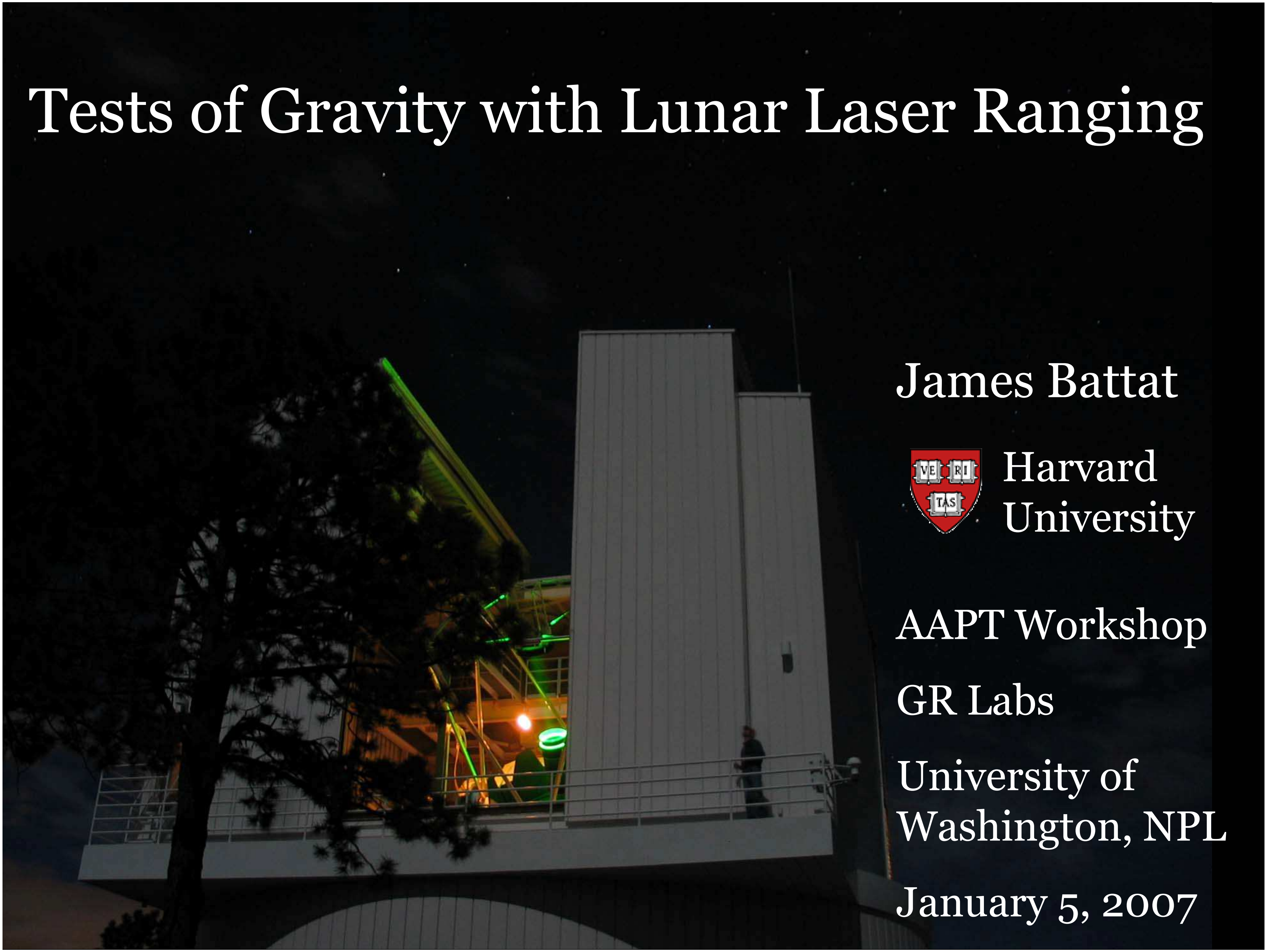
Tests of Gravity with Lunar Laser Ranging



