APOLLO: One-millimeter LLR

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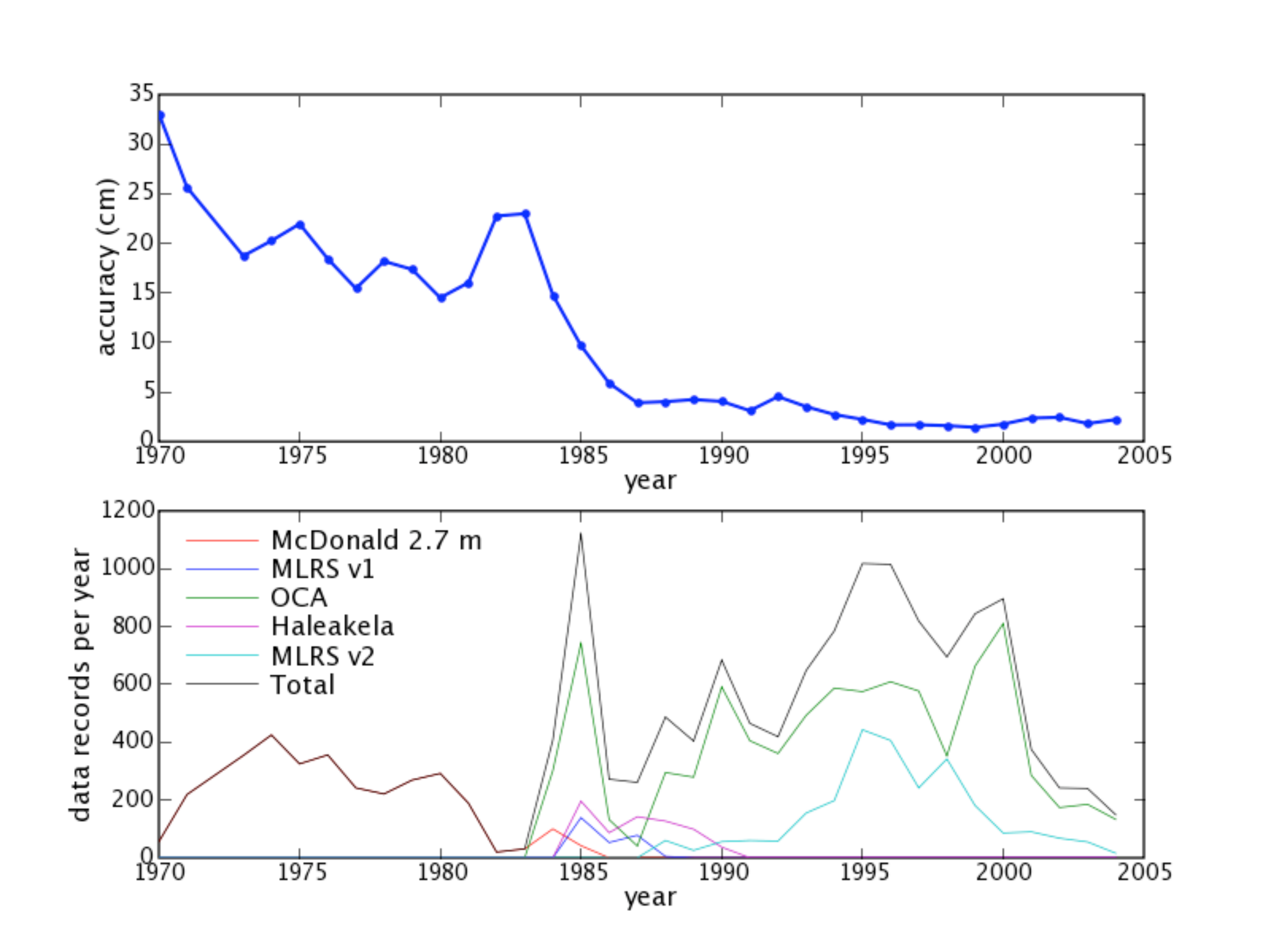
Background photo by Jack Dembicky

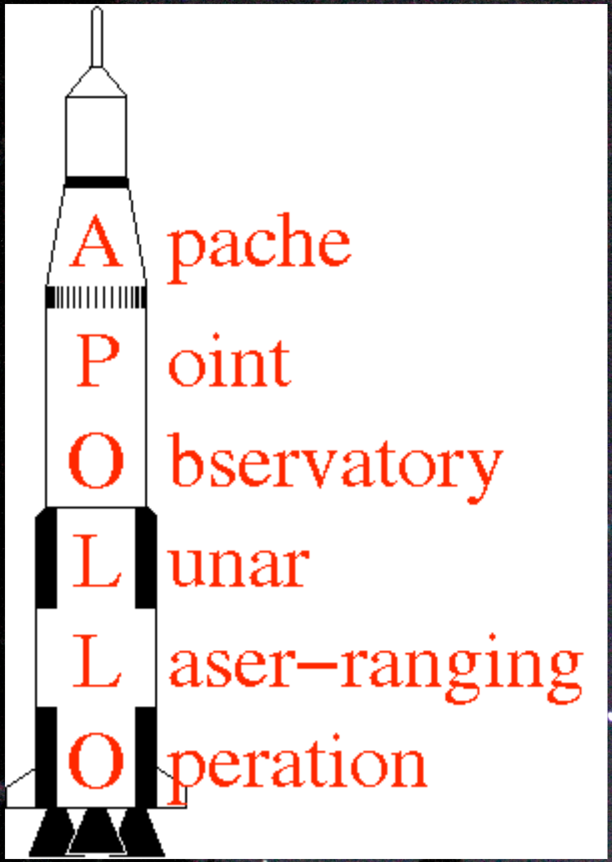
Testing Gravity

- Gravity is the most poorly-tested of the fundamental forces
  - owing to its relative weakness
  - how do we reconcile the incompatibility of gravity and quantum mechanics?
  - is the apparent acceleration of the universe a consequence of our not understanding large-scale gravity?
- Lunar Laser Ranging (LLR) provides many of our most incisive tests of gravity
  - tests Weak Equivalence Principle to $\Delta a/a < 10^{-13}$
  - tests the Strong Equivalence Principle to $< 4\times10^{-4}$
  - time-rate-of-change of G: $< 10^{-12}$ per year
  - geodetic precession: to < 0.6%
  - $1/r^2$ force law: to $< 10^{-10}$ times the strength of gravity (at 10^8 m scales)
  - gravitomagnetism (frame-dragging) to < 0.1%
- APOLLO, through 1 mm ranging, will improve all of these limits by approximately 10×

