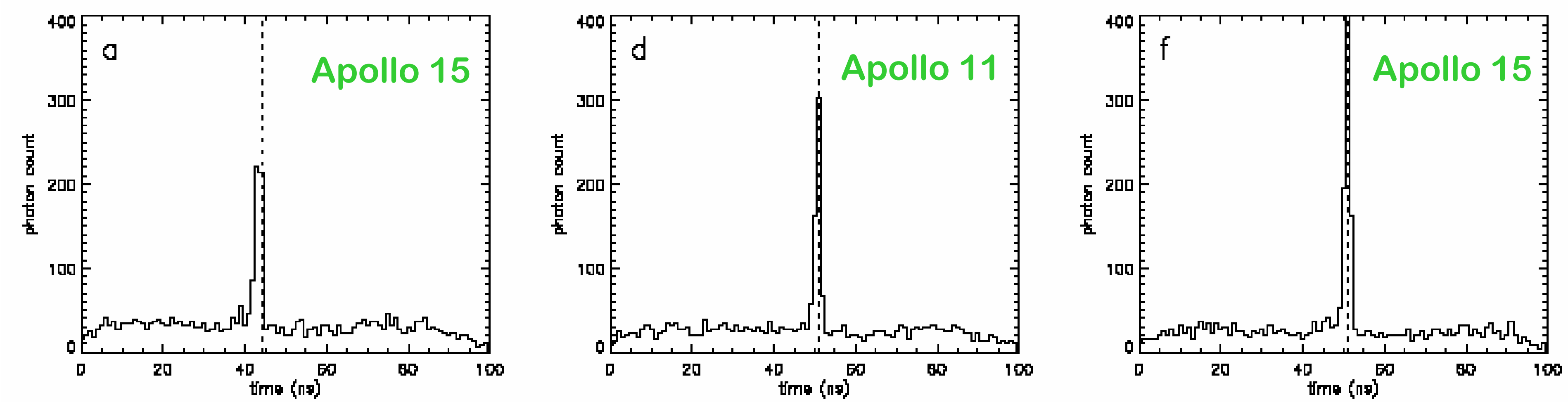
First Light: July 24, 2005



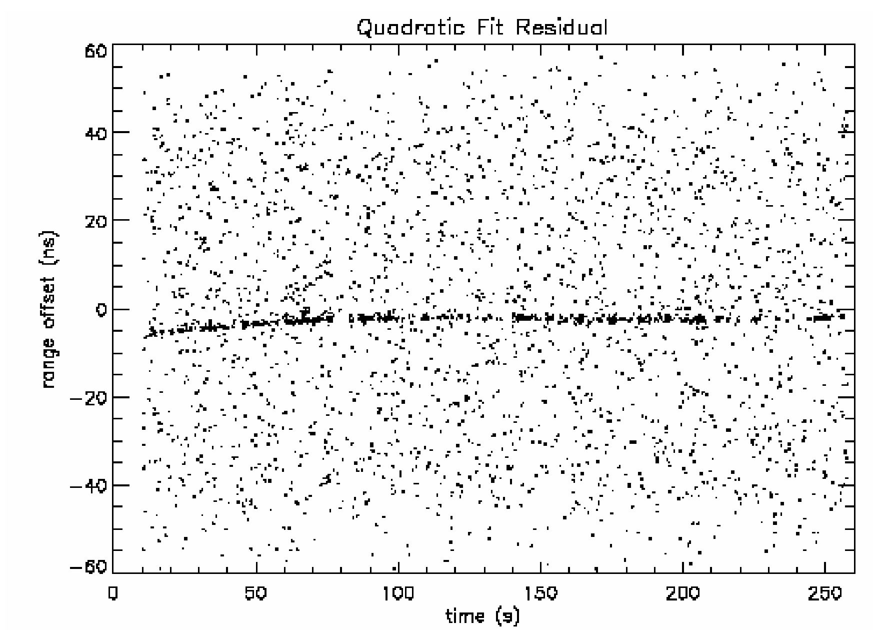
First Light: July 24, 2005

Blasting the Moon

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.

