Lunar Laser Ranging Science

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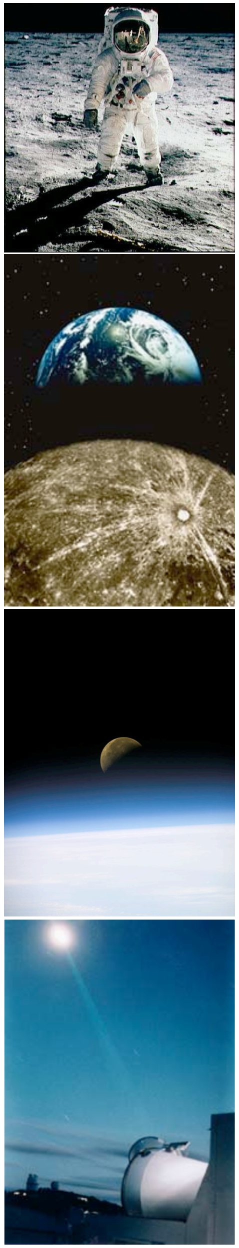
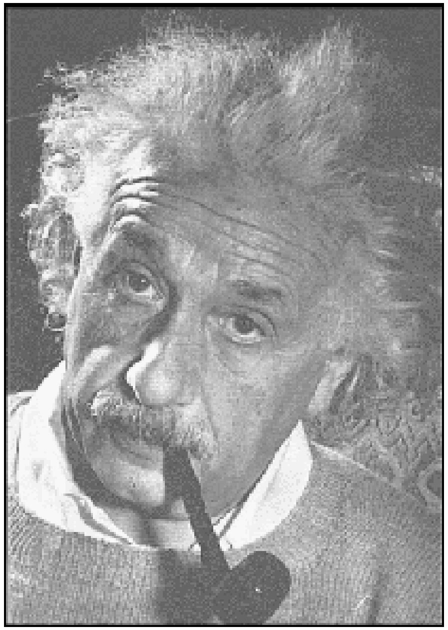
The Purpose:



Lunar Laser Ranging Technology in 21st century:
Optical Infrastructure in Space to Enable Exploration

Talk will cover:

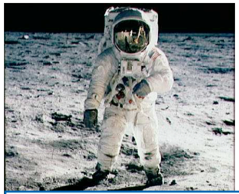
- LLR today:
  - History & Current State
- LLR Science:
  - Science from the Orbit
  - Lunar Science
  - Earth Science
  - LLR Future



Take-Away Message:

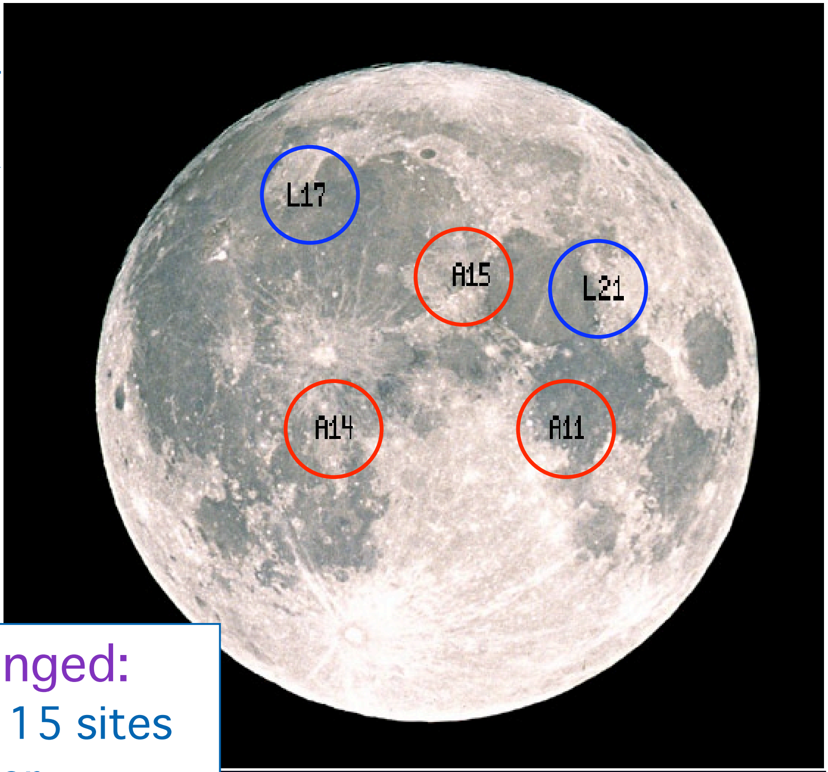
LLR is one of the best tools for comprehensive gravity tests.
LLR enables robust advances in lunar science & Fundamental physics.
LLR is about to go through a renaissance with APOLLO.

Lunar Laser Ranging



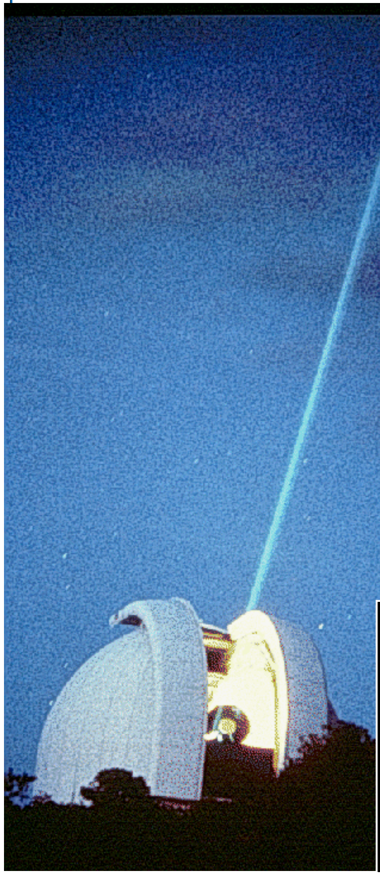
It all started 35 year ago…

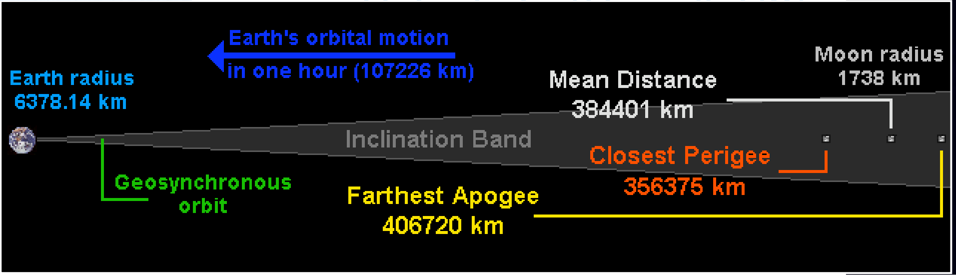
Laser Ranges between observatories on the Earth and retroreflectors on the Moon started by Apollo in 1969 and continue to