Historic LLR Range Precision

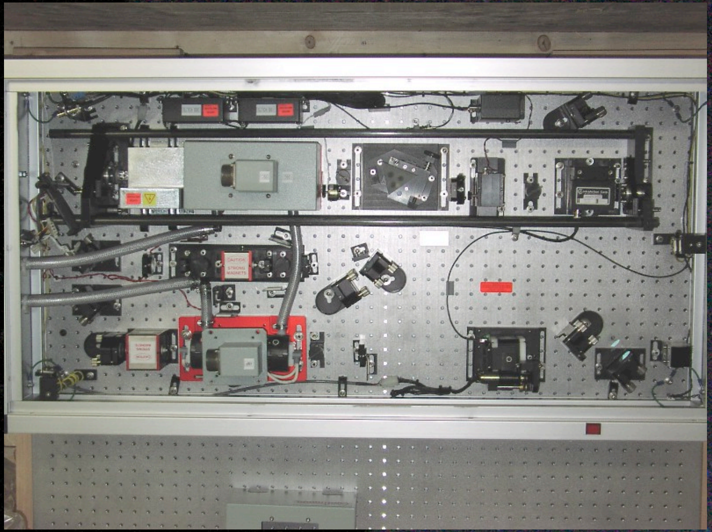


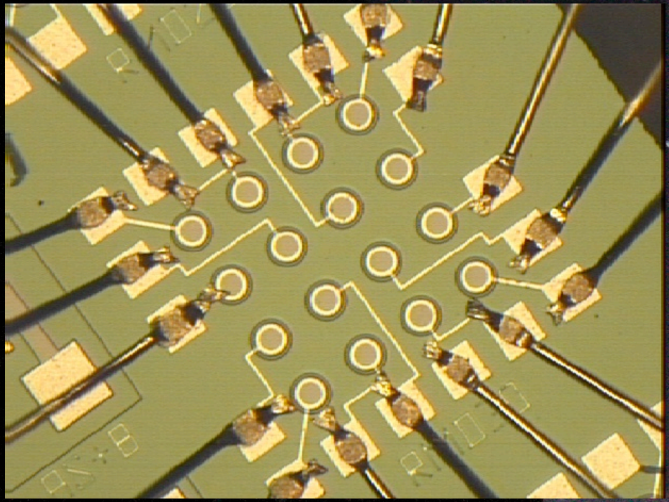
APOLLO: Achieving the 1 mm Goal



- APOLLO offers order-of-magnitude improvements to LLR by:
  - Using a 3.5 m telescope at a high elevation site
  - Using a 16-element APD array
  - Operating at 20 Hz pulse rate
  - Multiplexed timing capable of detecting multiple photons per shot
  - Tight integration of experiment with analysis
  - Having a fund-grabbing acronym
    - APOLLO is jointly funded by the NSF and by NASA

