New Timing Calibration Capability for the APOLLO LLR experiment

James Battat
Wellesley College

IWLR 2016 – Potsdam
October 11, 2016
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Overview

• Brief introduction to APOLLO science goals and instrument description
• Description and early results from our “Absolute Calibration System”
APOLLO, through the lens of yesterday

• For us, the target selection is trivial!
• Shot-by-shot calibration using a retro-reflector mounted to the secondary mirror.
• Shared facility (1h sessions, 8-10x per lunar month)
• No daytime operation (telescope restrictions on sun avoidance)
• Large aperture (3.5m), same for transmit & receive
• Seeing at site is very good (0.9 arcsec, median), but lose ~1/3 of our time to weather
Test fundamental physics through astrophysics

* Gravitation (post-Einstein)
* N>4 dimensional theories (braneworld gravity)
* Lorentz symmetry
APOLLO Collaboration

UCSD
Tom Murphy (PI)
Bob Reasenberg
Nick Colmenares
Shruti Singh

U. Washington
Eric Adelberger
Erik Swanson

Wellesley College
James Battat
Louisa Huang Ruixue
Sanaea Rose
Else Schlerman

Harvard
Christopher Stubbs
John Chandler
Irwin Shapiro

Humboldt State U.
C. D. Hoyle

Northwest Analysis
Ken Nordtvedt

Apache Point Observatory
Russet McMillan
APOLLO Collaboration

The ACS development team

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John Chandler

Special thanks to Christoph Skrobol and Konrad Birkmeier (Toptica)
APOLLO: the Earth end
APOLLO: the Earth end

Transponder-Based Aircraft Detector

Coles, Murphy et al., PASP 124 (2012)

arXiv:0910.5685

Fig. 7.—The antenna array mounted on the sky-facing side of the secondary mirror support structure on the APO 3.5 m telescope. The electronics box with white labels visible below the antenna plate contains the RF electronics, and consumes only 3 W of power. See the electronic edition of the PASP for a color version of this figure.

People (aircraft spotters)
Now replaced by TBAD
APOLLO: Instrument


• Laser:
  – 532 nm Nd:YAG, mode-locked, cavity-dumped
  – 90 ps pulse width
  – 115 mJ per pulse
  – 20 Hz repetition rate
  – 2.3 W average power

• Detector: Silicon APD Array
  – 4×4 made by Lincoln Laboratory
  – 30 µm elements, 100 µm centers
  – lenslet array recovers fill-factor
  – 1.4 arcsec on a side (0.35 arcsec/element)
  – allows multi-photon returns
  – permits real-time tracking
The Moon end

Apollo 11

Apollo 14

Apollo 15

Lunokhod 1

Lunokhod 2
**APOLLO Example Data**

**Apollo 15**

- **2007.11.19**
- magenta curves are theoretical profiles: convolve with fiducial to make lunar return

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

**Apollo 11**

- **2007.11.19**

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

Oct. 11, 2016

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**APOLLO Data & Precision**

- Ranging to all five reflectors (re-discovered L1 in 2010)
- Less reliance on A15 over time.
- Median nightly range error is 1.4mm
Quantify system timing accuracy

Comparison with lunar range models

• But… residuals of few-cm RMS
• Models under active development
  (see e.g. talks in this session, + JPL & PEP)

Few (but positive) internal APOLLO tests

• In a single night, NP scatter (about linear trend)
  consistent with quoted statistical uncertainties. Linear
  trend consistent with single change in site location.

• Ranging to $\geq 3$ reflectors in a session constrains lunar
  orientation, which builds confidence in NP uncertainty

(as described at previous IWLR meetings by Tom Murphy)
Compare segments over ~0.5 hr

We can get 1 mm range precision in single “runs” (< 10 minutes)

The scatter about a linear fit is small: consistent with estimated random error (true for all nights studied this way)

0.5 mm effective data point for Apollo 15 reflector on this night

Constraining lunar libration
Residuals if APOLLO data downweighted by 15mm RSS
Constraining lunar libration

When ≥ 3 reflectors, estimate ad-hoc libration correction per night

\[ \chi_r = 3.9 \]

\[ \chi_r = 1.8 \]

APOLLO data down-weighted by 15mm RSS. Large, unmodeled libration is indicated.

APOLLO data at full weight largely eliminates the libration offset.

1 nrad is 1.7 mm lateral motion on lunar surface
Absolute Calibration System

• Measure timing of short calibration laser pulses inserted at a known, stable rate

• Simultaneous with lunar ranging

An “optical ruler” overlaid on data.

Cs Frequency Standard
Microsemi 5071A
df/f ~ 10^{-12}

Fiber Laser
Toptica
PicoFYb
80 MHz

Laser locked to Cs with sub-ps jitter.
Absolute Calibration System

• Phase 1: Clock comparison: Cs vs. GPS
  Installed February 2016

• Phase 2: Laser (ranging with the ACS on)
  Installed August 2016

“Laser Slicer Board”
Phase 1: Clock installation (Feb. 2016)

12m fiber run to telescope

Universal Counter (Clock comparison)

Cs clock

GPS clock
Measure GPS clock offsets

From frequency difference between Cs and GPS clocks (measured by UC)

GPS clock offsets equivalent to ~2.5mm added in quadrature to the raw range precision

APOLLO NPs already included 1.4mm in quadrature as an estimate of this
Correct for GPS clock offsets
Correct for GPS clock offsets