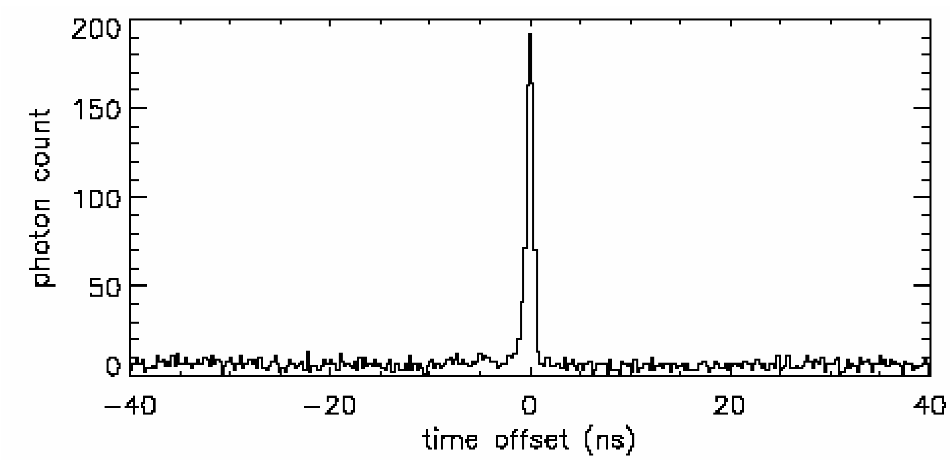


Error Source	Round-Trip Time Uncertainty, [ps]	One-Way Range Error, [mm]
Retro Array Orientation	100–300	15–45
APD Illumination	60	9
APD Intrinsic	<50	< 7
Laser Pulse Width	45	6.5
Timing Electronics	20	3
GPS-slaved Clock	7	1
Total Random Uncert.	136–314	20–47