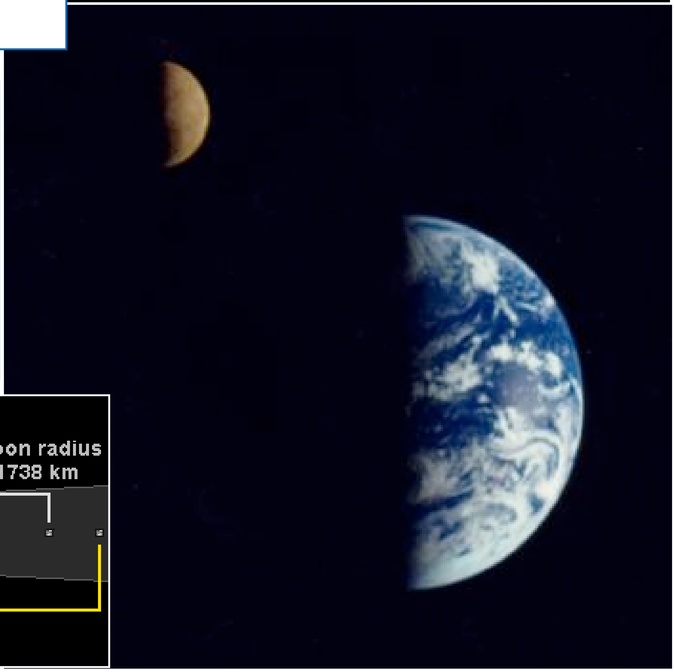


- 4 reflectors are ranged:
  - Apollo 11, 14 & 15 sites
  - Lunakhod 2 Rover

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

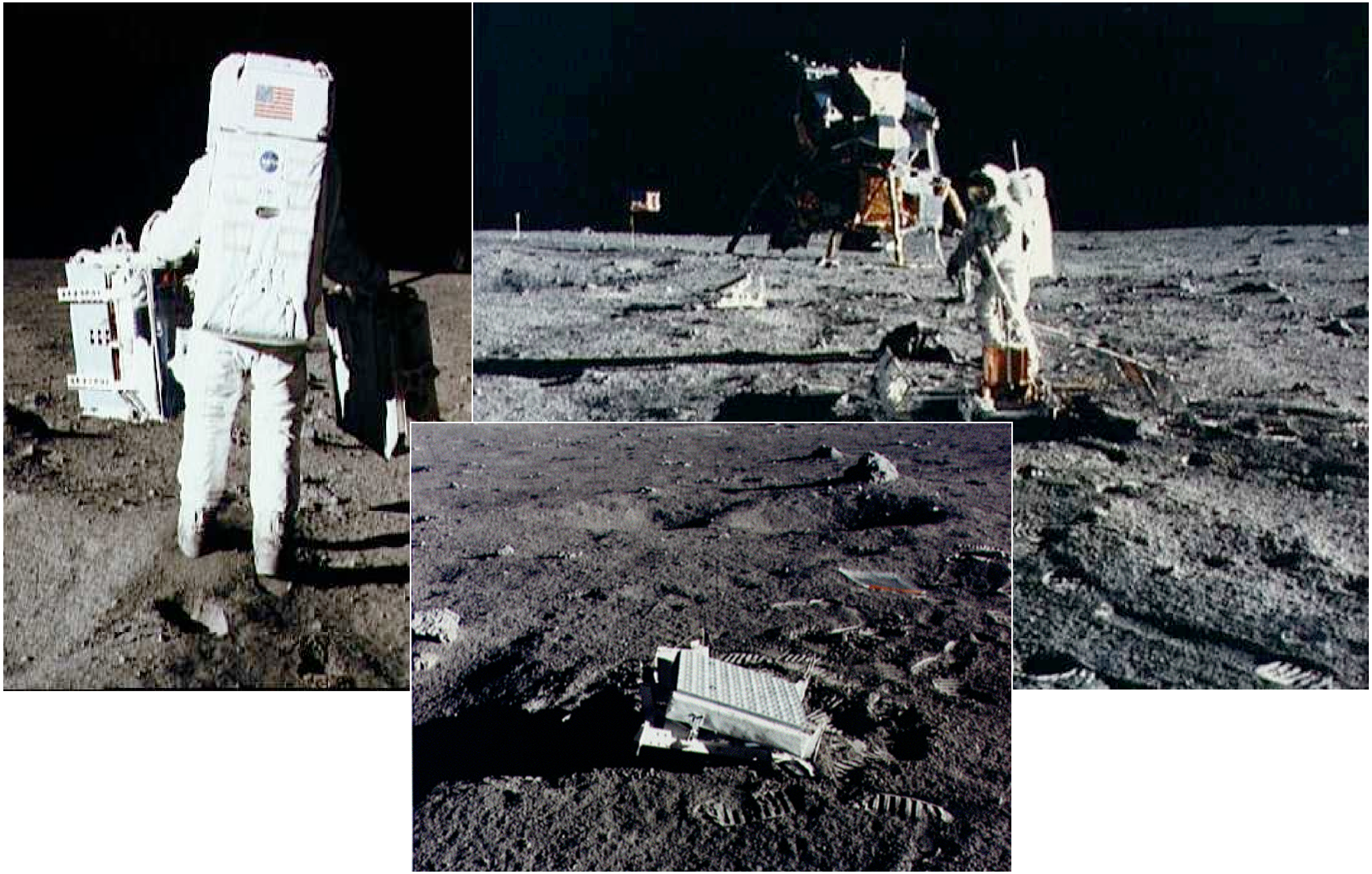






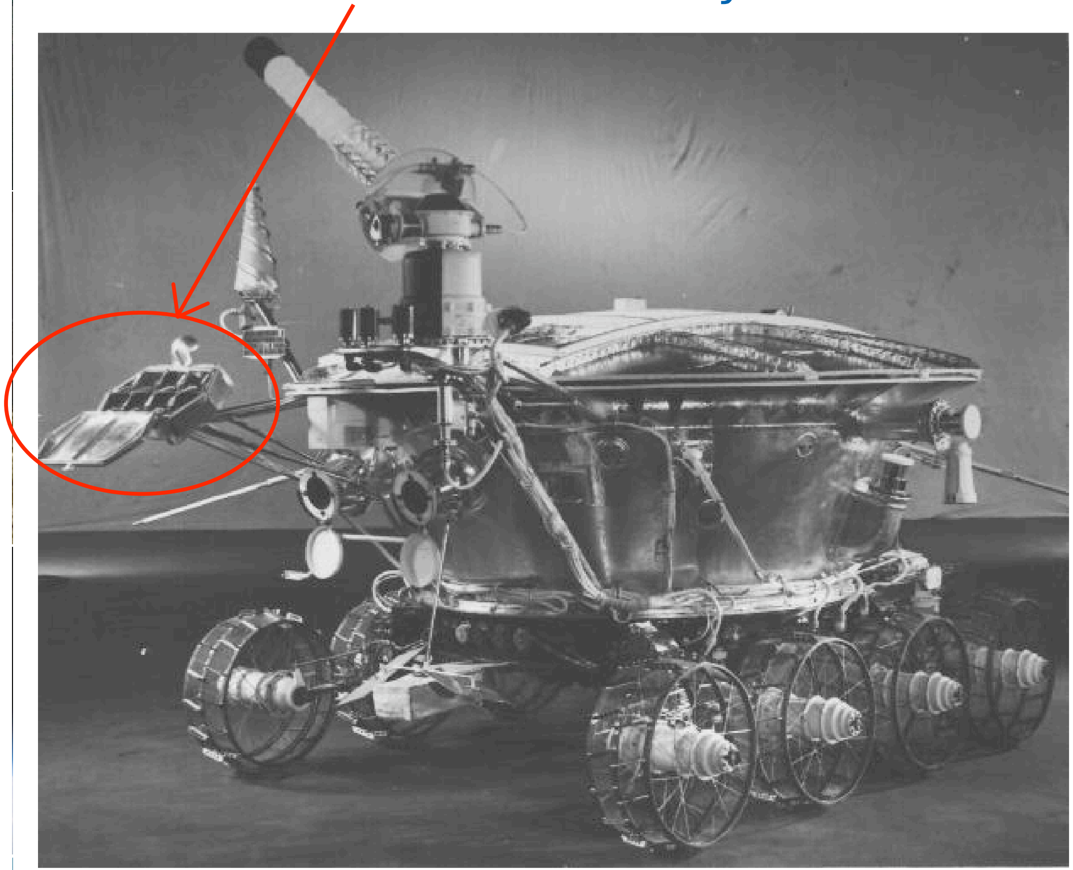