Big bonus: can **retroactively apply** this correction to our **entire archive**
Phase 2: Laser + Electronics installation (August 2016)
Couple calibration photons into optical system without disruption to lunar ranging (45-deg mirror patch in shadow of secondary mirror)
Lunar returns are not synchronous with our 50 MHz system clock. Uniformly populate a 20ns-wide range of our timing space. TDC = time-to-digital converter. 4096 channels, 100ns range: 25ps/bin
ACS: an optical ruler

ACS comb
(for small clock drift)

STOP pulse

later

TDC Bin #

earlier

GPS clock
50 MHz

Cs clock
80 MHz

pick next

Oct. 11, 2016
ACS Observations atop Lunar Returns 2016.09.12

Total shots 10k
ACS photons (11k)
Lunar returns (3k)
Neither (bkg)
– clock comparison

Can tag ACS photons very efficiently even when overlaid with Lunar returns.

Use knowledge of ACS phase relative to GPS
ACS Observations atop Lunar Returns 2016.09.12

All events
Lunar returns
Neither (bkg)

Clear Lunar signal (3k photons in 10k shots), even amid heavy ACS rate (11k photons in 10k shots)
Measure $\Delta t$ of ACS for “transmit” and “receive” gates. Compare with $N \cdot 12.500000$ ns.

Find ~mm timing accuracy (in-situ, simultaneous with LLR observations)
Many possibilities with such a system…
Still the early days. For now:

- Clock comparison (Cs vs. GPS) reveal that GPS clock offsets cause ~2.5mm range error
- Can likely correct for ~75% of this over our entire 10-year data archive using logged GPS clock reports (10s)
- Can separate ACS photons from Lunar returns
- ACS overlaid on LLR data reveal no unexpected anomalies in our timing accuracy (~mm as expected)
- Next up:
  - measure channel-to-channel offsets, and time evolution, for each of the 16 APD channels
  - Probe/characterize time offsets induced by EM noise from laser fire (cavity dumped by switching 4kV in 1ns)
  - Use Cs as the APOLLO system clock?
Thank you!
Extras
APOLLO Optical System

Gravitational Redshift Signature

PPS of Cs minus PPS of XL-DC

Slope = 15 ns/d

Gravitational Redshift: $3.0 \times 10^{-13}$
Cs clock intrinsic: $-1.3 \times 10^{-13}$
Net: $1.7 \times 10^{-13}$

Predict: 15 ns/day phase accumulation
BS = beamsplitter; M = mirror; L = lens
FPD = fast photodiode
TDC = time-to-digital converter
APD = avalanche photodiode
T/R = transmit/receive
Coupling calibration light into receiver box
APOLLO Data & Precision

Results from Previous NSF Support

The NSF, together with NASA, has supported APOLLO in three installments. The first (NSF portion: PHY-0245061; $525,000) funded the initial construction and first-light. The second (NSF: PHY-0602507; $538,836) supported an observing campaign that began in 2006 and saw the installation of a superconducting gravimeter at Apache Point. The latest (NSF: PHY-1068879; $750,000) continued the observation effort and established a collaboration with the Planetary Ephemeris Program (PEP) group to pursue advances in LLR modeling.

3.1 Intellectual Merit of Previous Results

By the end of its first year of steady operation, APOLLO had realized its goal of millimeter range precision (formal, statistical measure) on a routine basis; Figure 1 shows the performance results. This accomplishment was due largely to APOLLO's high photon return rate. We have exceeded the previous record return rates (all held by the French station) by a factor of 70 for the three Apollo reflectors, and by a factor of 50 for the Lunokhod 2 array.

Figure 1:

APOLLO performance history. At left is the accumulated number of range points as a function of time. The larger Apollo 15 reflector—used for acquisition and instrument tests—dominates the dataset, although its fractional contribution trends downward. The discovery of Lunokhod 1 is apparent, as is a seasonal lull brought about by summer monsoon season. At right is the combined nightly statistical uncertainty for each reflector on each night of ranging. Many points lie below the line at 1 mm. The median uncertainties for the A11, L1, A14, A15, and L2 reflectors are 2.8, 3.7, 2.7, 1.9, and 5.2 mm, respectively. Combining all reflectors within a night yields a median uncertainty of 1.45 mm per night.

Uncertainties are per night, per reflector
Medians are 2.4, 2.7, 2.4, 1.8, 3.3 mm for A11, L1, A14, A15, L2, respectively
Combined nightly median range error is 1.4 mm
## APOLLO Random Error Budget per Photon

<table>
<thead>
<tr>
<th>Error Source</th>
<th>rms Error (ps)</th>
<th>rms Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APD illumination</td>
<td>60</td>
<td>9</td>
</tr>
<tr>
<td>APD intrinsic</td>
<td>&lt;50</td>
<td>&lt;7.5</td>
</tr>
<tr>
<td>Laser pulse</td>
<td>45</td>
<td>7</td>
</tr>
<tr>
<td>Timing electronics</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>GPS clock</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Total APOLLO</td>
<td>93</td>
<td>14</td>
</tr>
<tr>
<td>Retroreflector array</td>
<td>100–300</td>
<td>15–45</td>
</tr>
<tr>
<td>Total random uncertainty</td>
<td>136–314</td>
<td>20–47</td>
</tr>
</tbody>
</table>
APOLLO in action

Credit: Dan Long