APOLLO Springs to Life

One-millimeter LLR

Tom Murphy (UCSD)
The APOLLO Collaboration

UCSD:
Tom Murphy (PI)
Eric Michelsen
Adam Orin
Eric Williams

U Washington:
Eric Adelberger
C. D. Hoyle
Erik Swanson

Harvard:
Chris Stubbs
James Battat

JPL:
Jim Williams
Slava Turyshhev
Dale Boggs
Jean Dickey

Northwest Analysis:
Ken Nordtvedt

Lincoln Lab:
Brian Aull
Bob Reich
Relativistic Observables in the Lunar Range

- Lunar Laser Ranging currently provides a **comprehensive** probe of gravity, boasting the **best tests** of:
  - Equivalence Principle (two flavors)
    - WEP to $\Delta a/a < 10^{-13}$; SEP to $< 4\times10^{-4}$
  - time-rate-of-change of $G$: $< 10^{-12}$ per year
  - geodetic precession: to $< 0.35\%$
  - $1/r^2$ force law: to $< 10^{-10}$ times the strength of gravity
  - gravitomagnetism (frame-dragging) to $< 0.1\%$

- **Equivalence Principle (EP) Violation**
  - Happens if gravitational mass and inertial mass are not equal
  - Earth and Moon would fall at different rates toward the sun
  - Would appear as a *polarization* of the lunar orbit
  - Range signal has form of $\cos D$ ($D$ is lunar phase angle)
WHAT COULD BE FOUND IN THE ORBITS

If the equivalence principle is true, the sun’s gravity pulls equally on the Earth and the moon. Therefore Earth’s orbit and the moon’s average orbit follow the same path.

The moon orbits the Earth, but it also orbits the sun, giving its actual path this wavy shape.

Moon orbit moves closer to sun.

If the equivalence principle isn’t true, gravity treats the objects differently, and one orbit would be skewed.

This would disprove the equivalence principle, and scientists would have to go back to the drawing board.

Graphic excerpt from San Diego Union Tribune
Aside on Gravitomagnetism

- Stems from “motional” term in equation of motion:

\[
\mathbf{a}_i = -\frac{\mu_j (2 + 2\gamma)}{c^2 r_{ij}^3} \mathbf{v}_i \times (\mathbf{v}_j \times \mathbf{r}_{ij})
\]

- If earth has velocity \( \mathbf{V} \), and moon is \( \mathbf{V} + \mathbf{u} \), two terms of consequence emerge:
  - One proportional to \( \mathbf{V}^2 \) with 6.50 meter \( \cos 2D \) signal
  - One proportional to \( \mathbf{V}\mathbf{u} \) with 6.1 meter \( \cos D \) signal

- LLR determines \( \cos D \) to 4 mm precision and \( \cos 2D \) to < 8 mm
  - Constitutes a \( \approx 0.1\% \) measurement of effect

- The same exact \( \mathbf{v} \times \mathbf{v} \times \mathbf{g} \) term can be used to derive the precession of a gyroscope in the presence of a spinning mass
  - recovers the full effect sought by GPB
Previously 200 meters
APOLLO: recipe for success

- APOLLO offers order-of-magnitude improvements to LLR by:
  - Using a 3.5 meter telescope
  - Gathering multiple photons/shot
  - Operating at 20 pulses/sec
  - Using advanced detector technology
  - Achieving millimeter range precision
  - Tightly integrating experiment and analysis
  - Having the best acronym
Lunar Retroreflector Arrays

Corner cubes

Apollo 11 retroreflector array

Apollo 14 retroreflector array

Apollo 15 retroreflector array
APOLLO’s Secret Weapon: Aperture

- The Apache Point Observatory’s 3.5 meter telescope
  - Southern NM (Sunspot)
  - 9,200 ft (2800 m) elevation
  - Great “seeing”: 1 arcsec
  - Flexibly scheduled, high-class research telescope
  - 7-university consortium (UW, U Chicago, Princeton, Johns Hopkins, Colorado, NMSU, Virginia)
The Link Equation

\[ N_{\text{rx}} = N_{\text{tx}} \eta^2 f Q n_{\text{refl}} \left( \frac{d}{\phi r} \right)^2 \left( \frac{D}{\Phi r} \right)^2 \]