Excellent Legacy of the Apollo Program

Today LLR is the **only** continuing experiment since the Apollo-Era

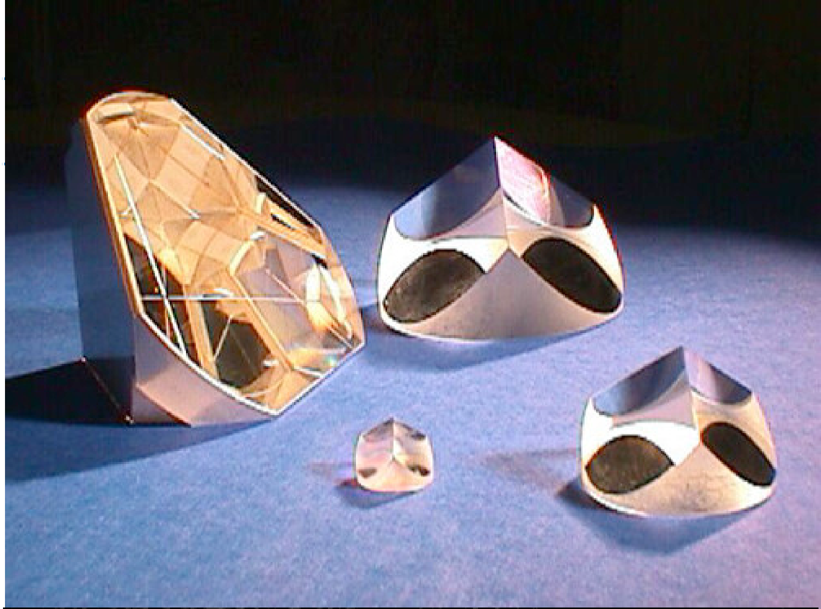


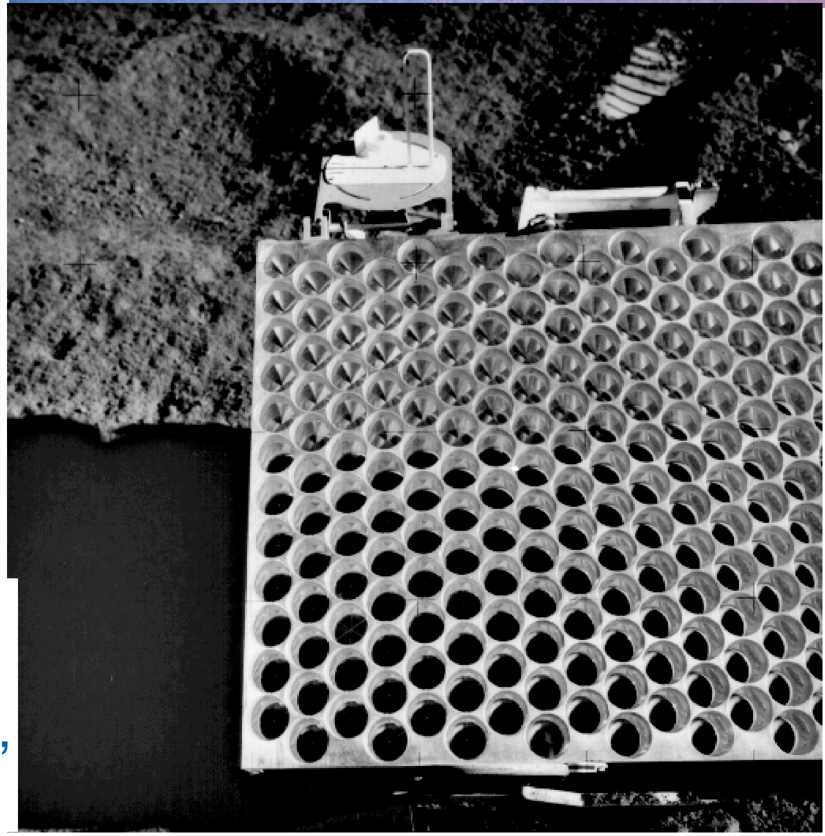
Lunar Retroreflectors

French Retroreflector array



Lunakhod Rover (USSR, 1972)