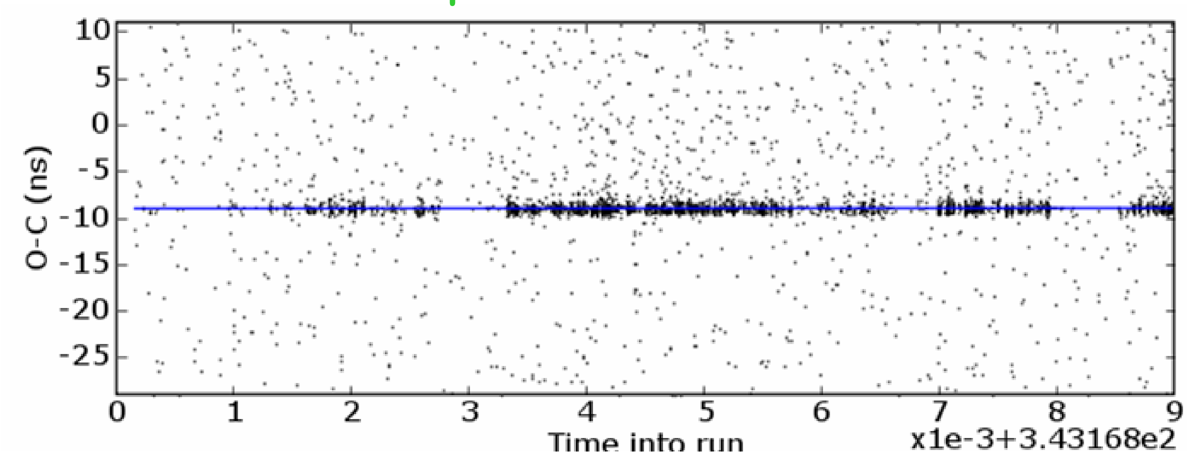
Single-photon random error budget

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

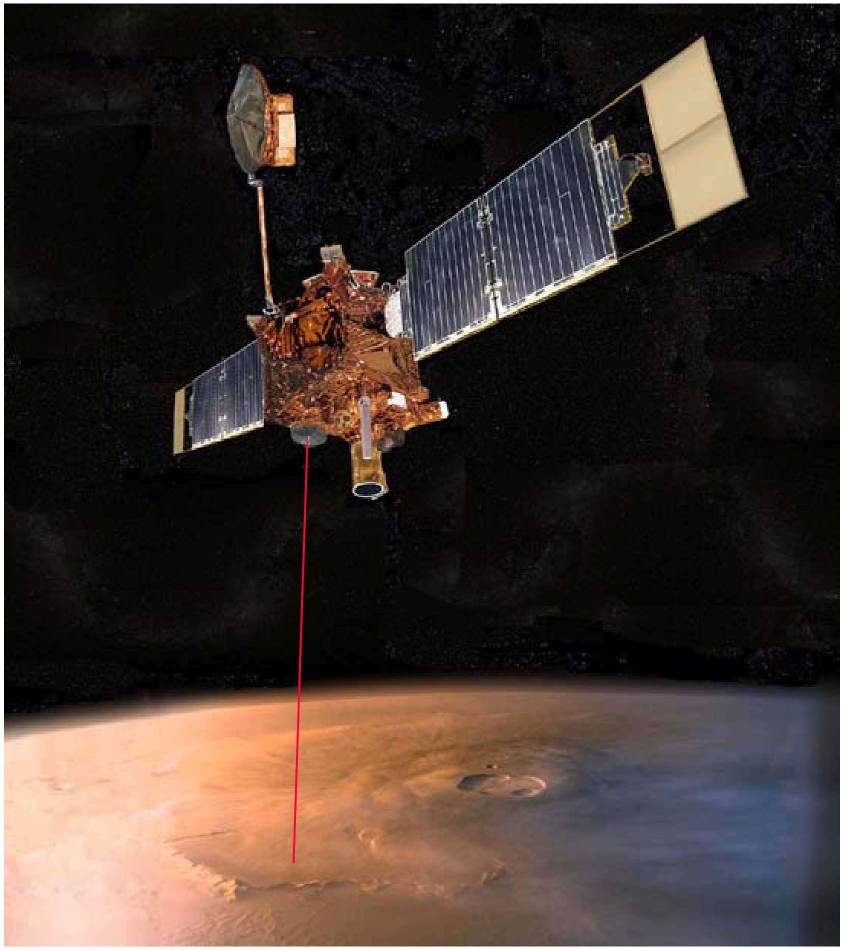
Pulsed Lidar Space Missions: History

Mission	Launch	Objective	Performance
– Apollo 15, 16, 17	1971-2	Ranging, Moon	Success
– 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	Cost/Schedule Slips [Son of GLAS]
– Calipso	2006	Profiling	Launch delayed [Boeing strike]
– *T2L2/Jason 2*	*2007*	*TT, Altimeter, Ranging*	*Healthy program (CNES)*
– *ADM*	*2007*	*Wind Demo.*	*Was 2006 (ESA)*
– LOLA/LRO	2008	Altimeter, Moon	
– MLCD/MTO	2009	Lasercomm	Cancelled
– Mars Smart Lander	2009	Ranging, Mars	
– *BepiColombo*	*2011*	*Altimeter, Ranging*	*Being Decided (ESA)*

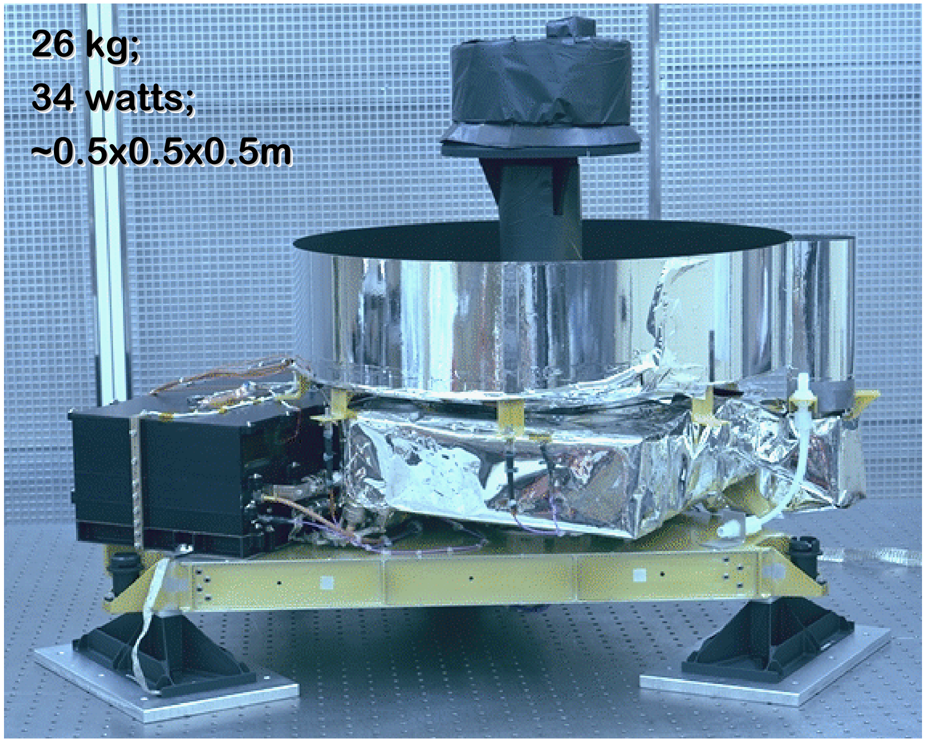
*

***Since 1990, NASA, launched & no reported problems, free-flyer: 1/8**

Mars Orbiter Laser Altimeter (MOLA)