\( \eta \) = one-way optical throughput (encountered twice)
\( f \) = receiver narrow-band filter throughput
\( Q \) = detector quantum efficiency
\( n_{\text{refl}} \) = number of corner cubes in array (100 or 300)
\( d \) = diameter of corner cubes (3.8 cm)
\( \phi \) = outgoing beam divergence (atmospheric “seeing”)
\( r \) = distance to moon
\( \Phi \) = return beam divergence (diffraction from cubes)
\( D \) = telescope aperture (diameter; 3.5 m)

\[ N_{\text{rx}} = 5.4 \left( \frac{E_{\text{pulse}}}{115 \text{ mJ}} \right) \left( \frac{\eta}{0.4} \right)^2 \left( \frac{f}{0.25} \right) \left( \frac{Q}{0.3} \right) \left( \frac{n_{\text{refl}}}{100} \right) \left( \frac{1 \text{ arcsec}}{\phi} \right)^2 \left( \frac{10 \text{ arcsec}}{\Phi} \right)^2 \left( \frac{385000 \text{ km}}{r} \right)^4 \]

- APOLLO lands safely in the multi-photon regime
- Other LLR stations get < 1 photon per 100 pulses
- Even at 1% of expected rate, 1 photon/sec good enough for feedback
APOLLO Laser

- 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
Catching All the Photons

- Several photons per pulse necessitates multiple “buckets” to time-tag each one
  - 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
Differential Measurement Scheme

- **Corner Cube** at telescope exit returns *fiducial* pulse
- Same optical path, attenuated by 10 O.D.
- Same APD detector, electronics, TDC range
- Diffused to present *identical illumination* on detector elements
- Result is *differential* over 2.5 seconds
- Must correct for distance between telescope axis intersection and corner cube
# APOLOLO Random Error Budget

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Time Uncert. (ps) (round trip)</th>
<th>Range error (mm) (one way)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retro Array Orient.</td>
<td>100–300</td>
<td>15–45</td>
</tr>
<tr>
<td>APD Illumination</td>
<td>60</td>
<td>9</td>
</tr>
<tr>
<td>APD Intrinsic</td>
<td>&lt;50</td>
<td>&lt; 7</td>
</tr>
<tr>
<td>Laser Pulse Width</td>
<td>45</td>
<td>6.5</td>
</tr>
<tr>
<td>Timing Electronics</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>GPS-slaved Clock</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total Random Uncert</strong></td>
<td><strong>136–314</strong></td>
<td><strong>20–47</strong></td>
</tr>
</tbody>
</table>

Ignoring retro array, APOLOLO system has 93 ps (14 mm) error per photon
Systematic Error Sources

- We can cut the 50 mm (worst-case) random uncertainty down to 1 mm with 2500 photons
  - 2 minutes at 20 Hz and 1 photon per pulse
- Systematic uncertainties are more worrisome
  - Atmospheric delay (2 meter effective path delay)
  - Deflection of earth’s crust by:
    - Ocean: even in NM, tidal buildup on CA coast → few mm deflection
    - Atmosphere: 0.35 mm per millibar pressure differential
    - ground water: ????
  - Thermal expansion of telescope and retroreflector arrays
  - Radiation pressure (3.85 mm differential signal)
  - Implementation systematics
    - Detector illumination
    - Strong signal bias
    - Temperature-dependent electronic timing
    - Observation schedule/sampling: danger of aliasing
Beating the Systematics

- Precision barometry for atmospheric delay (0.2 mbar)
- Precision GPS installation
  - 0.5 mm horizontal
  - 2.5 mm vertical
- Superconducting gravimeter
  - Invented at UCSD by John Goodkind
  - Can sense sub-mm vertical offsets by change in $g$
  - Refurbishing Goodkind sensor for use in NM
- Tight feedback between data collection and analysis
  - Sensitive to alias, bias, etc.
Periodicity: Our Saving Grace