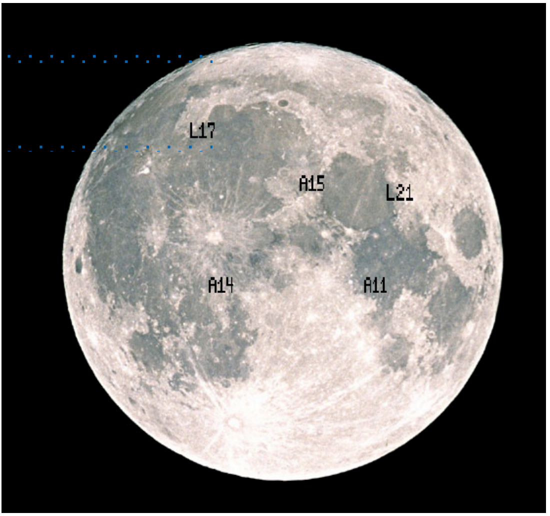


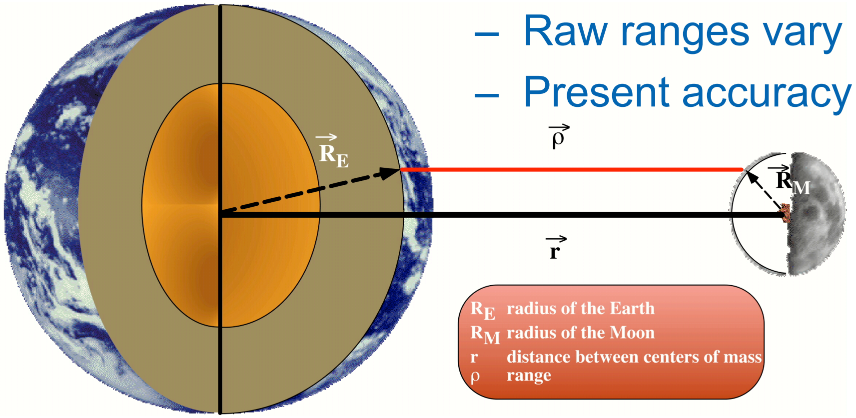
Beginning of the laser ranging technology.
Today, laser ranging has many applications:

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

Historical Accuracy of LLR

- Raw ranges vary by several ~1000s km
- Present accuracy down to ~1.5cm level



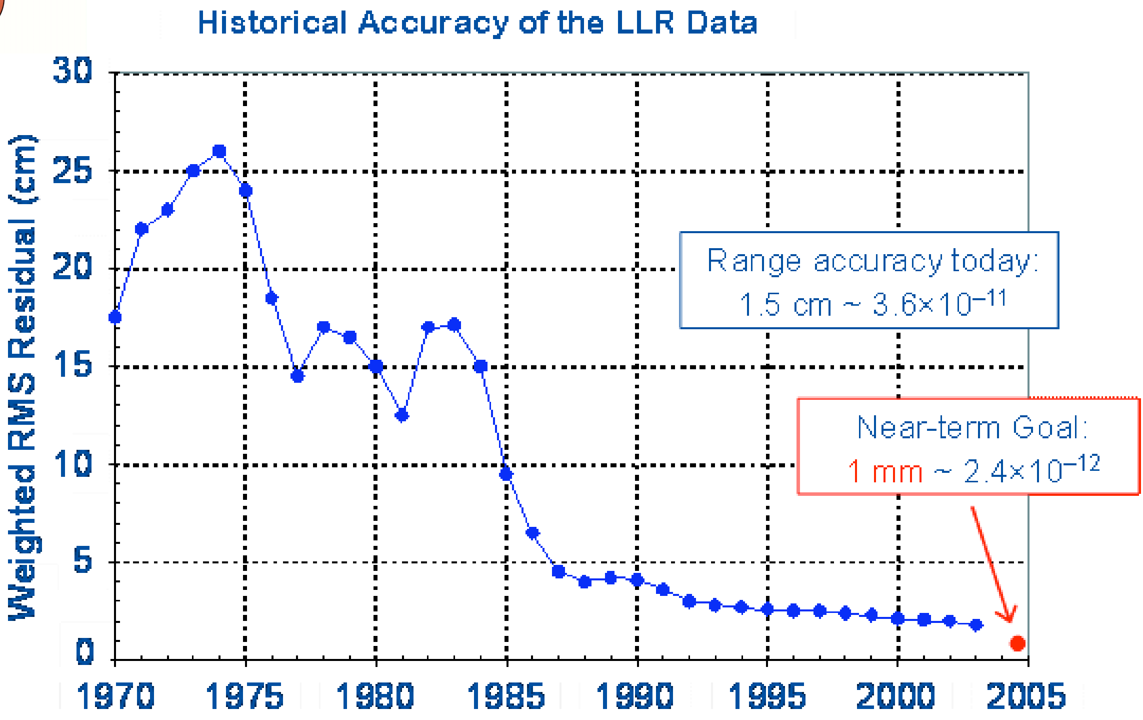


R_E radius of the Earth
R_M radius of the Moon
r distance between centers of mass
ρ range

Lunar laser ranging schematics

Solution parameters include:

- Dissipation: tidal and solid / fluid core 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;
- Relativity parameters.

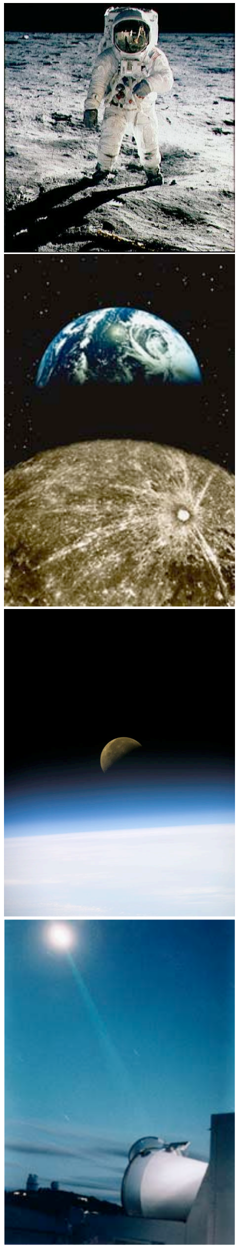


Range accuracy today:
1.5 cm ~ 3.6×10^{-11}

Near-term Goal:
1 mm ~ 2.4×10^{-12}

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

Science from the Orbit



- Lunar ephemerides are a product of the LLR analysis used by current and future spacecraft missions.
- The analysis is sensitive to astronomical parameters such as orbit and mass.
- The 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 (used for an accurate determination of the PPN parameter □),
  - limits on the time variation of the gravitational constant G, and
  - geodetic precession.

Earth Science:

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

35 Years of Relativistic Gravity Tests

Techniques for Gravity Tests:

Radar Ranging:
- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Cassini, MGS, MO accuracy ~few meters
- VLBI, GPS, etc.