James Battat

Harvard University

AAPT Workshop

GR Labs

University of Washington, NPL

January 5, 2007

LLR Outline

- What LLR measures
- What LLR tests
- LLR and the equivalence principle

Lunar Laser Ranging Basics

1. Point strong laser at moon

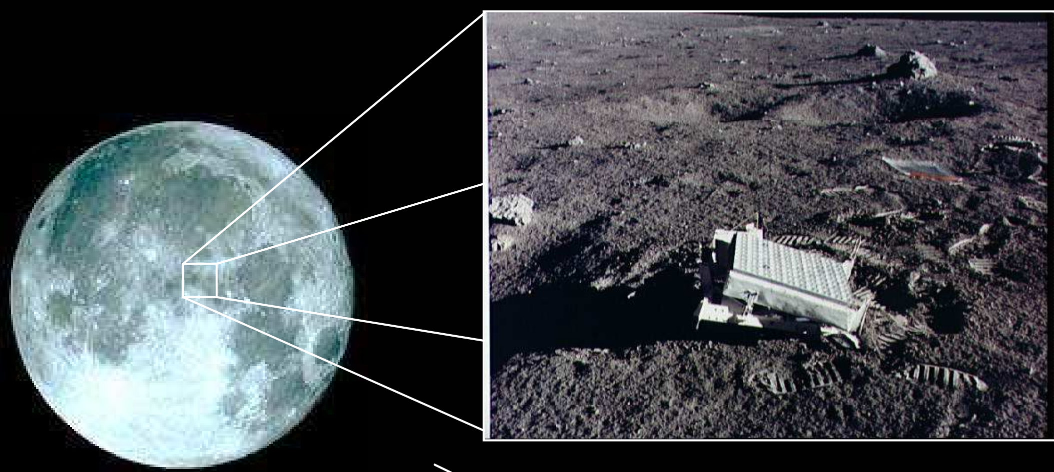
20 Hz pulses

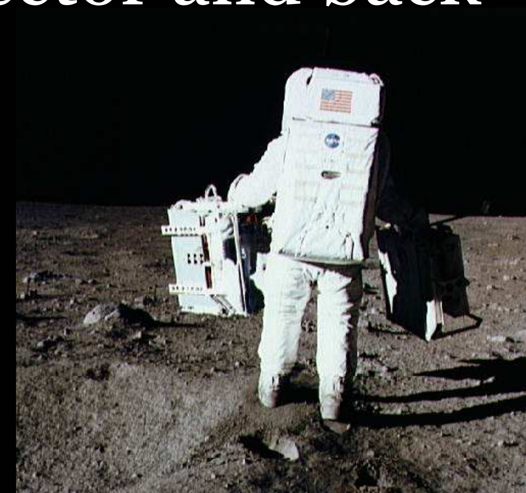
~ 2.5 second round trip travel time

~ 50 pulses in air simultaneously

Lunar Laser Ranging Basics

2. Measure travel time to reflector and back

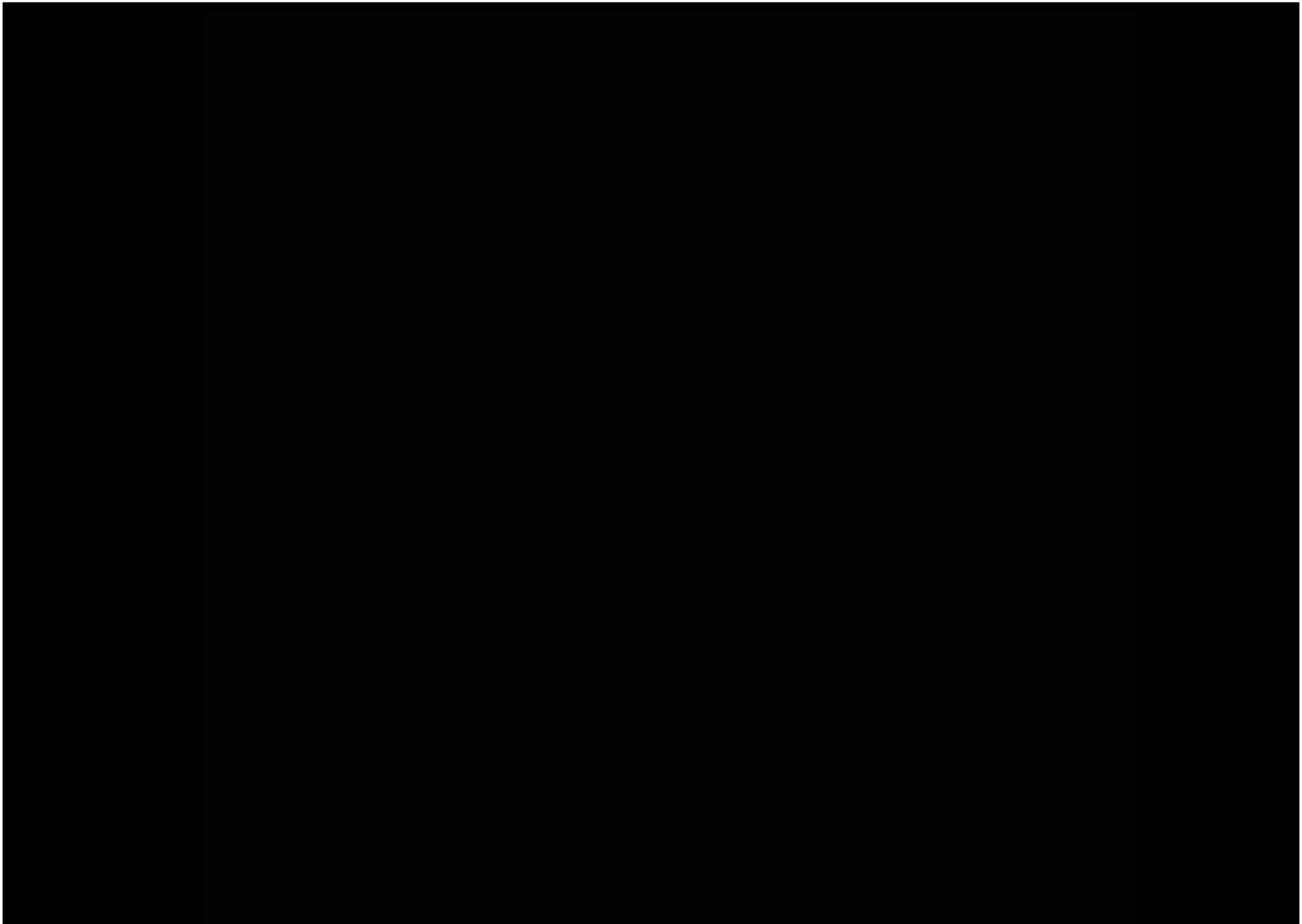




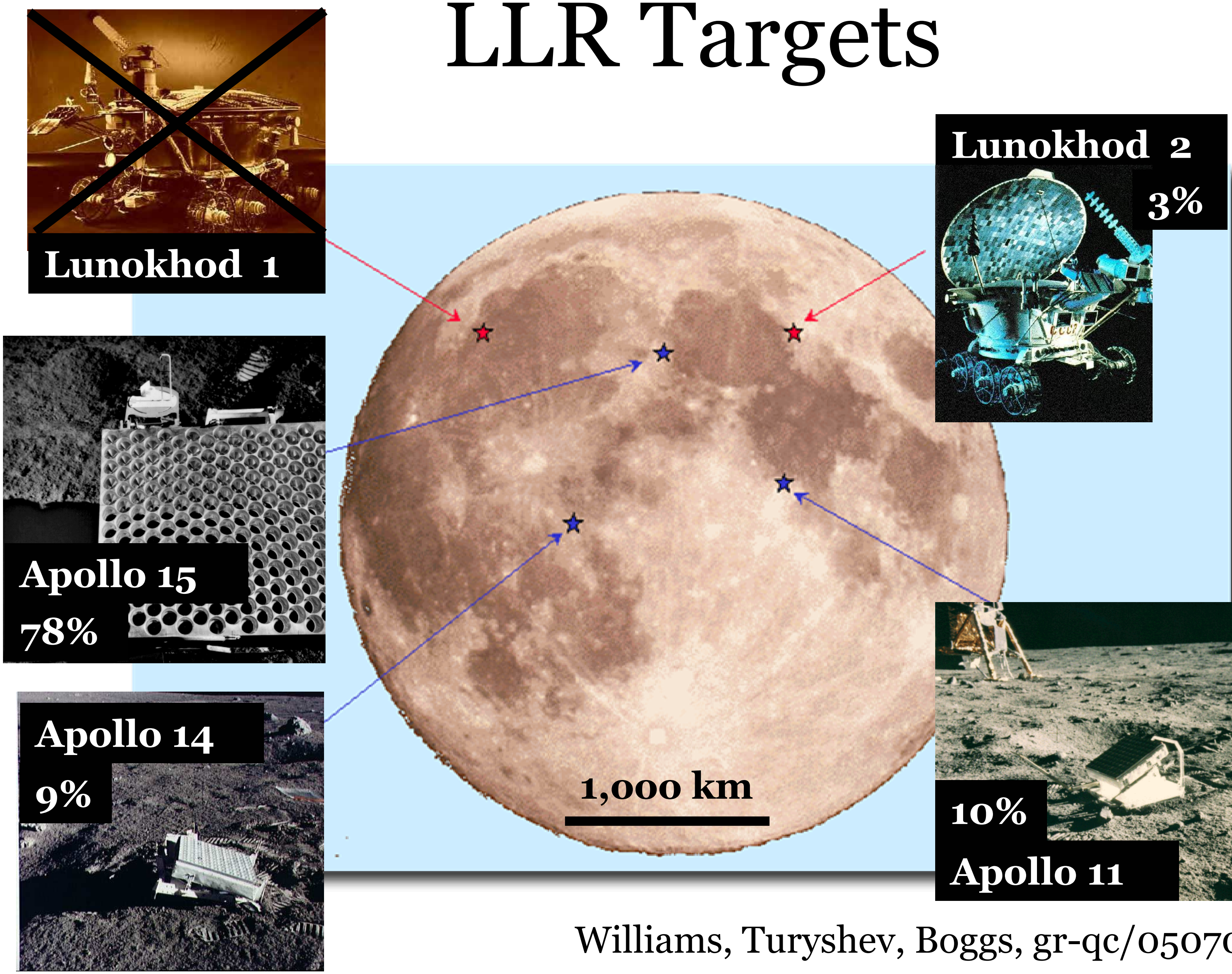
LLR is a Powerful Test of Gravity

With ***one millimeter*** range uncertainty:

• Weak EP	$\Delta a/a$	**10^{-14}**
• Strong EP	$\eta=4\beta-3-\gamma$	**3×10^{-5}**
• Gravitomagnetism		**10^{-4}**
• (dG/dt)/G		**10^{-13}** yr^{-1}
• Geodetic precession		**3×10^{-4}**
• Long range forces		**10^{-11}** × the strength of gravity

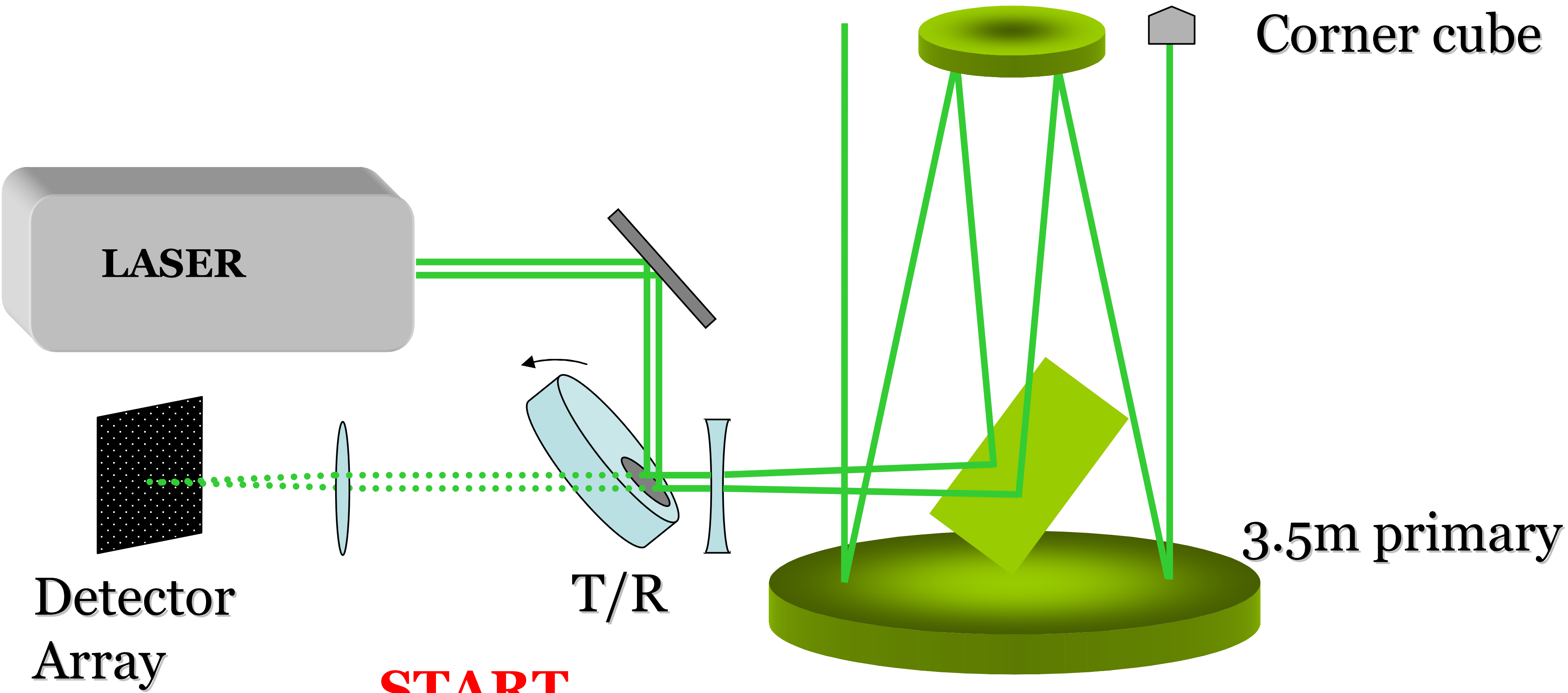


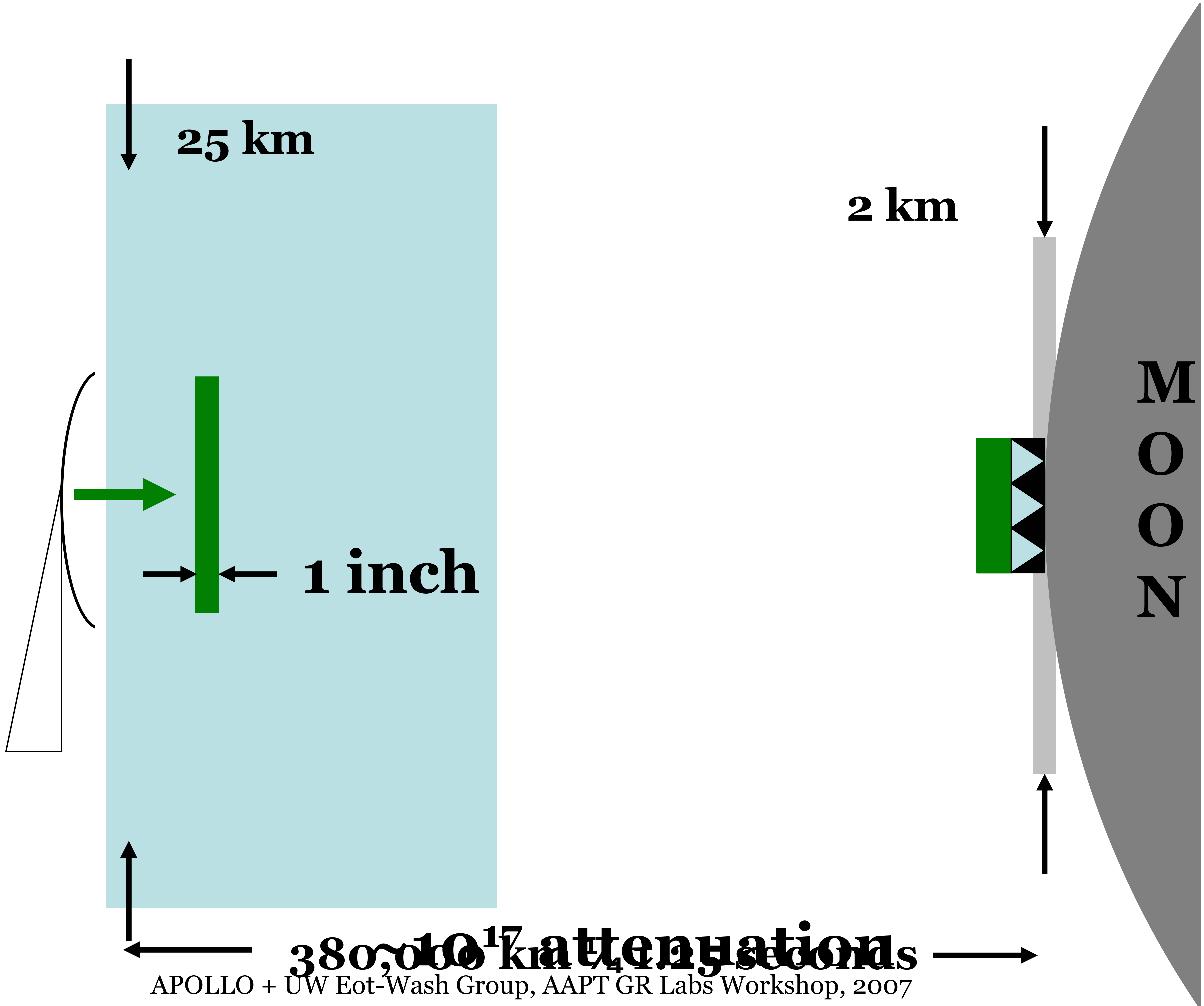
LLR Targets



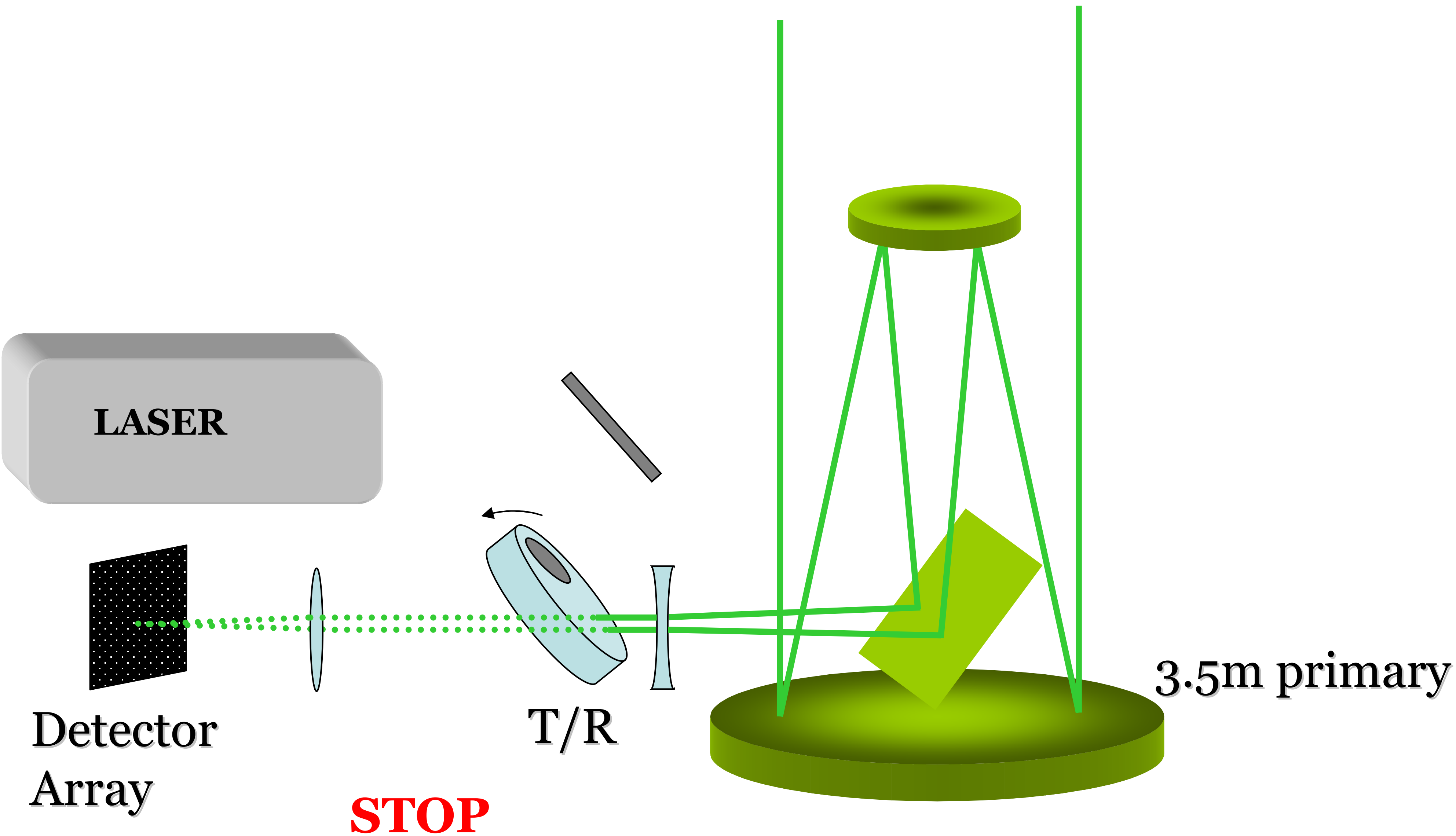
Williams, Turyshev, Boggs, gr-qc/0507083