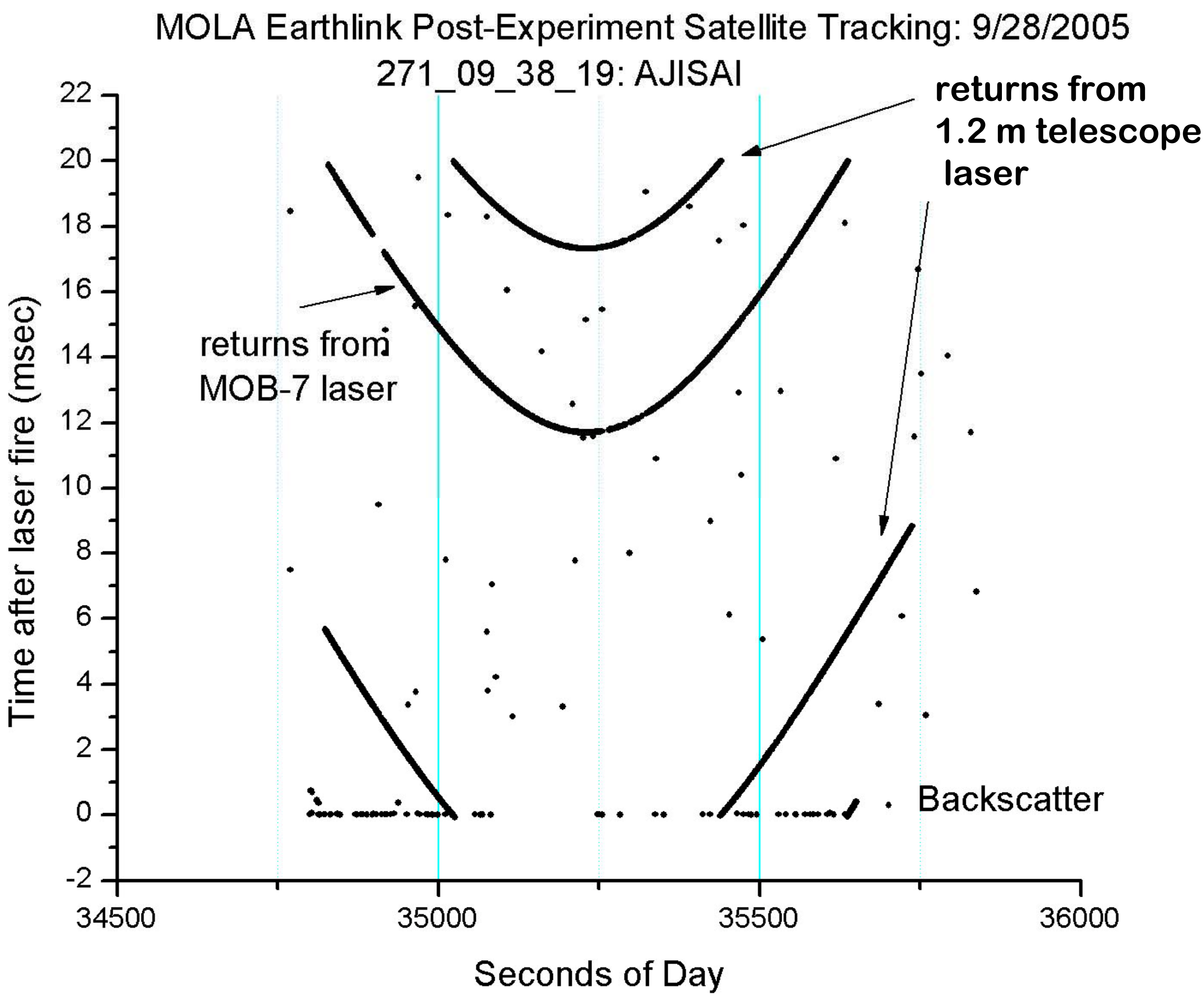


Lunch: Nov. 7, 1996.
Currently in circular orbits around Mars at 400km altitude and 2 hour orbit period.