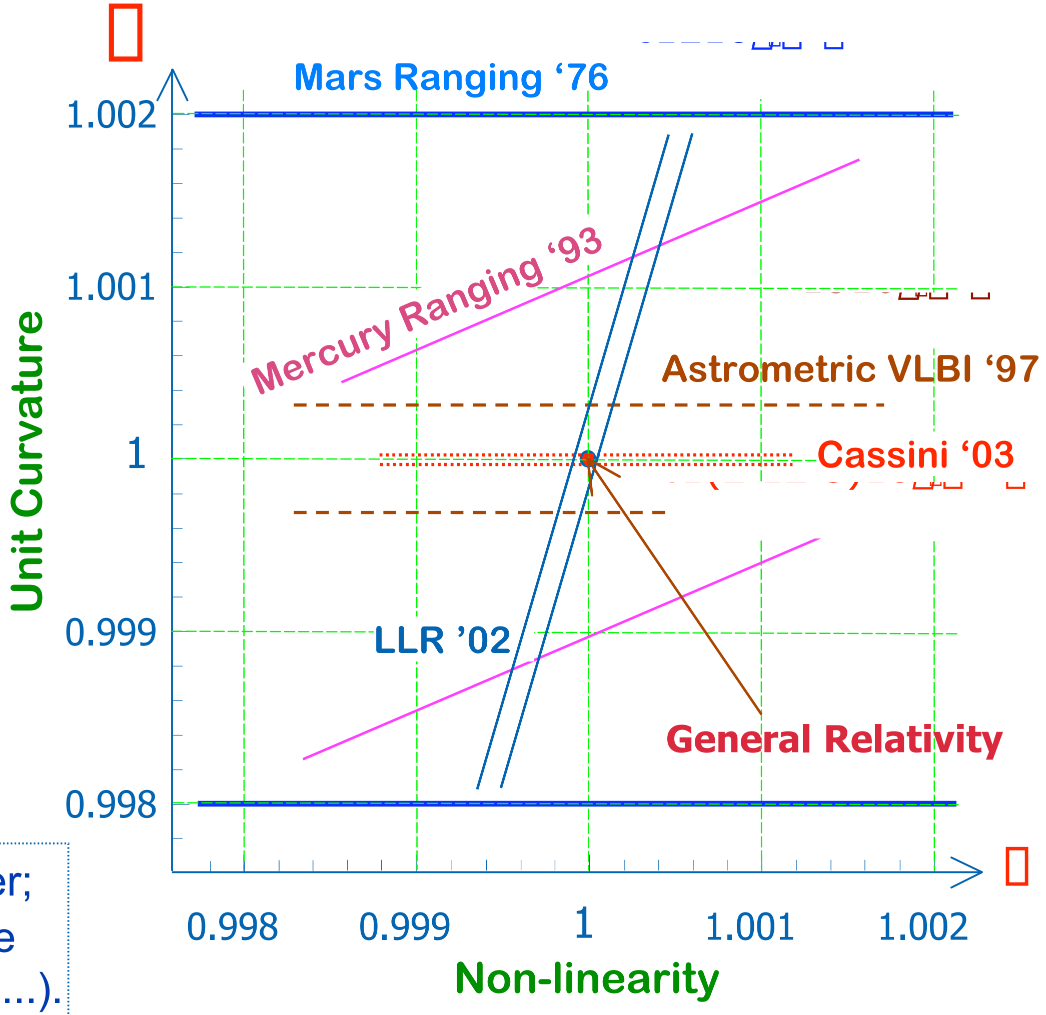
Laser:
- LLR, SLR, etc.

Designated Gravity Missions:

- **LLR (1969 - on-going!!)**
- GP-A, ’76; LAGEOS, ’76, ’92; GP-B, ’04; LISA, 2012

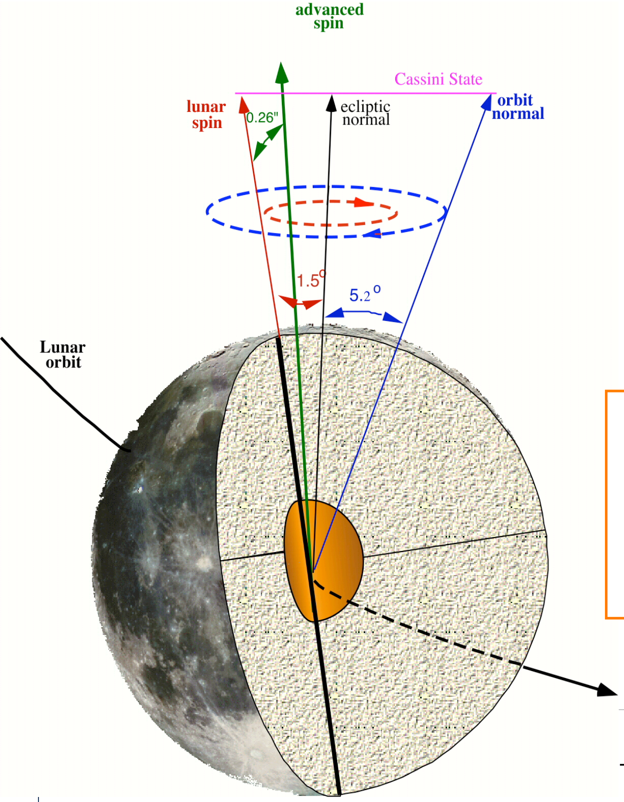
New Engineering Discipline – Applied General Relativity:

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



LLR contributed to a factor of 100 improvement in the gravity tests in 35 years

Relativity with LLR Today



In PPN formalism the EEP violation effect has the form:

If ▯=1, this would produce a 13 m displacement of lunar orbit.
By 2004, range accuracy is ~ 1.5 cm··· the effect was not seen.

Recent LLR results (April 2004):