- If we don’t get all this supplemental metrology right, we’re still okay:
  - Our science signals are at discrete, well-defined frequencies
  - Equivalence Principle signal at 29.53 days
  - Other science via 27.55 day signal (eccentricity)
- Meteorological influences are broadband
  - Atmospheric, ground-water loading are random
  - Even tides, ocean loading don’t have power at EP period
  - Thermal effects are seasonal
Laser Mounted on Telescope
Optical System
Optical Layout

Legend:
- NB: narrow band filter
- BS: beamsplitters (89°)
- ND: neutral density filter
- DP: diffuser
- RL: receiver lens
- PPD: fast photodiode
- IR: infrared
- SHG: second harmonic generator
- L: lens
- M: mirror
- VND: variable ND filter
- TL: transmit lens

Laser Enclosure

Optical Bench

receiver enclosure

APD array

RL3

RL2

pinhole

mask

L3

L1

TL1

BS

M7

CCD lens

M5

L3

IR: infrared

IR + green

dichroics

IR + red

primary green

red/green

NL

NB

TL2

PPD

M6

rot. axis

to telescope

laser receiver

beam dump

beam dump
Electronics Cabinet
Custom timing system uses 16-channel TDC (100 ns range; 25 ps resolution; 13 ps jitter) plus custom CAMAC state machine to get multiplexed 15 ps timing (up to 4 kHz rate)

- Common STOP sliced from 50 MHz ECL clock train (Truetime XL-DC base)
- Each APD channel produces independent START
- Clock Slicer can also produce STARTs based on 50 MHz calibration via 20.00, 40.00, 60.00, 80.00, 100.00 ns START/STOP pairs
First Light: July 24, 2005
First Light: July 24, 2005
The Raw Data

range evolves rapidly: mostly earth rotation

we slew our gate to track motion

all events plotted:
background & laser returns

range rate: 1500 ns/sec $\rightarrow$ 222 m/s

100 ns gate width is $1/4000^{th}$ of vertical scale
Subtracting Linear Fit…

retroreflector return is clearly visible in middle of gate
Subtracting Quadratic Fit...
**Example Data**

- **Randomly-timed background photons (bright moon)**
- **Return photons from reflector width is < 1 foot (finite array size)**
- **2150 photons in 14,000 shots**
Hands-off run

2500 photons in 10000 shots

mild double-pulse behavior of laser
Another example

2000 photons in 8000 shots
no more double pulse
Millimeter Accomplished

June 4, 2006 run

600-photon run (laser double-pulsing)

< 500 ps FWHM → 200 ps RMS

centroid error: 200/sqrt(600) → 8 ps → 1.2 mm one way error

well-separated double pulse is okay, but has been fixed nonetheless

prediction offset is a few nanoseconds

100 ps bins
Channel-by-Channel Fiducial Measurement

The fiducial corner-cube provides local time-of-departure measurement.

Each APD channel is separately “calibrated” for time offset, timing performance, detection efficiency, etc.

250 ps FHWM → 100 ps RMS → 15 mm single-photon time error (matches error budget predictions)

1 mm in 225 photons ignoring libration error
APOLLO Superlatives

- More lunar return photons in 10 minutes than other LLR stations get in months to years
  - best single run: >2500 photons in 10,000 shots (8 minutes)
- Peak rates of >0.5 photons per shot (10 per second)
  - and steady rates at 1/4 photons per shot
  - compare to typical 1/500 for McDonald, 1/100 for France
- Range with ease at full moon
  - APOLLO’s very first returns were at full moon
  - other stations can’t fight the high background
- As many as 8 photons detected in a single pulse!
  - In best runs, half of detected photons in multi-photon clumps
  - APD array is essential
Project Timeline

- First acquisition in fall 2005
  - Lenslet installed in October; photons followed
- First “science-quality” data April 6, 2006
  - following fix of known systematic error sources and proper interleaving of fiducial returns
- Acquisition puzzle solved June 2006
- Entered campaign mode: Oct. 1, 2006
- Sufficient data for order-of-magnitude EP in ~1 year
  - expect first results in spring/summer 2007
- Now pushing on data reduction → normal points
- Model refinement/improvement campaign in parallel
  - in conjunction with JPL/Jim Williams
- Continued data collection/analysis for years to come