APOLLO Instrument Overview

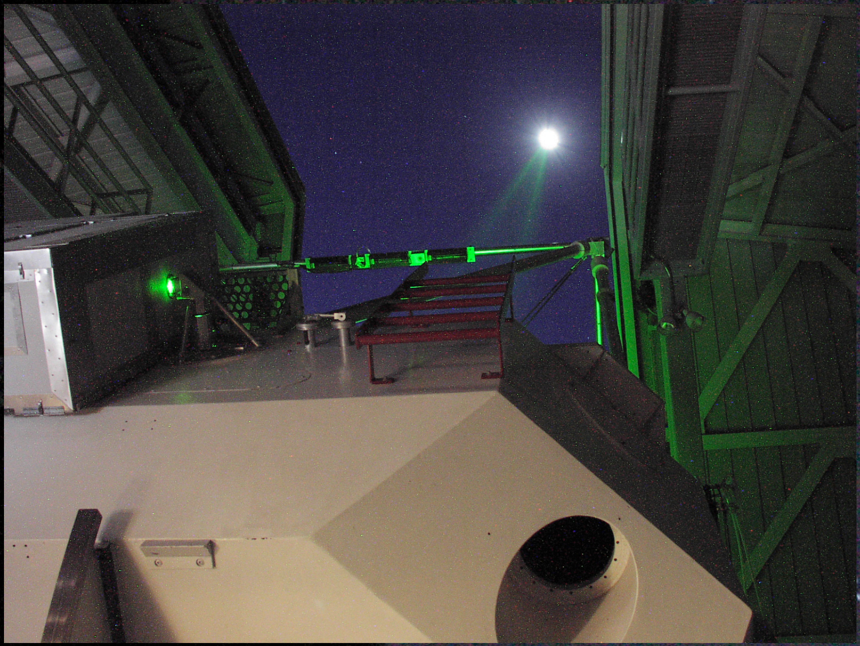




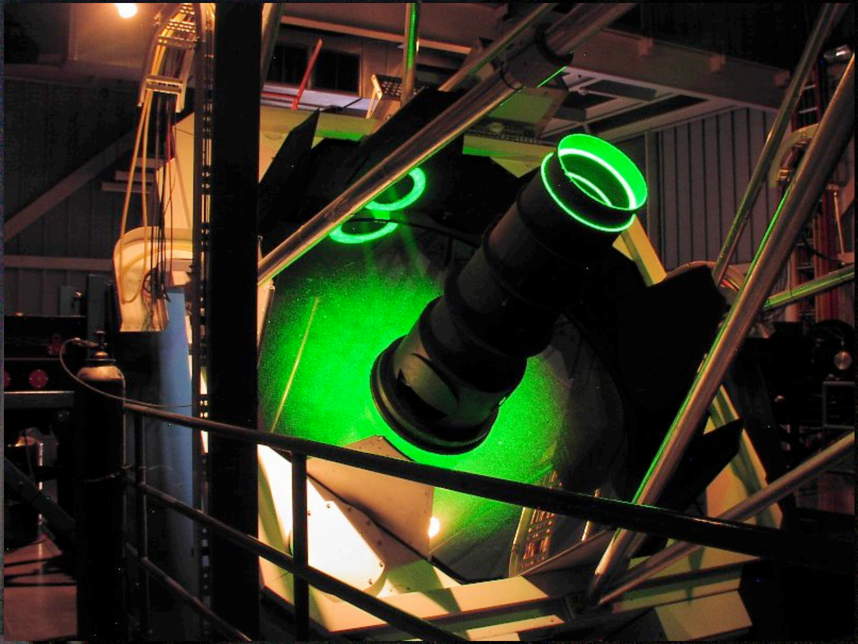
- Laser:
  - 532 nm Nd:YAG, mode-locked, cavity-dumped
  - 90 ps pulse width
  - 115 mJ per pulse
  - 20 Hz
  - 2.3 W average power
- Detector: APD Array
  - 4×4 Silicon array made by Lincoln Lab
  - 30 μm elements on 100 μm centers
  - Lenslet array in front recovers fill-factor
  - 1.4 arcsec on a side (0.35 arcsec per element)
  - allows multi-photon returns
  - permits real-time tracking

Laser on Telescope

System in Action



For a complete description of instrument, see the article published in the Publications of the Astronomical Society of the Pacific (PASP), volume 120, p. 20 (2008)

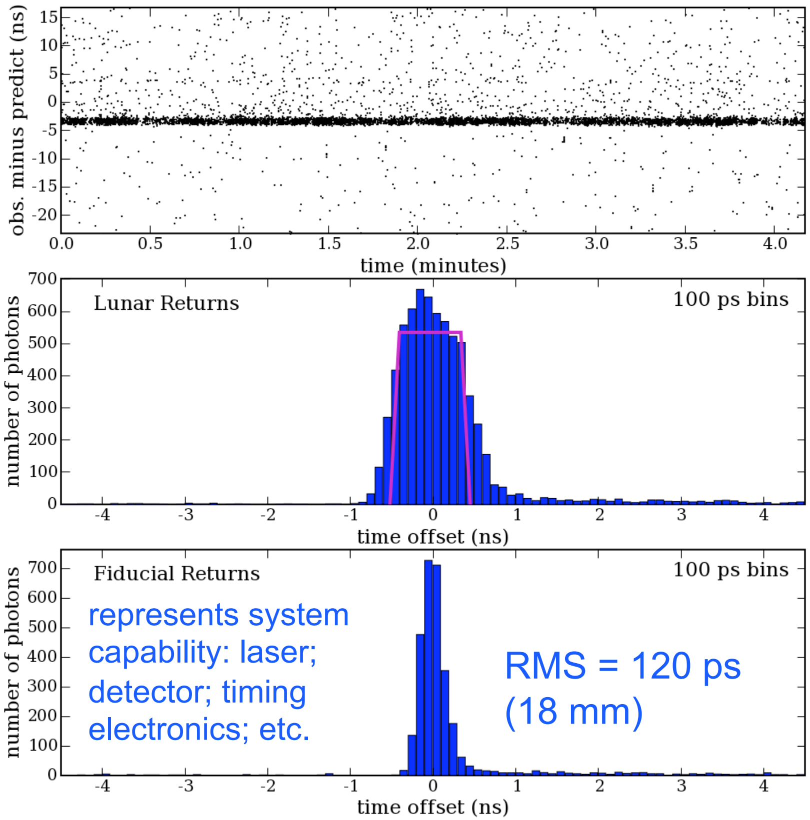


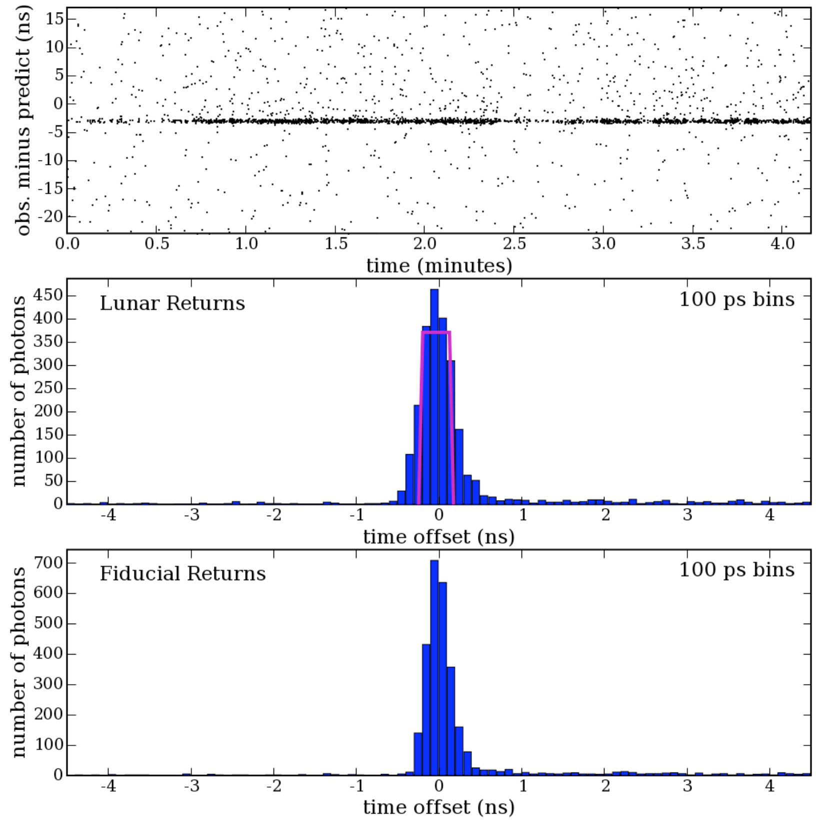
APOLLO Example Data

Apollo 15 2007.11.19 Apollo 11

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

which array is physically smaller?