– corrected for solar radiation pressure

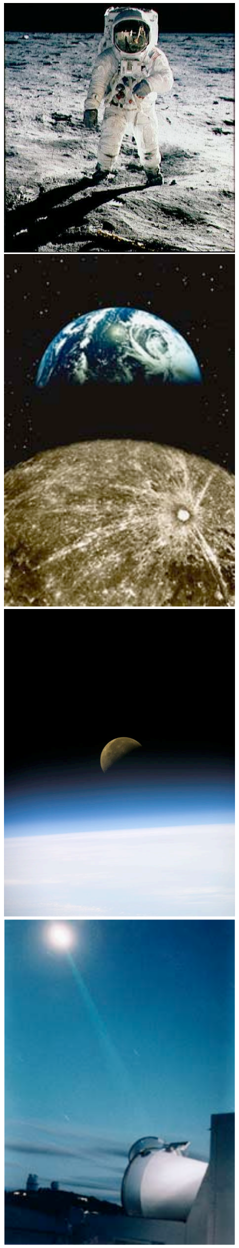
– Strong Equivalence Principle

Using Cassini '03 result

Geodetic precession

LLR advantage – new techniques and longer data span help to improve results

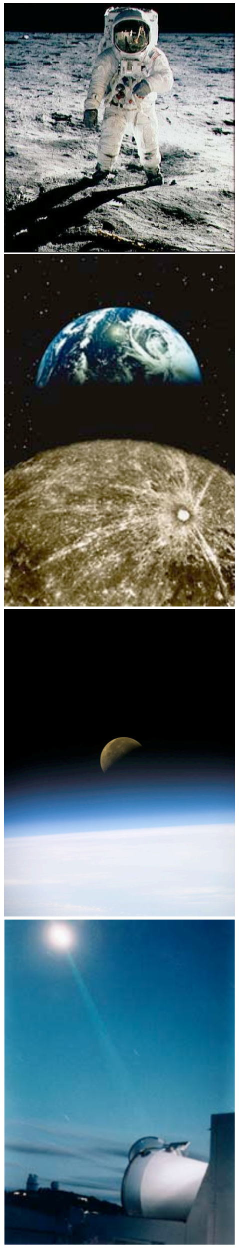
Lunar Science

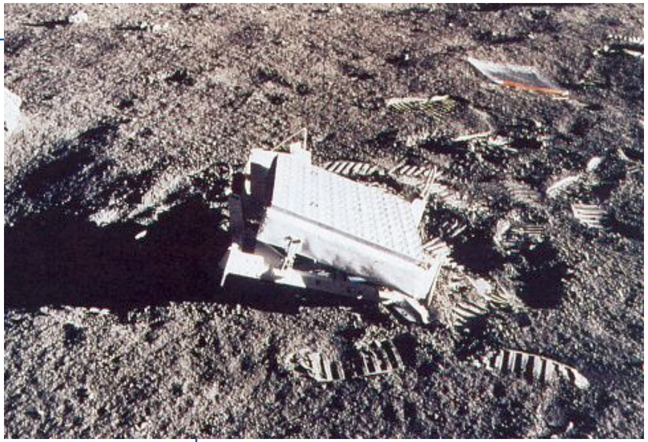


- LLR measurements are sensitive to:
  - Lunar rotation & orientation variations, tidal displacements
- Lunar rotation variations sensitive to:
  - Interior structure, physical properties and energy dissipation;
- Weaker sensitivity to:
  - Flattening of the CMB
  - Moment of inertia of the fluid core

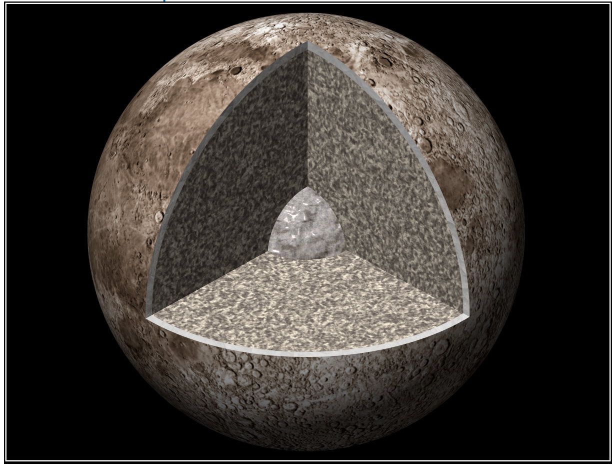
- The second-degree tidal lunar Love numbers are detected:
  - k_2 has an accuracy of 11%.
- Lunar tidal dissipation is strong:
  - Its Q has a weak dependence on tidal frequency;
  - A fluid core of ~20% the moon's radius is indicated by the dissipation data;
  - Evidence for the oblateness of the lunar 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.

Love Number Determinations





- Love number k_2 sensitive to:
  - Rotation and orientation
- Love numbers h_2 and l_2 sensitive to
  - Tidal displacement of retroreflectors
- LLR solutions
  - With l_2 fixed at 0.011
  - $k_2 = 0.0227 \pm 0.0025$ – a decrease from previous estimate due to core oblateness
  - $h_2 = 0.039 \pm 0.010$
- More Love Numbers from seismic velocities extrapolated down to core:
  - k_2 in the range 0.022-0.023
  - h_2 about 0.039
  - l_2 around 0.011
- Compatible spacecraft determination:
  - $k_2 = 0.026 \pm 0.003$
  - Larger than either LLR or elastic models but consistent within observational uncertainties



The Lunar Interior

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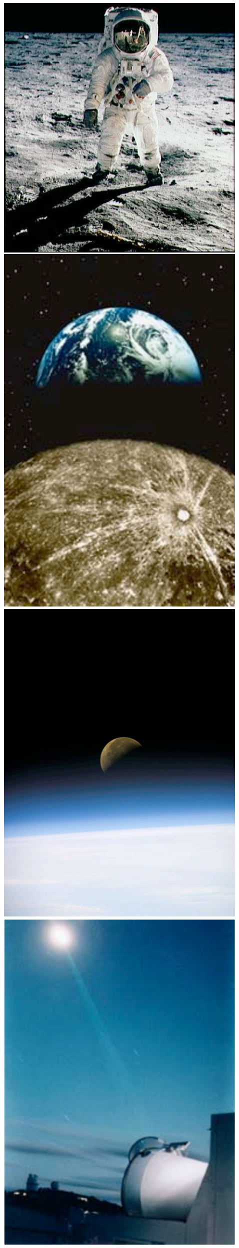
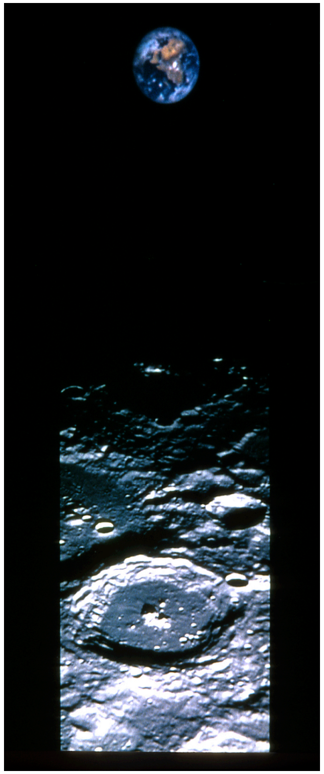
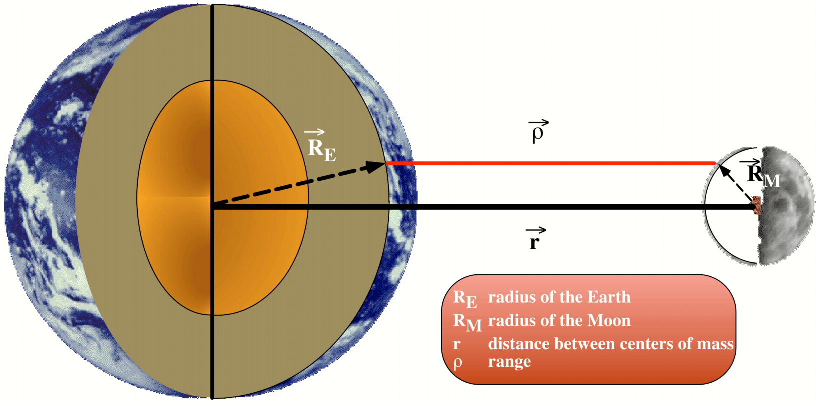
Dissipation: Fluid Core & Tides

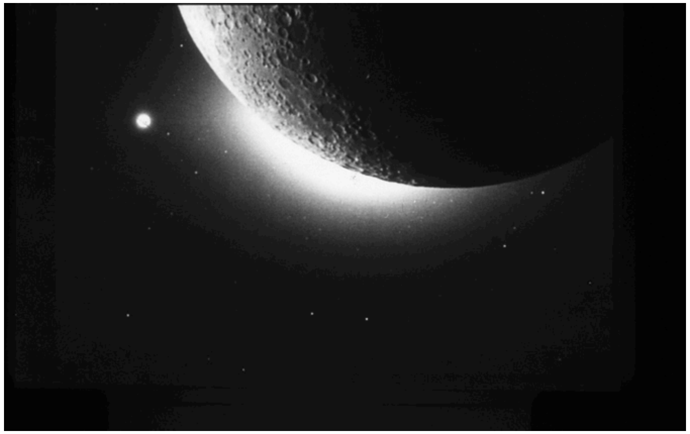


Analysis of dissipation coefficients shows the following:

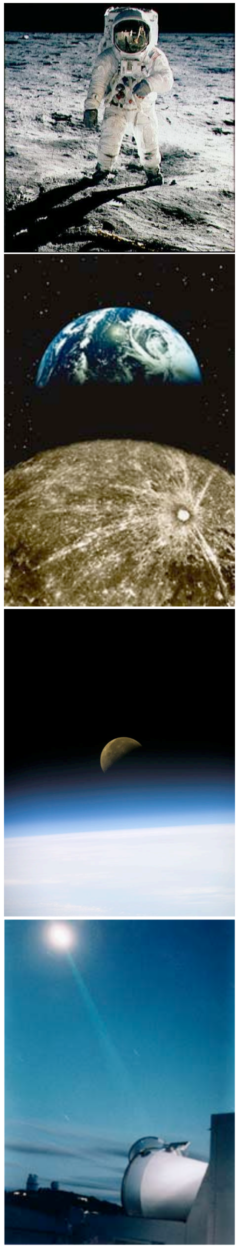
- Core component of dissipation stronger than earlier indications:
  - 41% of the largest dissipation term due to fluid core
- Tidal Q increases less with tidal period T, assuming the following parameterization $Q = Q_F(T / 27.212\ d)^{-w}$:
  - Thus for $k_2=0.0227$, $Q = 33\ (T / 27.212d)^{0.05}$
  - $Q_{monthly} = 33\ Q_{annual} = 38$
- Turbulent boundary layer theory implies fluid core
  - For pure $F_E(=7000\ kg\ m^{-3})$, $R_c=350$ km
  - CMB topography would decrease this value
  - Lower density would increase the value for R_c







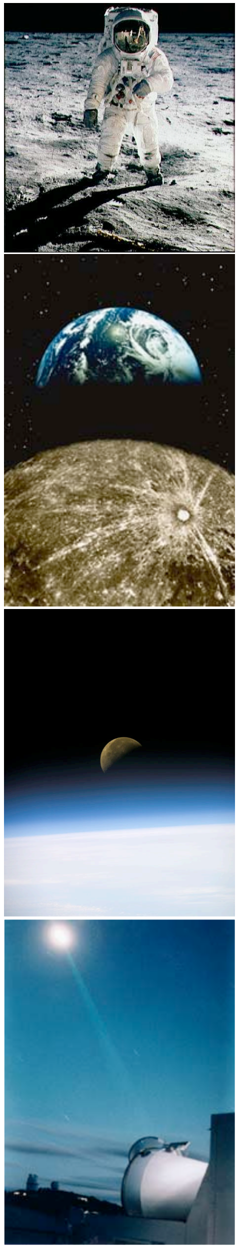
Core Oblateness



- To first approximation, CMB oblateness affects tilt of lunar equator to ecliptic plane.
- Solutions contain analytical tilt correction:
  - tilt correction solution value is 2 times its _
  - tilt parameter anti-correlates with k_2
    - larger CMB oblateness → smaller k_2

- Additional solution parameters that affect tilt
  - Moment differences, gravity harmonics, Love number k_2
- Tilt correction depends on fluid core moment & CMB flattening
  - for pure Fe fluid core with R_c = 350 km
    - $C_c/C_m = 7 \times 10^{-4}$ gives flattening of 3×10^{-4}
  - whole Moon dynamical flattening is
    - $(2C-A-B)/2C = 5.18 \times 10^{-4}$
  - surface geometrical flattening is 1.3×10^{-3}
- Detection of core oblateness would confirm presence of fluid core
- Considering size of the noise, core oblateness detections are regarded as tentative

Core Moment of Inertia



Analytical development represents a rotation term that is sensitive to the fluid core via moment of inertia; detection of this term would:

- confirm presence of fluid core;
- give a direct measurement of the moment of the fluid core.

This term is difficult to detect, however

- close in frequency to a free libration term;
- 81 year beat period.

Current solutions give:

- ratio of core to mantle moments of $C_c/C_m = (15 \pm 19) \times 10^{-4}$
- not a detection and larger than the limit inferred from dissipation

Inner Core:

A solid inner core may exist within the fluid core

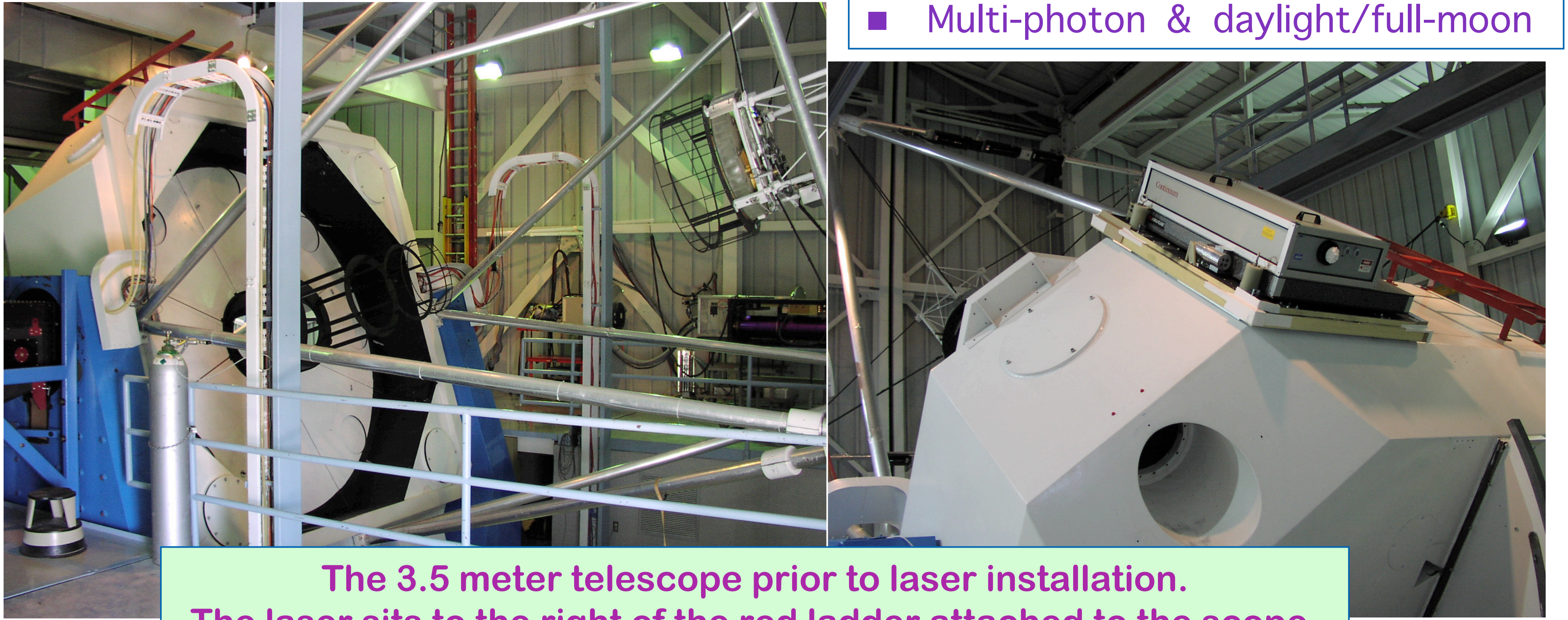
- Gravitational interactions between inner core & mantle might be detectable
  - inner core rotating independently
  - inner core gravitationally locked to mantle
- Inner core would complicate interpretation of LLR solutions, however
  - two surfaces for turbulent dissipation at solid/fluid interfaces
  - inner core not rotating w/ fluid core will affect core moment & flattening