Laser Ranging Apparatus: Transmit




25 km
2 km
1 inch
M O O N
~10^{17} attenuation
380,000 km ¼ 1.25 seconds

Laser Ranging Apparatus: Receive



Historical LLR Accuracy

Station	Dish	Seeing	Rate (γ/min)
MLRS, USA	0.8 m	3”	1
OCA, France	1.5 m	1-7”	4

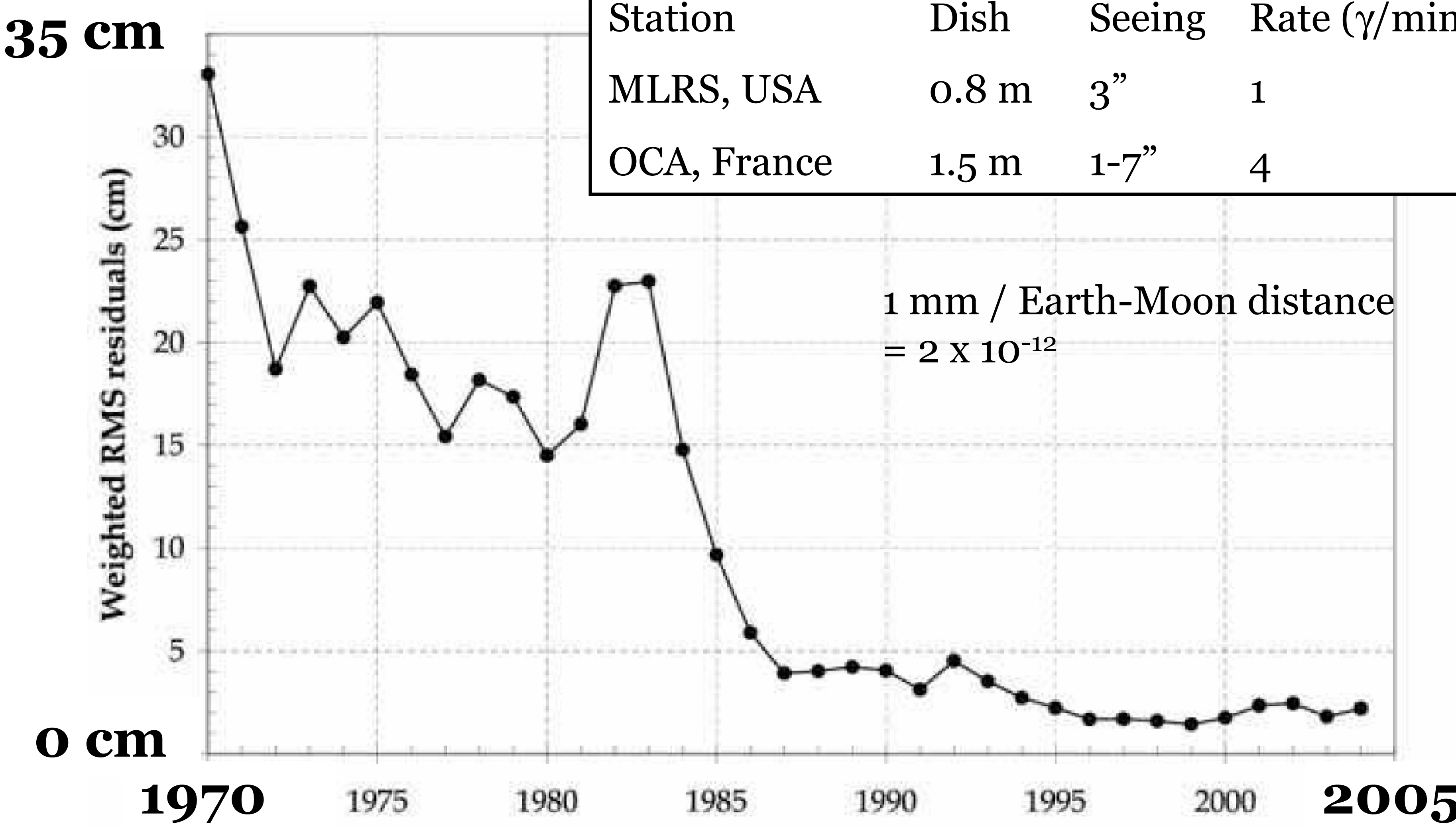
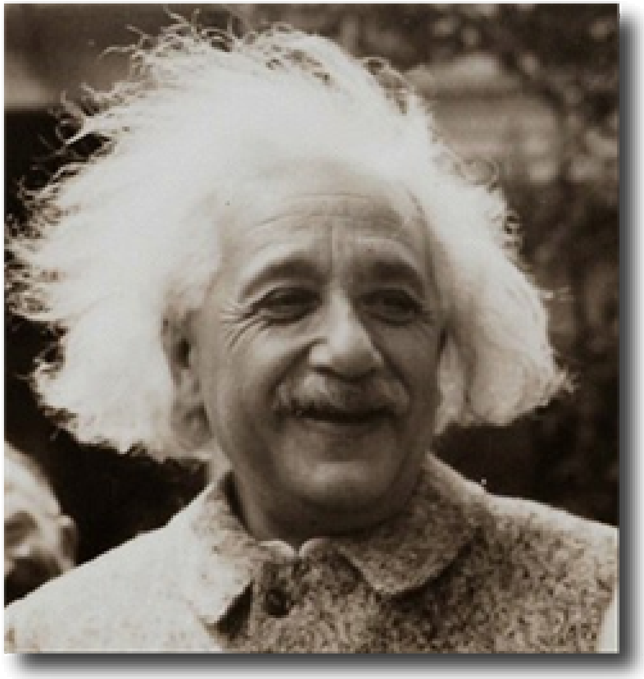


Image from Williams, Turyshev, Boggs gr-qc/0507083

LLR is a Powerful Test of Gravity

With ***one millimeter*** range uncertainty:

• Weak EP	$\Delta a/a$	$\mathbf{10^{-14}}$
• Strong EP	$\eta=4\beta-3-\gamma$	$\mathbf{3\times10^{-5}}$
• Gravitomagnetism		$\mathbf{10^{-4}}$
• (dG/dt)/G		$\mathbf{10^{-13}}$ yr^{-1}
• Geodetic precession		$\mathbf{3\times10^{-4}}$
• Long range forces		$\mathbf{10^{-11}}$ × the strength of gravity



“The general theory of relativity owes its existence in the first place to the empirical fact of the **numerical equality of the inertial and gravitational mass of bodies**.”

Lecture at King’s College, London, 1921

The Strong Equivalence Principle

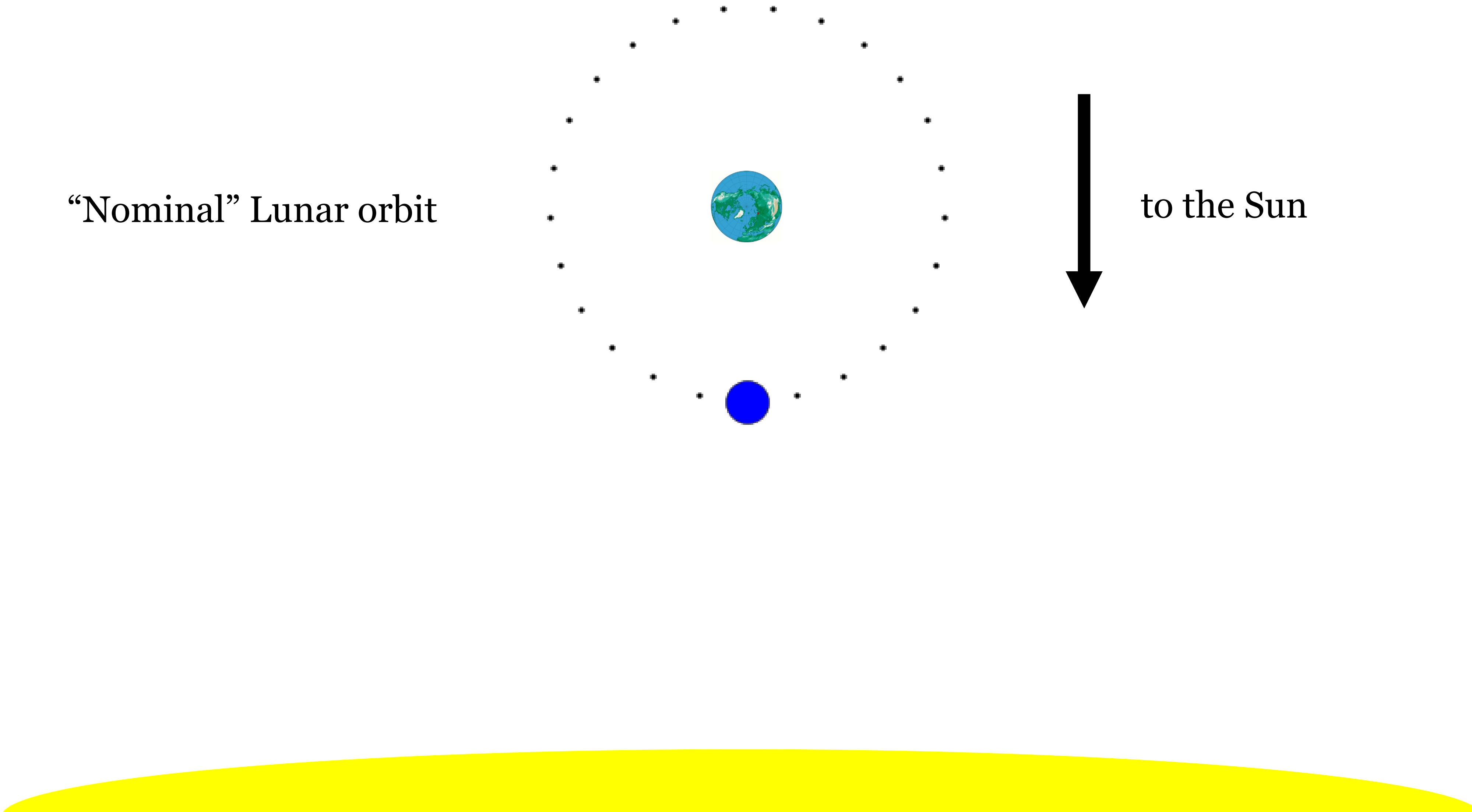
- Independent of gravitational binding energy