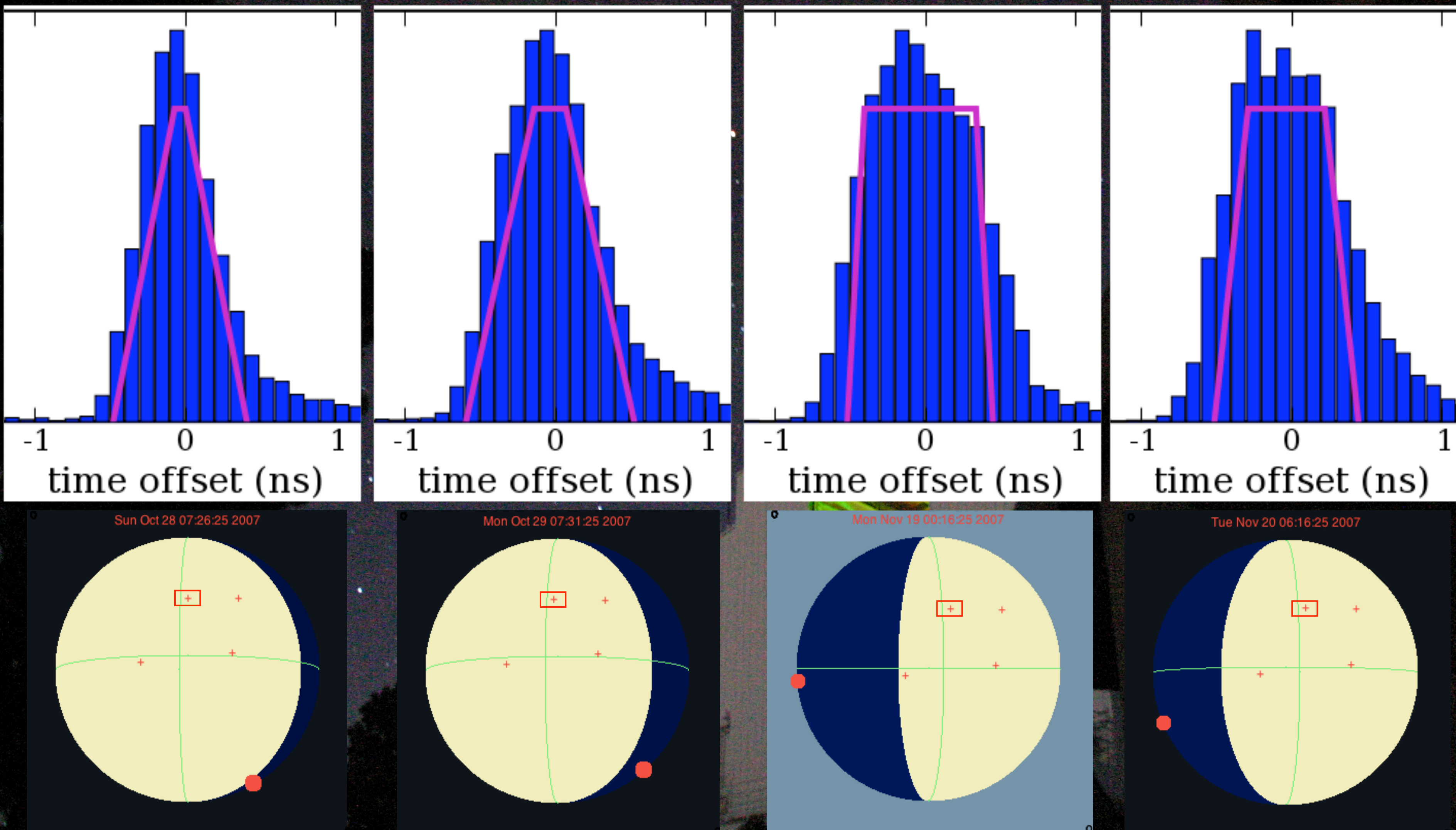


- 6624 photons in 5000 shots
- 369,840,578,287.4 ± 0.8 mm
- 4 detections with 10 photons