The APOLLO Project & Apparatus:

Apache Point Observatory Lunar Laser-ranging Operation

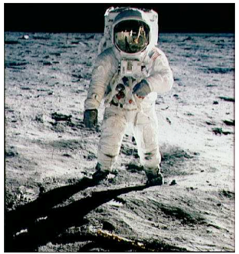
- Move LLR back to a large-aperture telescope
  - 3.5-meter: more photons!
- Incorporate modern technology
  - Detectors, precision timing, laser
- Re-couple data collection to analysis/science
  - Scientific enthusiasm drives progress

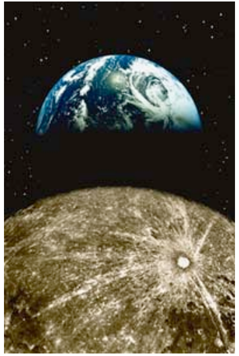
- Uses 3.5-meter telescope at 9200-ft Apache Point, NM
- Excellent atmospheric "seeing"
- 532 nm Nd:YAG, 100 ps, 115 mJ/pulse, 20 Hz laser
- Integrated avalanche photodiode (APD) arrays
- Multi-photon & daylight/full-moon



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

LLR in the near Future





- One millimeter range precision
- Weak Equivalence Principle (WEP) to □a/a _ 10^{-14}
- Strong Equivalence Principle (SEP) to □ _ 3 □ 10^{-5}
- Gravitomagnetism (frame dragging) to 10^{-4}
- dG/dt to 10^{-13}·G per year
- Geodetic precession (□) to _ 3 □ 10^{-4}
- Long range forces to 10^{-11} _ the strength of gravity

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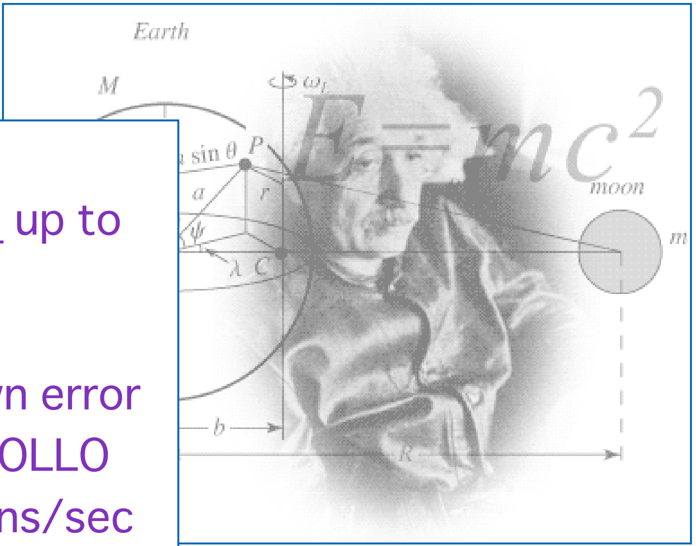
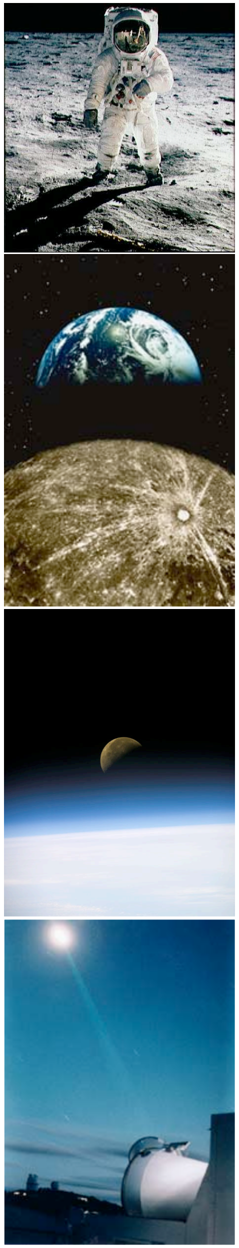
APOLLO Recipe for a mm-range:

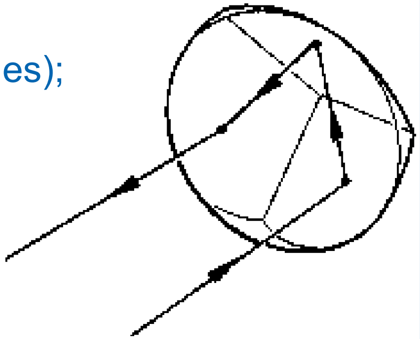


- 7 ps round-trip travel time error
- Half-meter lunar reflectors at ±7° tilt _ up to 35 mm RMS uncertainty per photon
- 95 ps FWHM laser pulse _ 6 mm RMS
- Need ~40^2 = 1600 photons to beat down error
- Calculate ~5 photon/pulse return for APOLLO
- "Realistic" 1 photon/pulse _ 20 photons/sec _ mm statistics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

Interplanetary laser ranging is the next logical step

Summary and LLR Challenges





- Ways to improve lunar science:
  - Multiple reflector data is important (to get rotation and tides);
  - Continued data will give improved accuracy of results;
  - Long time spans are important;
  - Also multiple ranging sites on Earth are important.
- Unsolved problems:
  - Cause of anomalous de/dt,
  - Does moon has an inner solid core?
- Improved range accuracy gives improved tests of gravitational physics
- When APOLLO accuracy is demonstrated, the next logical questions:
  - Are accuracy upgrades at other LLR sites likely?
  - Are new LLR stations likely?
  - Would new retroreflectors or optical transponders help?
  - Is analysis of mm LLR data easier than mm SLR data due to stable orbit?
- “Return to the Moon” may be an opportunity to place new retroreflectors and/or optical (dual optical/radio) transponders on moon:
  - Ideas, suggestions? How to optimize accuracy/signal strength?
  - New missions, technologies, capabilities?
  - Continuing (and increasing?) need for future LLR data.

Laser Ranging technology is important for space exploration!

Thank You!