- 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: ~ 0.1fJ/pulse at >90% detection probability.

MOLA-Earthlink Experiment



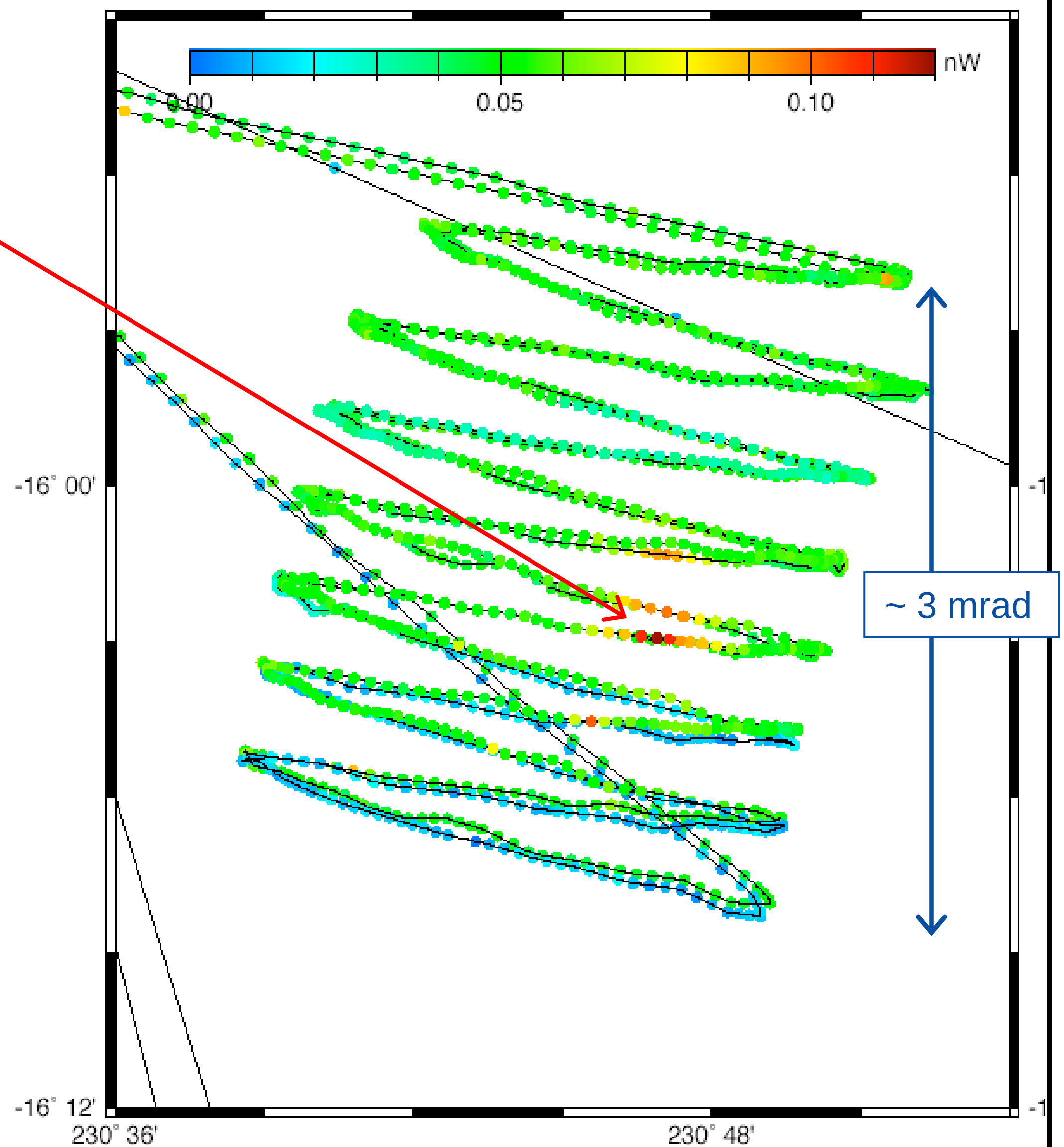
MOLA Earth Scan (2005)