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

Sensing Array Size and Orientation

2007.10.28 2007.10.29 2007.11.19 2007.11.20



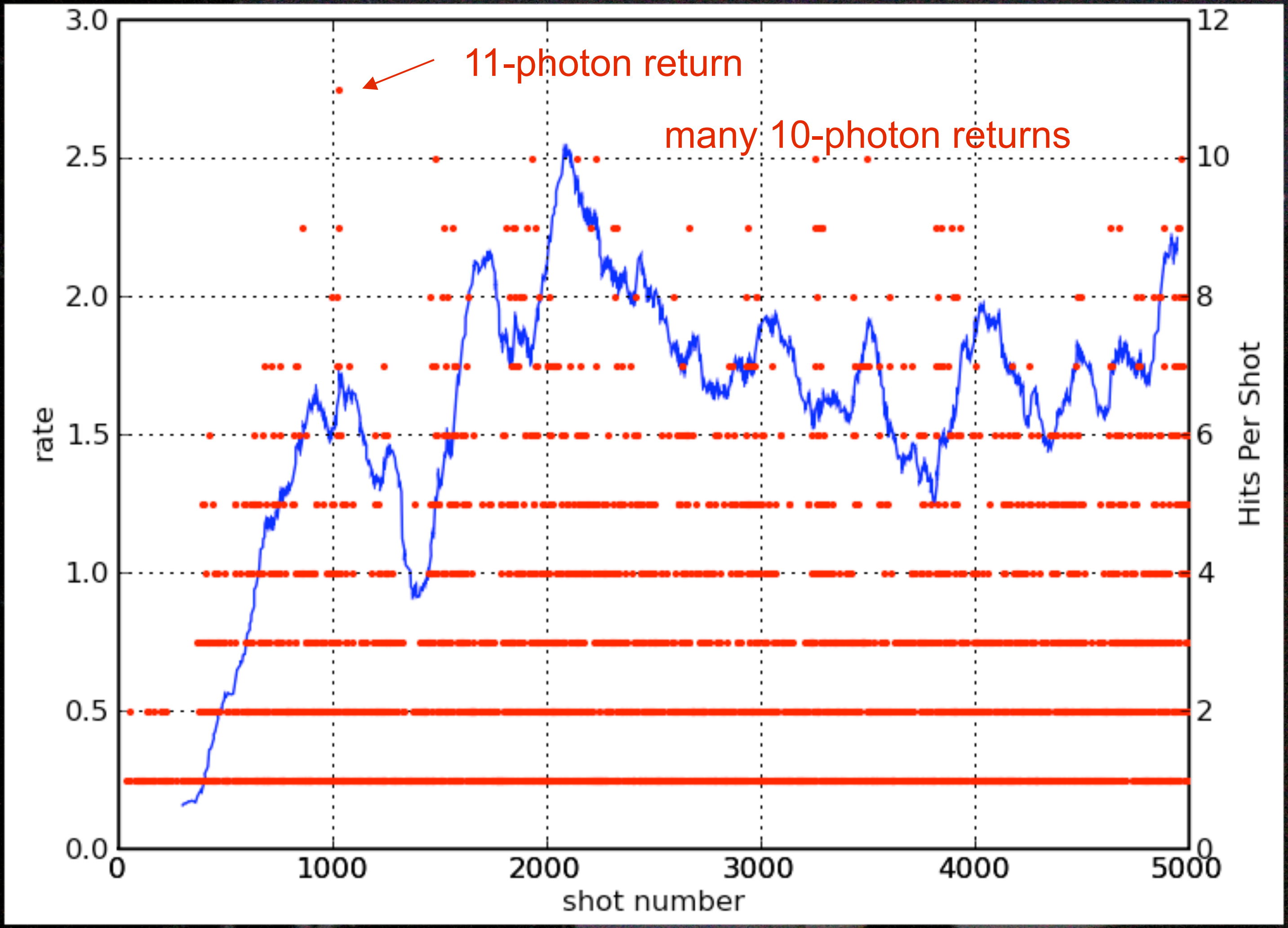
APOLLO Return Rates

Reflector	APOLLO max photons/run	APOLLO max photons/5-min	APOLLO max photons/shot (5 min avg)	APOLLO max photons/shot (15 sec avg)
Apollo 11	4288 (25×)	3120 (38×)	0.52	1.0
Apollo 14	5100 (24×)	5825 (44×)	0.97	1.4
Apollo 15	12524 (21×)	9915 (35×)	1.65	2.8
Lunokhod 2	750 (11×)	900 (31×)	0.15	0.24

(relative to pre-APOLLO record)

- APOLLO's best runs are solidly in the multiple photon/shot regime
  - APD array is crucial for catching all the photons
  - Have seen 11 of 13 functioning APD elements register lunar photons in a single shot
  - see approximate 1:1:3 Apollo reflector ratio; Lunokhod is reduced
- Can operate at full moon (background not limiting), but signal is far weaker than expected (by 100×)
- Overall signal is still about 10× weaker than we expect

Strong Apollo 15 Run: Stripchart

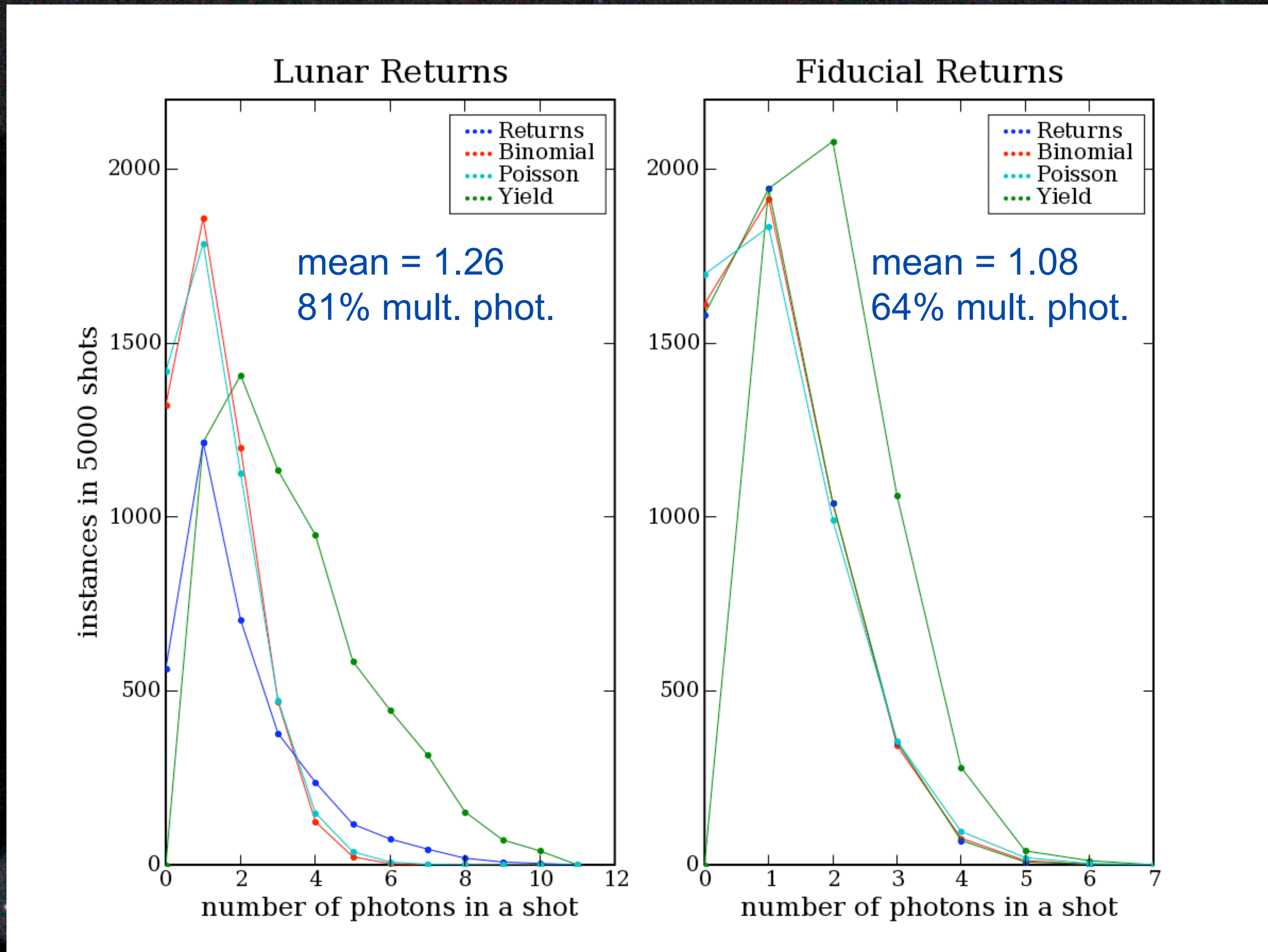


Stripchart based on 300-shot (15 sec) running average rate (blue curve), represented in photons per shot (left axis).