Sky and Telescope, December 2006

Gravitational Self-Energy

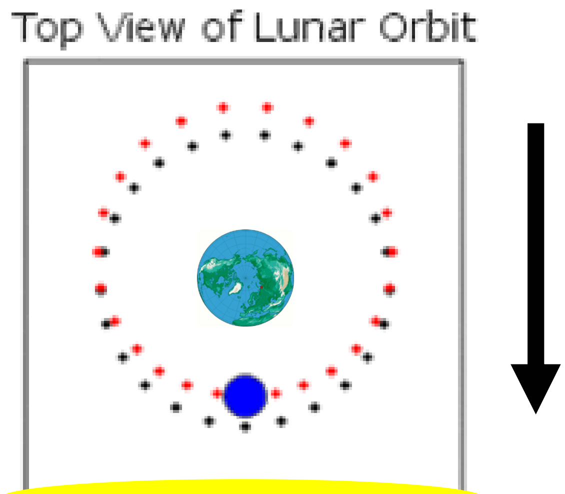
Object	Fraction of mass in binding energy
1 kg sphere, 6” diam	10^{-27}
Moon	10^{-11}
Earth	10^{-10}

The Nordtvedt Effect
EP Violation in Lunar Orbit



The Nordtvedt Effect

EP Violation in Lunar Orbit



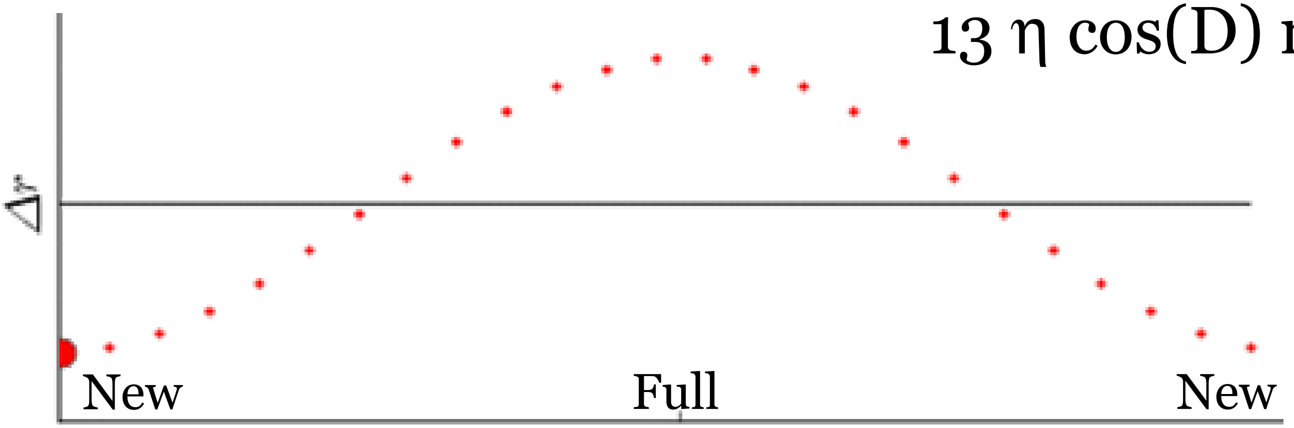
to the Sun

