APOLLO

Testing Gravity and Geodesy
via
Laser Ranging to the Moon

Tom Murphy (UCSD)

photo credit: Jack Dembicky
Lunar Retroreflector Arrays

Corner cubes

Apollo 11 retroreflector array

Apollo 14 retroreflector array

Apollo 15 retroreflector array
The Reflector Positions

- Three Apollo missions left reflectors
  - Apollo 11: 100-element
  - Apollo 14: 100-element
  - Apollo 15: 300-element
- Two French-built, Soviet-landed reflectors were placed on rovers
  - Luna 17: Lunokhod 1 rover
  - Luna 21: Lunokhod 2 rover
  - similar in size to A11, A14
- Signal loss is huge:
  - \( \approx 10^{-8} \) of photons launched find reflector (atmospheric seeing)
  - \( \approx 10^{-8} \) of returned photons find telescope (corner cube diffraction)
  - \( >10^{17} \) loss considering other optical/detection losses
Previously 200 meters

LLR through the decades

Graph showing the range precision (mm) over the years from 1970 to 2010. The graph includes two lines:
- Blue line labeled "modeled post-fit residuals"
- Red line labeled "APOLLO median uncert."
APOLLO: one giant leap for LLR

• APOLLO offers order-of-magnitude improvements to LLR by:
  – Using a 3.5 meter telescope
  – Operating at 20 pulses/sec
  – Using advanced detector technology
  – Gathering multiple photons/shot
    • Achieving millimeter range precision
  – Tightly integrating experiment and analysis
  – Having the best acronym
    • funded by NASA & NSF
The APOLLO Collaboration

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Humboldt State:
C. D. Hoyle

Apache Point Obs.:
Russet McMillan

Northwest Analysis:
Ken Nordtvedt
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
    - APOLLO gets 8–10 < 1 hour sessions per lunar month
  - 7-university consortium (UW NMSU, U Chicago, Princeton, Johns Hopkins, Colorado, Virginia)
APOLLO Laser

- Nd:YAG; flashlamp-pumped; mode-locked; cavity-dumped
- Frequency-doubled to 532 nm
  - 57% conversion efficiency
- 90 ps pulse width (FWHM)
- 115 mJ (green) per pulse
  - after double-pass amplifier
- 20 Hz pulse 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
Timing System

- XL-DC (Truetime/Symmetricomm)
  - GPS-disciplined ovenized quartz
  - low phase noise (-155 dBC/Hz)
  - multiplied to 5× for 50 MHz ECL clock “backbone”

- 16-channel CAMAC Time-to-Digital Converter
  - 13 ps jitter
  - measures from photon START to clock-derived STOP

- Error budget dominated by finite reflector, tilted by libration
  - could certainly do better timing, but would wash out anyway
A Telescope in Reverse
Killer Returns

Apollo 15  2007.11.19  Apollo 11

red curves are theoretical profiles: get convolved with fiducial to make lunar return

- 6624 photons in 5000 shots
- 369,840,578,287.4 ± 0.8 mm
- 4 detections with 10 photons

- 2344 photons in 5000 shots
- 369,817,674,951.1 ± 0.7 mm
- 1 detection with 8 photons

RMS = 120 ps (18 mm)
Fitting the Return & Reflector Trapezoid

Fiducial Return
- FWHM = 294 ps
- $\sigma = 135$ ps
- $N_{\text{phot}} \approx 4718$
- $\sigma_{\text{r}} = 2.0$ ps
- $\sigma_{\text{mm}} = 0.3$ mm

Lunar Return
- FWHM = 790 ps
- $\sigma = 293$ ps
- $N_{\text{phot}} \approx 1672$
- $\sigma_{\text{r}} = 7.2$ ps
- $\sigma_{\text{mm}} = 1.1$ mm
Sensing the Array Size & Orientation

2007.10.28

2007.10.29

2007.11.19

2007.11.20

Stanford PNT Symposium
**Breaking All Records**

<table>
<thead>
<tr>
<th>Reflector</th>
<th>APOLLO max photons/5-min</th>
<th>APOLLO max photons/shot (5 min avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 11</td>
<td>5395 (65×)</td>
<td>0.90</td>
</tr>
<tr>
<td>Apollo 14</td>
<td>9125 (69×)</td>
<td>1.52</td>
</tr>
<tr>
<td>Apollo 15</td>
<td>18875 (67×)</td>
<td>3.15</td>
</tr>
<tr>
<td>Lunokhod 2</td>
<td>900 (31×)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

APOLLO has greatly surpassed previous records
- max rates for French and Texas stations about 0.1 and 0.02, respectively

APOLLO can operate at full moon
- other stations can’t (except during eclipse), though EP signal is max at full moon!