Red points indicate photon count (within 1 ns of lunar center) for each shot (right axis).

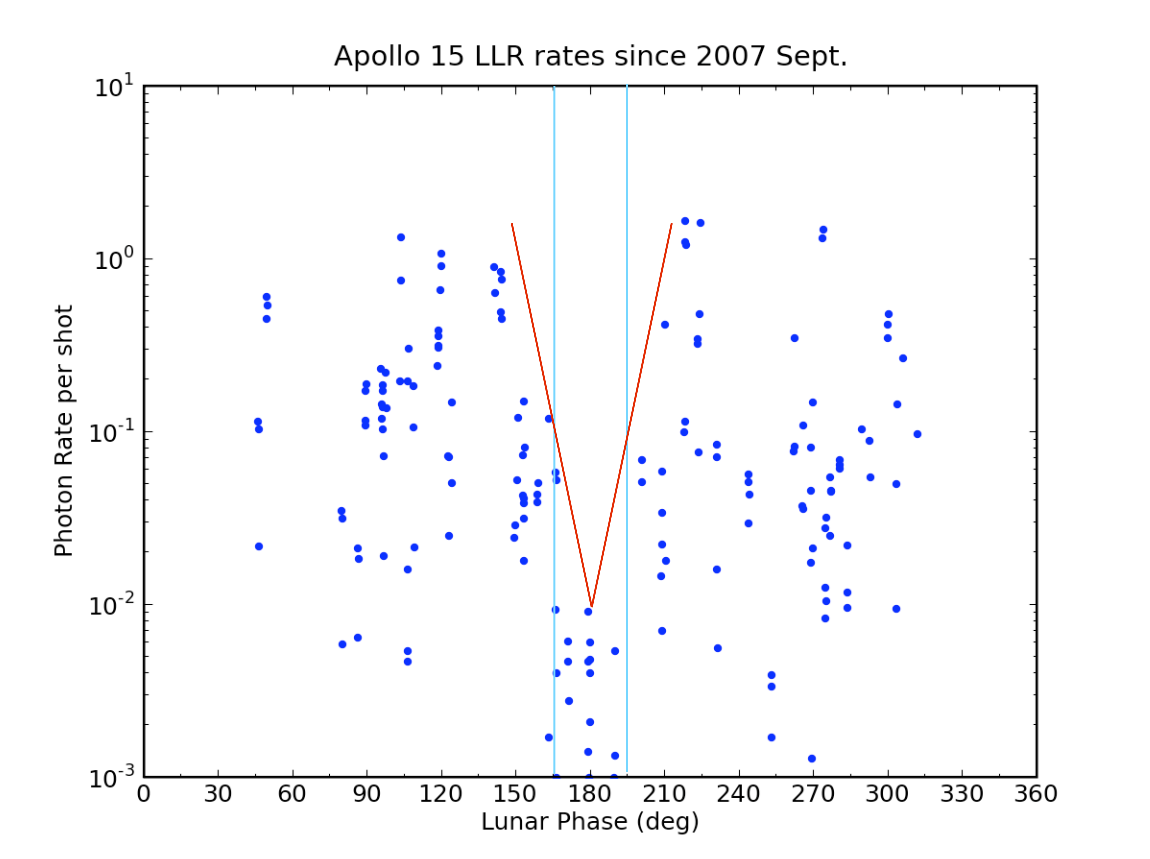
One shot delivered 11 photons, many delivered 10, and so on.

Catching All the Photons?



The Lunar returns (blue; left) deviate substantially from binomial (red) (due to speckle)
The Fiducials are faithful to binomial (thus the lunar deviation is not a systematic issue)
But the trailing-off of lunars suggests we're catching (virtually) all the photons