Nordtvedt, Phys Rev, 169, 1014, 1968

Nordtvedt, Phys Rev, 169, 1017, 1968

Nordtvedt, Phys Rev, 170, 1186, 1968

$13\ \eta \cos(D)$ meters



Synodic Period
~29 days

APOLLO + UW Eot-Wash Group, AAPT GR Labs Workshop, 2007

Turn Range Measurements into Gravity Constraints

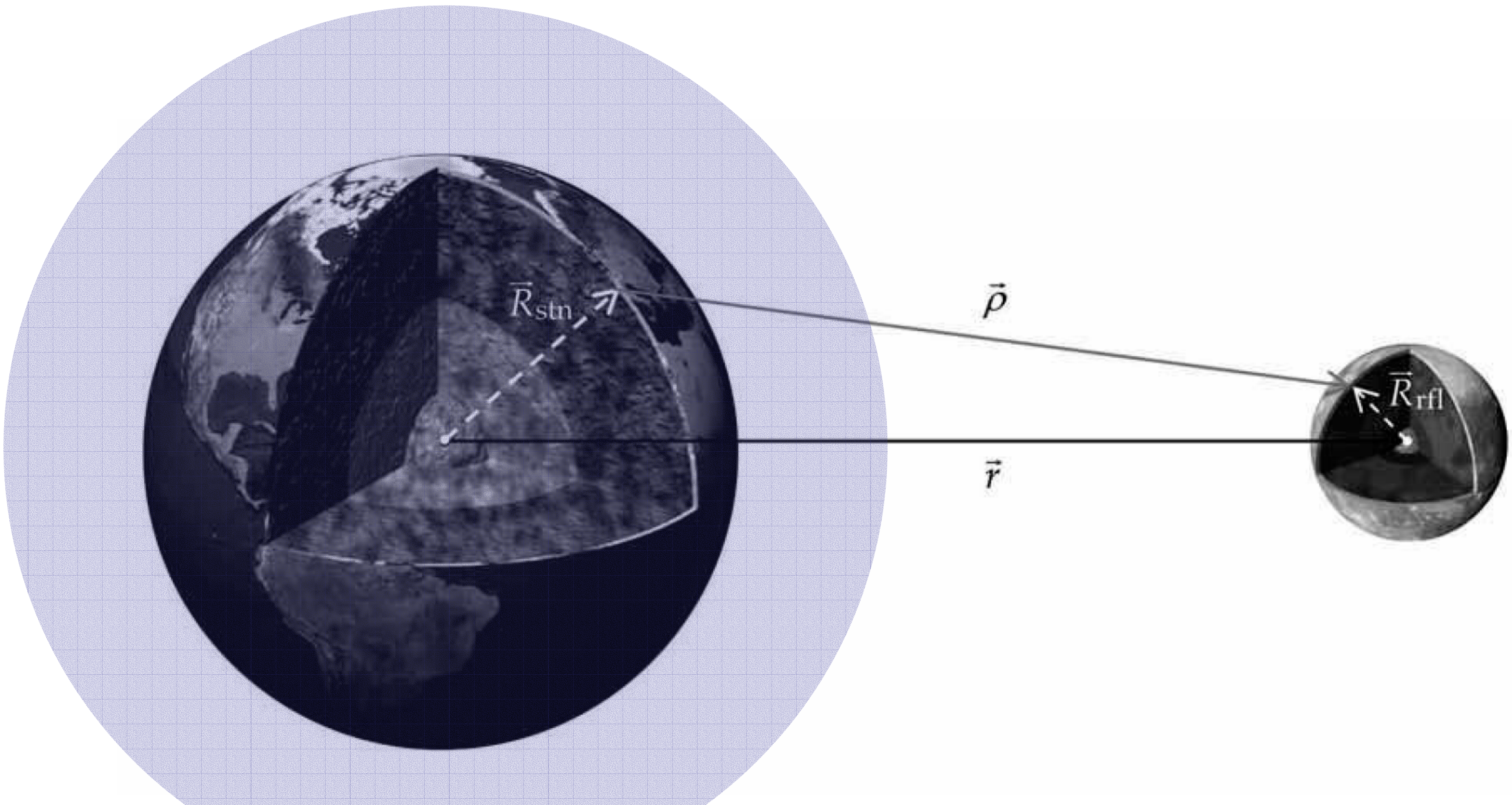
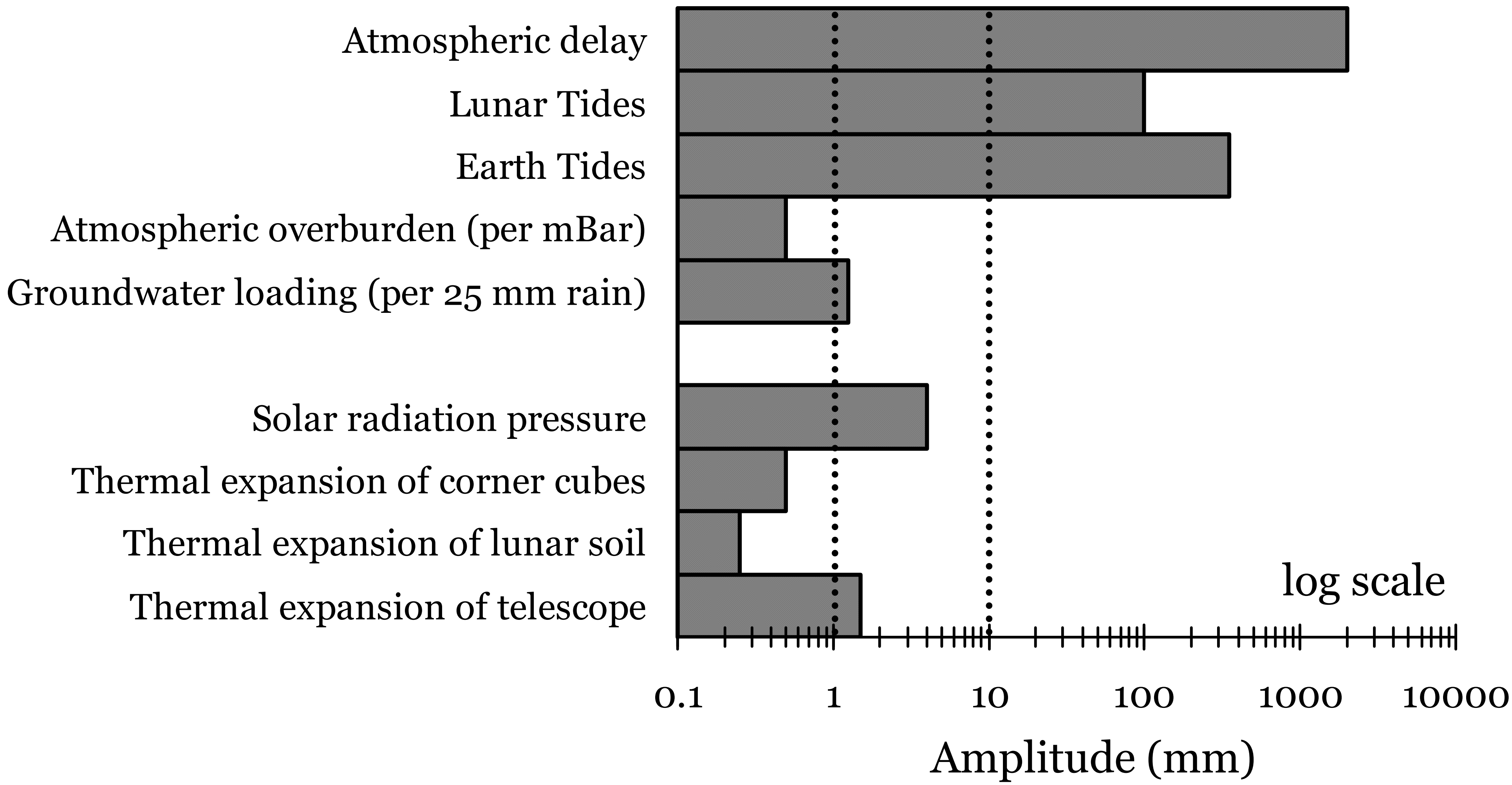
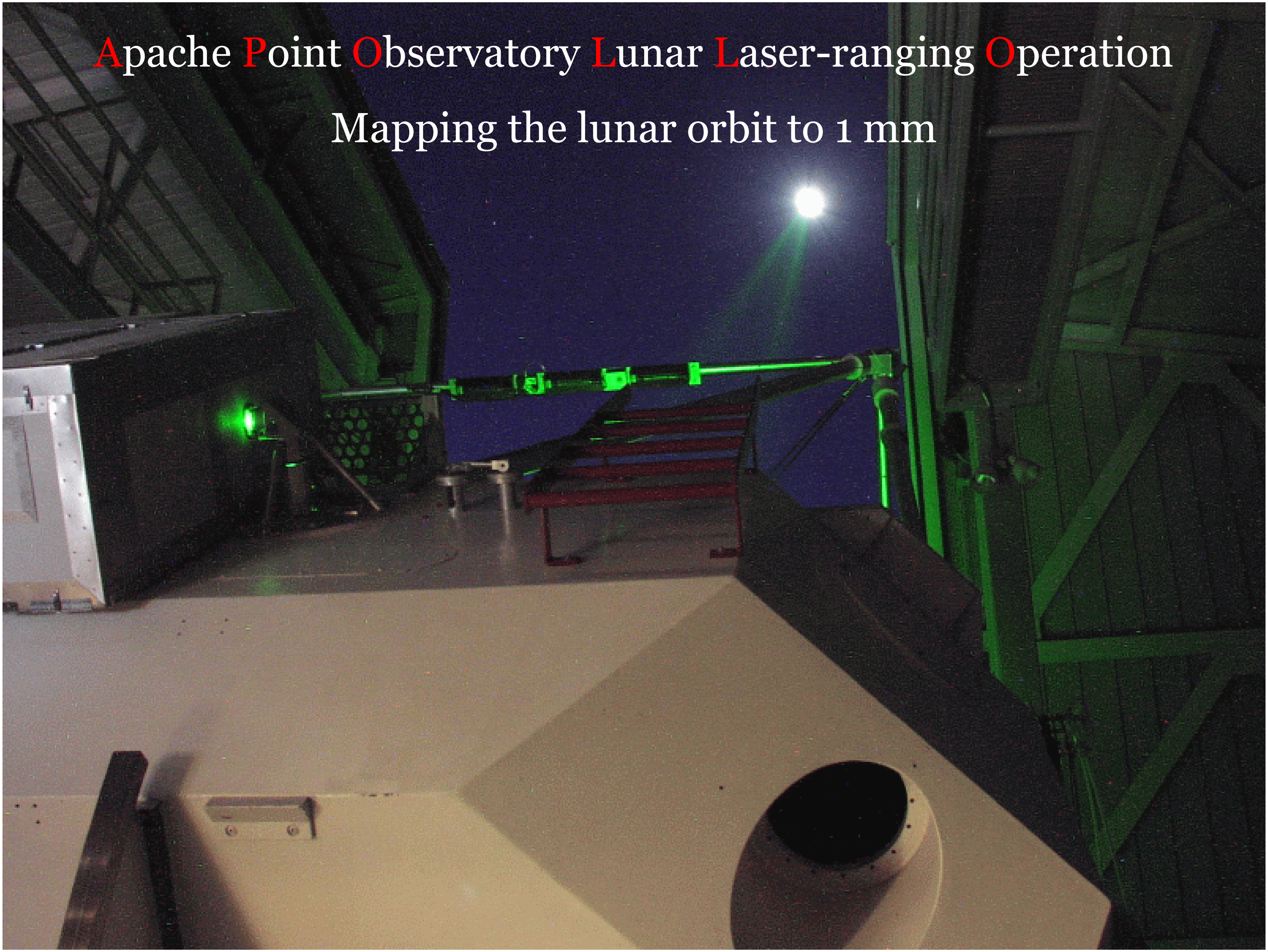