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

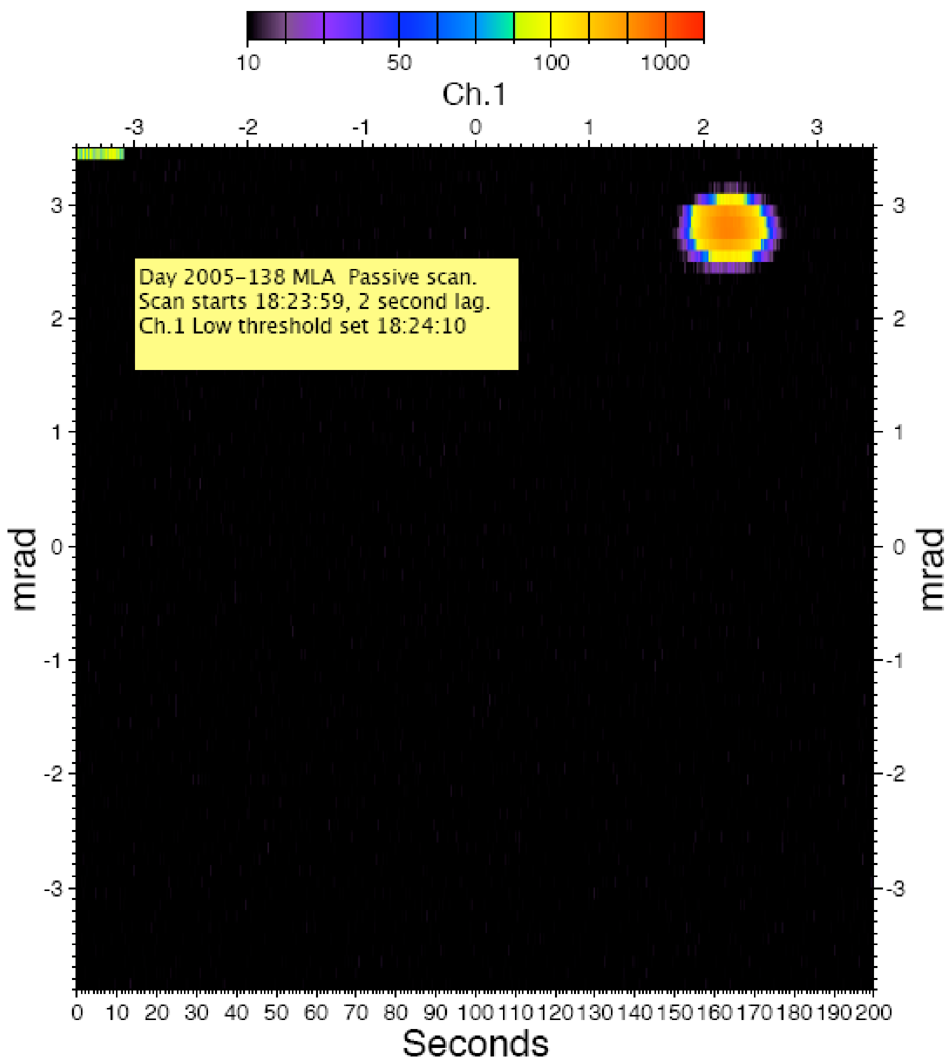
Each day's experiment consisted of two back-to-back scans.

Scans were very repeatable.

- Performed on 3 scheduled dates with spacecraft (9/21, 9/24, 9/28): at ~ 08:00 UTC.
- Each tested lasted ~ 45 min and 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.



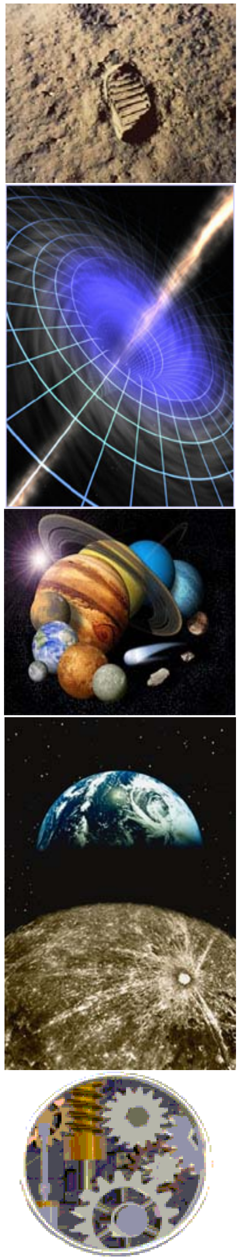
MLA-Earthlink Experiment Results:



- 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 and verified spacecraft pointing.
- MLA laser pulses were detected at the ground. MLA also detected laser pulses from ground laser.