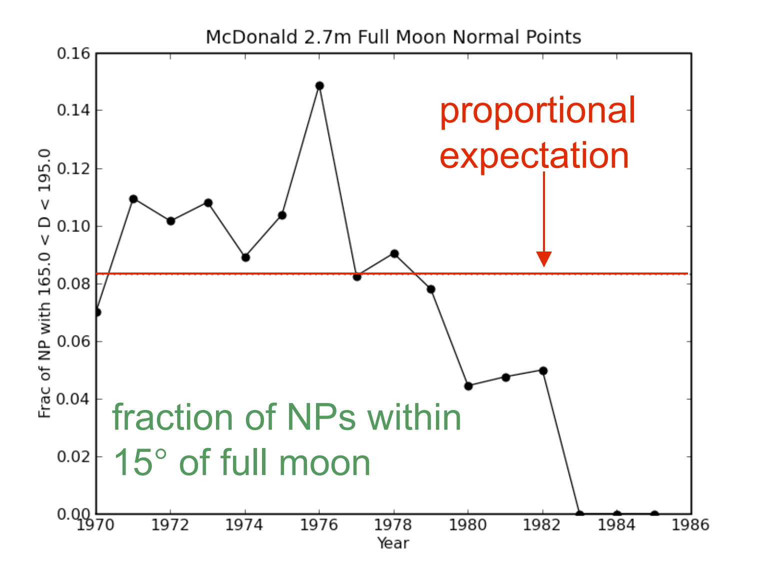
The Full Moon Hole



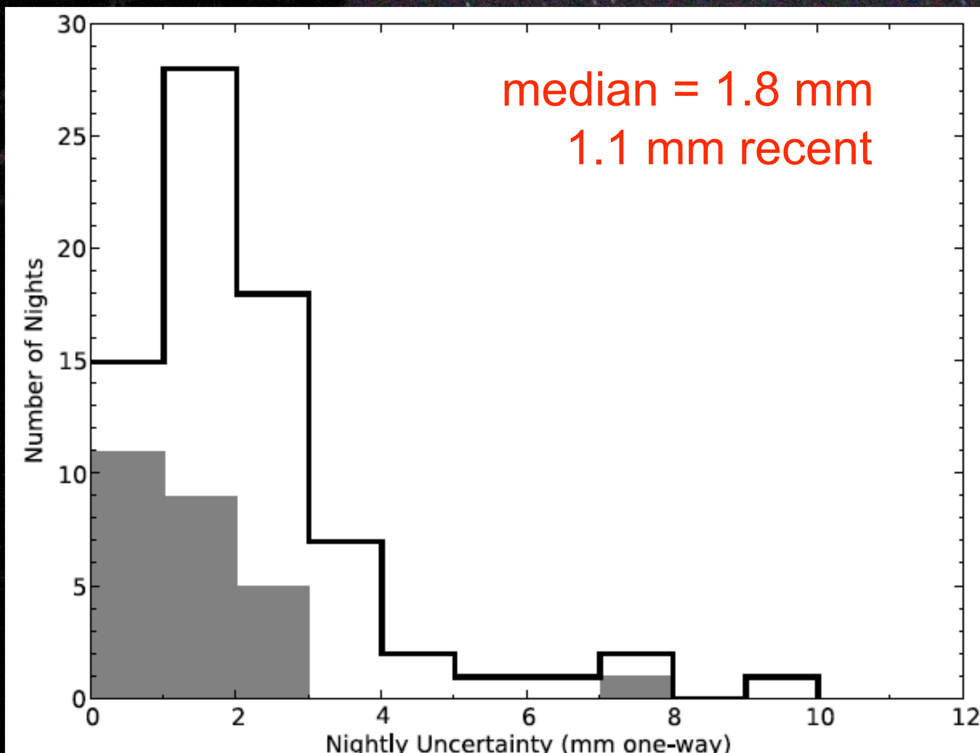
This log plot shows our Apollo 15 return rates as a function of lunar phase angle, D. Within 15° of full moon (D=180°), we see a hundred-fold reduction in signal.

This is not due to background.

The 2.7 m McDonald LLR station routinely got full-moon normal points, until about 1980. They ultimately stopped scheduling full moon times.



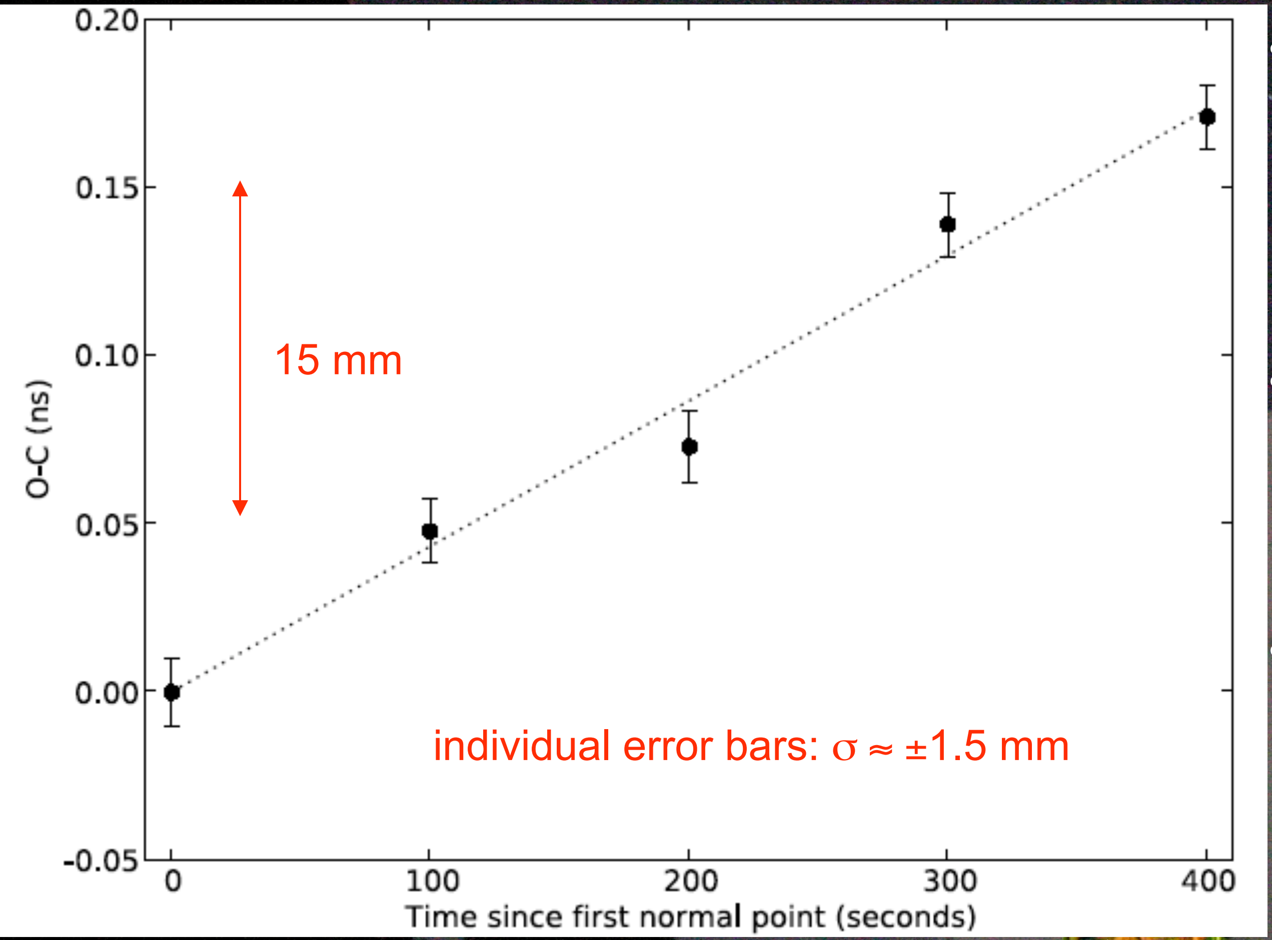
Reaching the Millimeter Goal?