Image from Williams, Turyshev, Boggs gr-qc/0507083

Sources of Noise in LLR

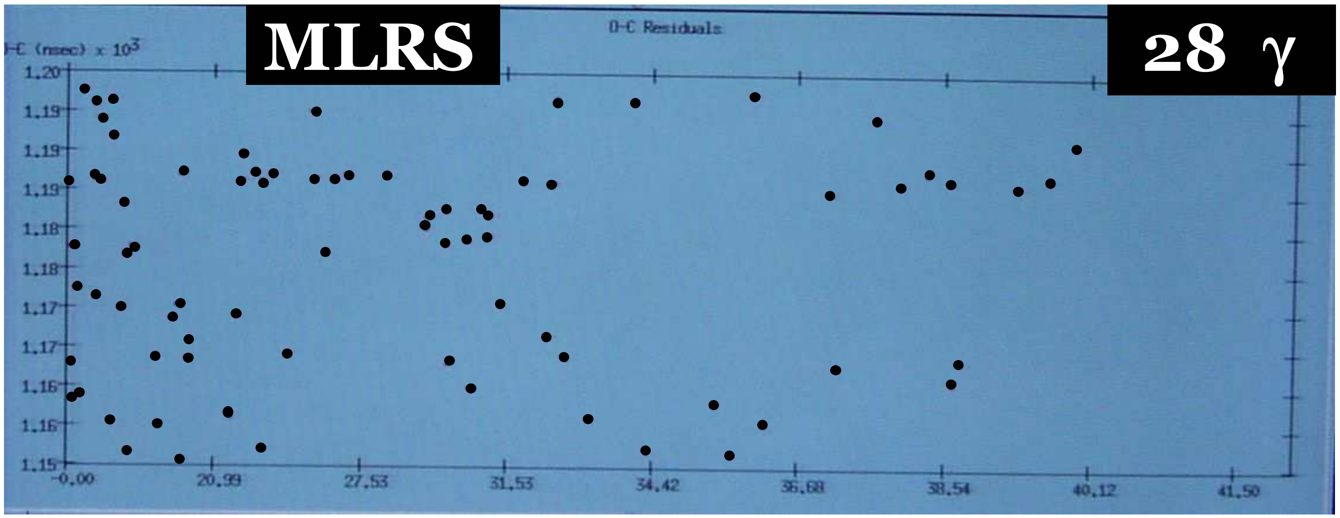


Meteorology, GPS, Gravimetry and improved physical models

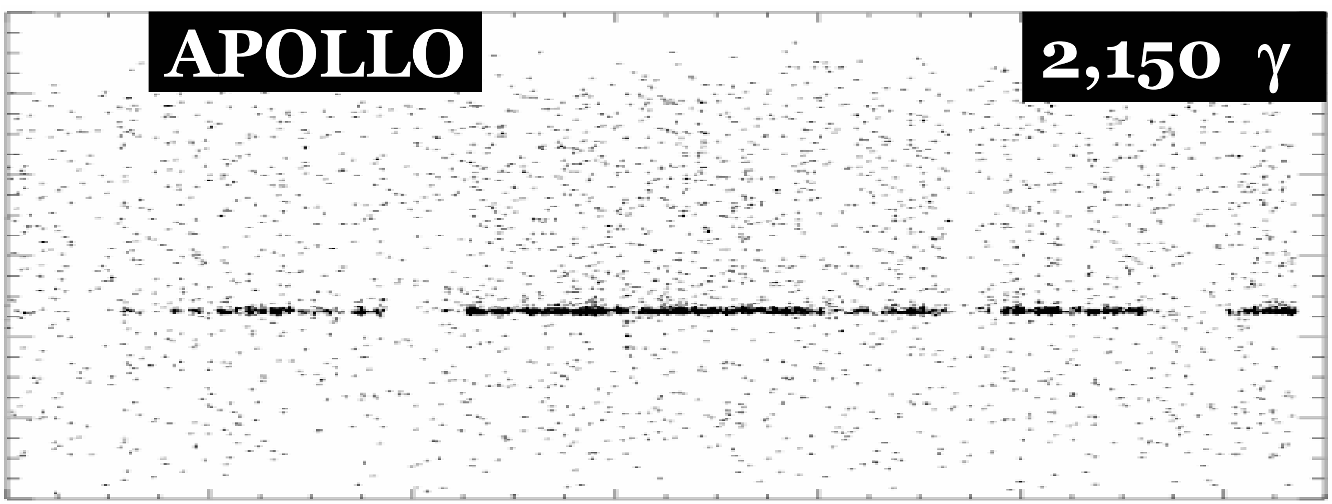

Apache Point Observatory Lunar Laser-ranging Operation
Mapping the lunar orbit to 1 mm

APOLLO Redefines LLR

Observed Minus Theory



40 minutes



100 ns

13 minutes

APOLLO + UW Eot-Wash Group, AAPT GR Labs Workshop, 2007

Conclusions

- Precision, broad test of gravity
- 35+ years of LLR data
- Hard: 1 photon return
- Know orbit to 1 cm → 1 mm

APOLLO Collaboration

UCSD
Tom Murphy (PI)
Eric Michelsen
Adam Orin

Harvard
Christopher Stubbs
James Battat

U. Washington
Eric Adelberger
Erik Swanson
C. D. Hoyle
Larry Carey

JPL
Jim Williams
Jean Dickey
Slava Turyshev

Lincoln Labs
Brian Aull
Bernie Kosicki
Bob Reich

Northwest Analysis
Ken Nordtvedt

Apache Point Obs.
Russet McMillan