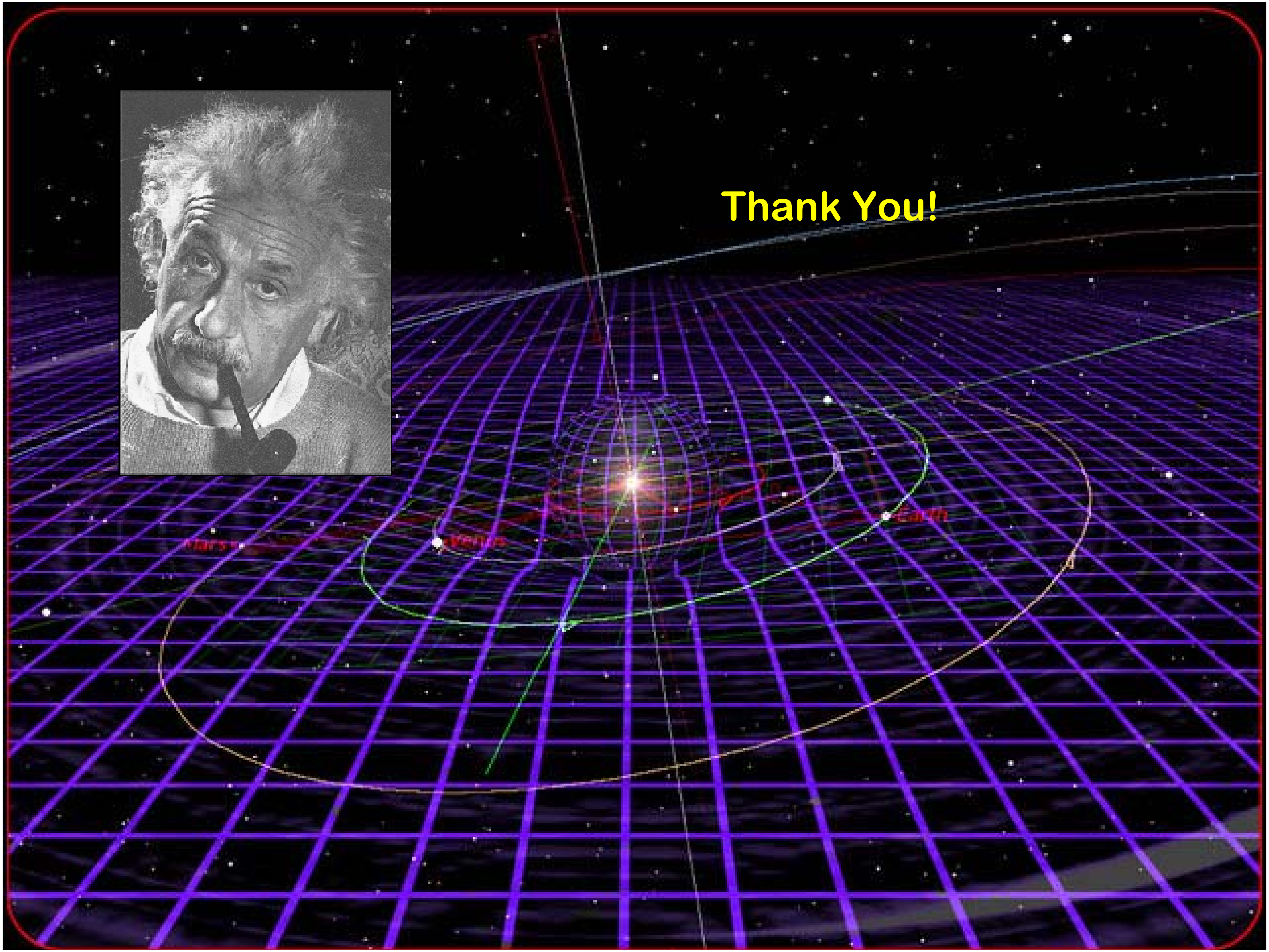
First successful 2-way lasercomm at interplanetary distances 24 mln km (acc ± 12 cm).

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)


Thank You!
Mars
Venus
Earth