shaded → recent results

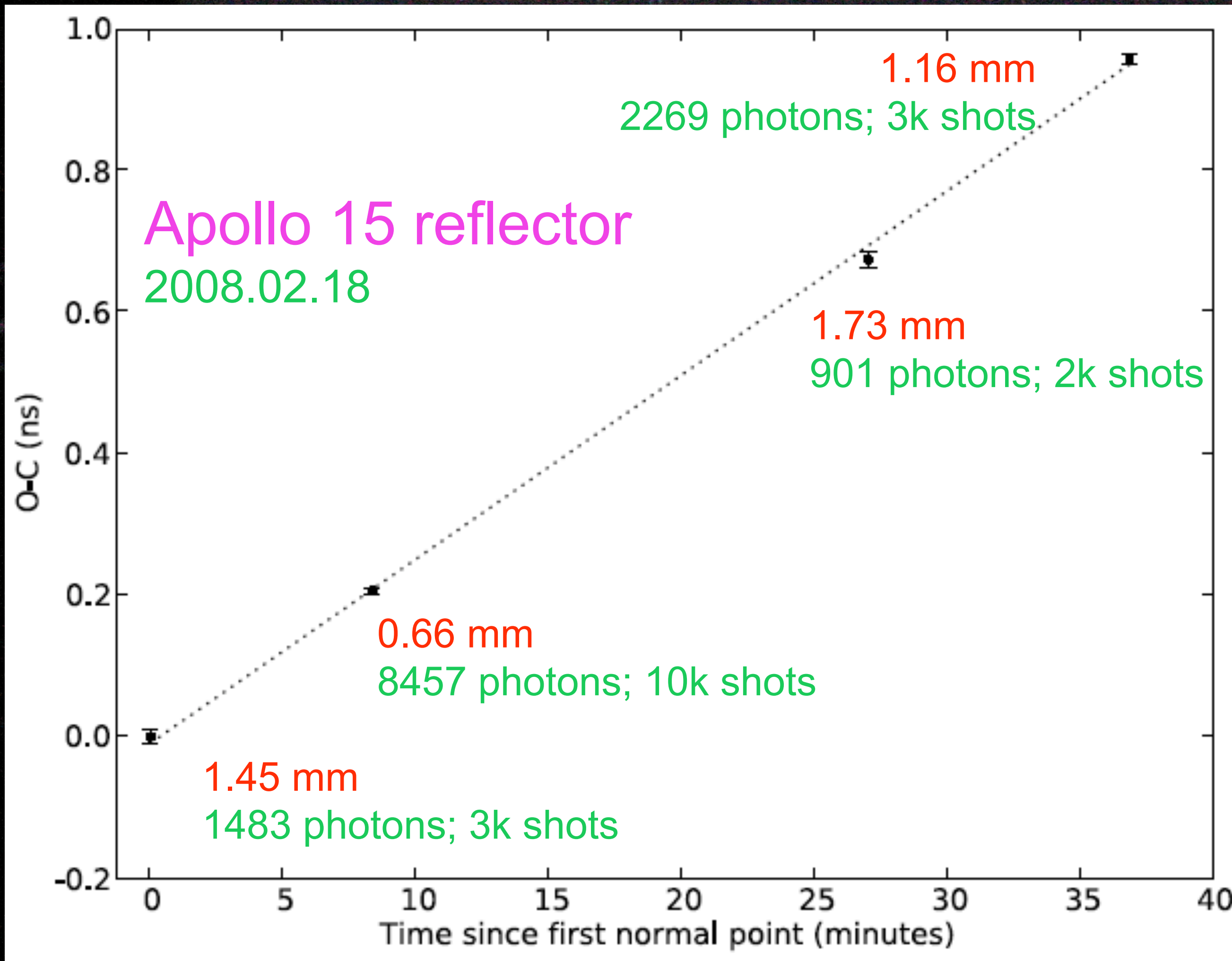
- 1 millimeter quality data is frequently achieved
  - especially since Sept. 2007
  - represents combined performance per reflector per night (< 1 hour observing session)
  - random uncertainty only
- Virtually all nights deliver better than 4 mm, and 2 mm is typical

Residuals Within a Run



- Breaking a 10,000-shot run into 5 chunks, we can evaluate the stability of our measurement
- Comparison is against imperfect prediction, which can leave linear drift
- No scatter beyond that expected statistically
  - consistent behavior for each run we've evaluated in this manner

Residuals Run-to-Run



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 (also true for all nights studied this way)

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

JPL Model Residuals

residuals plot redacted at request of JPL

Data points→individual “runs”; alternating shades→whole sessions

APOLLO data points processed together with 16,000 ranges over 38 years shows consistency with model orbit

Fit is not yet perfect, but this is expected when the model sees high-quality data for the first time, and APOLLO data reduction is still evolving as well

Weighted RMS is about 8 mm

$\chi \approx 3$ for this fit

APOLLO Impact on Model

residuals plot redacted at request of JPL

Data points→individual "runs"; alternating shades→whole sessions

If APOLLO data is down-weighted to 15 mm, we see what the model *would* do without APOLLO-quality data

Answer: large (40 mm) adjustments to lunar orientation—as seen via reflector offsets (e.g., arrowed sessions)

May lead to improved understanding of lunar interior, but also sharpens the picture for elucidating grav. physics phenomena

Current Status and Future Plans

- APOLLO is now beginning its third year of steady science campaign
  - our very best month was 2008 September, so still improving
  - we expect science results will be possible soon, awaiting model developments
  - working on data reduction subtleties (first photon bias, 16-element detector array)
- Part of the APOLLO goal is to more tightly integrate experimental and analysis efforts
  - this has been surprisingly difficult
  - asymmetric expectations (data vs. analysis results)
  - starting to work with Reasenberg/Shapiro/Chandler at Harvard/CfA to update the Planetary Ephemeris Program (PEP) to become an OPEN SOURCE cutting-edge analysis tool for LLR and solar system analyses
  - contact me if interested in contributing