Often a majority of APOLLO returns are multiple-photon events
- record is 12 photons in one shot (out of 12 functioning APD elements)
- APD array (many buckets) is crucial
APOLLO Data Campaign

- Steady accumulation of data; less reliance on Apollo 15 over time
- Found Lunokhod 1 in 2010
• Uncertainties are **per night, per reflector**; pre-APOLLO sub-centimeter rare
• Medians are 2.4, 2.7, 2.4, 1.8, 3.3 mm for A11, L1, A14, A15, L2, resp.
• Combined nightly median range error is 1.4 mm
Gravity Cries for Help

- General Relativity (GR) and Quantum Mechanics are fundamentally incompatible
  - gravity relatively poorly tested
- New physics of the dark sector could be misunderstanding of large-scale gravity
  - GR used as metric backdrop for cosmic expansion
- Scalar fields introduced by string-inspired and other modifications to GR produce potentially measurable effects
  - violation of the equivalence principle
  - time variation of fund. “constants”
Equivalence Principle Flavors

• **Weak EP**
  – Composition difference: e.g., iron in earth vs. silicates in moon
  – Probes all interactions but gravity itself
    • Currently tested by LLR to $\Delta a/a < 10^{-13}$
    • Comparable to best lab tests by Eöt-Wash group at UW
      – but better choices of mass pairs offer stronger WEP test than LLR

• **Strong EP**
  – Applies to gravitational “energy” itself
    • Earth self-energy has equivalent mass ($E = mc^2$)
      – Amounts to $4.6 \times 10^{-10}$ of earth’s total mass-energy
    • Does this mass have $M_G/M_i = 1.00000$?
  – Another way to look at it: gravity pulls on gravity
    • This gets at *nonlinear* aspect of gravity (PPN $\beta$)
  – LLR provides the best way to test the SEP
    • pulsar timing is closest competitor
EP Signal, Illustrated

**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.

- **Moon close**
- **Moon far**

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

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
Earth Orientation

- Millimeter LLR easily picks up Earth orientation vagaries
- But sampling unimpressive
Better Sampling: Transponder on Moon

- A laser transponder on the Moon solves many problems
  - devastating $1/r^4$ link becomes vastly more forgiving $1/r^2$
  - opens up LLR to global network of SLR stations
  - results in vastly improved data volume and sampling
  - global distribution averages out local variation
- Also good stepping stone to interplanetary ranging; optical communications
• We care about millimeter displacements of floppy Earth crust
  – gravimeter has sub-millimeter height sensitivity
• Will help us characterize tides, measure loading of crust
  – fight gravity with gravity!
Fun with gravimetry

- One day saw three **steps** in gravity record
  - unequal, within 10 minutes
- Turns out to have been giant **concrete blocks** used to load-test the observatory crane being moved away
  - can tell which was moved first, second, third
- Also see telescope dome rotation as up to 5 nm/s² offset
- See Earth ringing for a month after Chilean earthquake Feb. 2010 and Sendai in March 2011
  - 20 minute period “breathing” mode
Gravity Signal from Dome

Apache Point Gravimeter Signal

gravity residual (nm/s²)

gravity dome azimuth

time (UTC hour)
Superconducting Gravimeter Benefits

- SG is a great way to measure tides at site
- Gravity is a proxy to site displacement
- Probes ocean loading, ground water loading, atmospheric loading
EarthScope GPS Pitching In

- The NSF-funded Plate Boundary Observatory (part of EarthScope) installed a GPS station 2.5 km away from APOLLO
- Resolution in monthly interval is 0.3 mm horizontal, 1.2 mm vertical
- Will help constrain crust motion, loading phenomena
Surprises
Somewhere on this slide…

…which is less than 1 kilometer across…

…lurks Lunokhod 1.

Hint: it looks like this…

…and I haven’t covered it up.

100 m

2012.11.13

Stanford PNT Symposium
Your discovery gives hope to all of us who lost something during the seventies...

- Ed Leon
  Apache Point Observatory
Reflector Degradation

what we expect

what we really get...

10% 1% : “the full moon curse”
Transponder Detector

- Phased array passively listening to 1090 MHz transponder chatter
- Ratio of directional to omni-directional reliably determines if aircraft is near boresight
  – indep. of xmit power, distance, etc.
- Installed on APO and Keck, others interested
Summary & Next Steps

• **APOLLO** is a millimeter-capable lunar ranging station with unprecedented performance

• Given the order-of-magnitude gains in range precision, we expect order-of-magnitude gains in a variety of tests of fundamental gravity

• Besides gravity, LLR is sensitive to Earth orientation, the lunar interior, and coordinate frames

• Some surprises along the way
  – degradation of reflectors
  – found lost Lunokhod 1 reflector; now have 5
  – also developed aircraft transponder detector for illumination avoidance

• Trying 2-way ranging to corner cube array on LRO (1-way works...)