# APOLLO: Two Years of Science Data

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## Abstract

*APOLLO is a newly operational lunar ranging experiment aimed at achieving one-millimeter range precision in an effort to better probe the nature of gravity. After two years of operation, we can characterize its performance as obtaining return rates at least an order-of-magnitude higher than previous stations, attaining a resultant random uncertainty at the few-millimeter level. Such precision presents a new challenge to model capabilities, which will lead to improved scientific knowledge.*

## Introduction

The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) was established in an attempt to push lunar laser ranging (LLR) capabilities to a new regime of one-millimeter range precision as a way to advance tests of general relativity. LLR has long stood at the forefront of testing general relativity, boasting the best tests to date of the strong equivalence principle, time-rate-of change of Newton's gravitational constant, geodetic precession, the inverse-square law, and gravitomagnetism (see Williams et al., 1996; Murphy et al., 2007). Therefore, extending the precision capability of LLR promises to advance our understanding of gravity in a number of ways. In addition to improving our knowledge of gravity, LLR offers insight into properties of the lunar interior, earth orientation, and tidal processes on Earth.

## The Instrument

APOLLO is installed on the 3.5 meter astronomical telescope at the Apache Point Observatory in southern New Mexico at an altitude of 2780 meters. The telescope has a median image quality—including atmospheric seeing—below 1.5 arcsec, and is competitively scheduled for a variety of astronomical observations. A detailed description of the apparatus appears in Murphy et al. (2008). Here, we just summarize the principal features. APOLLO consists of:

- A 20 Hz, 90 ps pulse, 115 mJ/pulse, Nd:YAG laser operating at 532 nm
- A 16-element avalanche photodiode array detector, in 4×4 format, spanning 1.4 arcseconds on a side
- A 16-channel timing system with 25 ps resolution and 15 ps jitter
- Identical optical path/electronics fiducial corner cube measurement at the single-photon level

- Automation for remote operability and environmental self-control

APOLLO is typically allocated approximately 8–10 one-hour slots of telescope time per lunar month, typically allowing a few dozen normal point measurements to the various reflectors each month. The observations are primarily performed by R. McMillan, either at the site or remotely, with another APOLLO member participating in the observation and ready to assume control of the operation if necessary.

## Performance

The large aperture and good atmospheric conditions at the site permit APOLLO to detect multiple photons per pulse, thus necessitating the multiple-element detector array. Record yields may be characterized by photons per shot or photons per unit time, and characterized by maximum net yield or maximum net rate. Table 1 summarizes the results below. Note that a number of the records were obtained on the last day of the conference in Poznan.

**Table 1:** Summary of APOLLO record runs

| Reflector | Date | Laser Shots | Photons detected (× prev. record) | Photons/minute (× prev. record) | Phot/shot |
|---|---|---|---|---|---|
| Apollo 11 | 2008-10-17 | 5000 | 4497 (26×) | 1079 (65×) | 0.90 |
| Apollo 14 | 2008-10-17 | 5000 | 7606 (36×) | 1825 (69×) | 1.52 |
| Apollo 15 | 2008-10-17 | 5000 | 15730 (26×) | 3775 (67×) | 3.15 |
| Lunokhod 2 | 2008-09-22 | 5000 | 750 (11×) | 180 (31×) | 0.15 |

Aside from Lunokhod 2—which no longer performs as well as the Apollo reflectors, there is a remarkable consistency in the peak rate seen per reflector compared to that of the previous record runs. APOLLO appears to have record rates roughly two-orders of magnitude higher than the previous records (all obtained from OCA). Given more time, APOLLO will almost certainly improve on the records presented here. Since it is APOLLO's goal to improve precision by an order-of-magnitude—and this requires two orders-of-magnitude higher photon number if the result is statistically dominated—the photon performance of APOLLO is encouraging.

Figure 1 shows returns from Apollo 15 and 11 on 2007 November 19, in which 2346 and 3731 photons were recorded, respectively. In a temporary scheme to minimize the effect of first-photon bias, our current data reduction excludes pulses delivering multiple photon detections. Thus the plots in Figure 1 only display 1155 and 1041 photons that arrived as single-photon detections. Because the moon was at the same libration angle for both sets of data (taken minutes apart), and the arrays are both aligned to point at the mean-earth position within 1°, we can see immediately the smaller physical size of the Apollo 11 array.

The statistics of returning photon packets from the moon are subject to variations from—among other things—speckle interference from atmospheric turbulence. The illumination pattern on the moon is a complex and random array of hot-spots and valleys, numbering roughly $D/r_0$ across (thus this number squared for total number of speckles), where $D$ is the diameter of the laser beam and $r_0$ is the atmospheric Fried parameter, such that the atmospheric seeing scale is $\lambda/r_0$. For APOLLO, $D/r_0 \approx 20$, and is larger in bad seeing. The result is that many pulses deliver very strong returns when a “hot-spot” happens to land on the lunar reflector. Because we have a multiple-photon detector, we can verify these statistics.

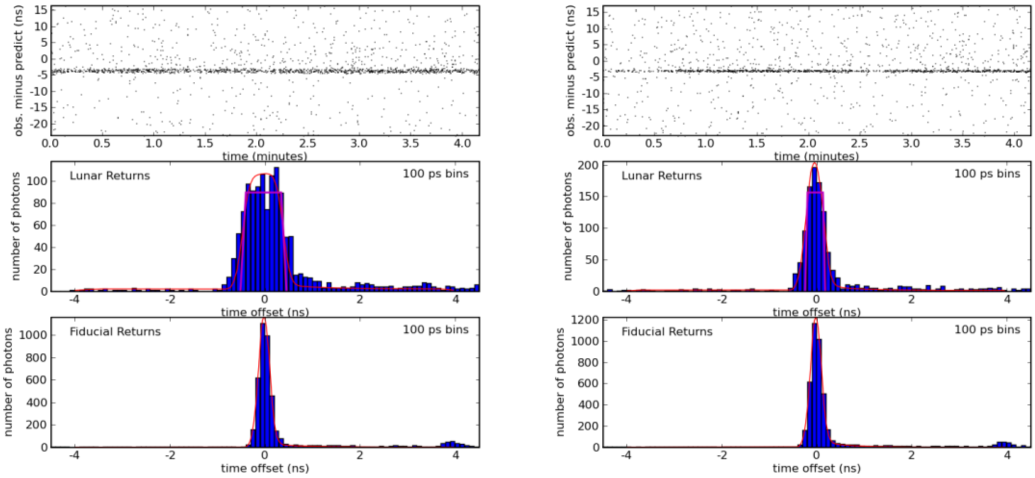

**Figure 1.** 5000-shot runs on Apollo 15 (left) and Apollo 11 (right) on 2007 November 19. The total yields for the two runs are 3371 and 2346 photons, respectively—though only 1155 and 1041 are shown here. The lower histogram is the local (ficucial) corner cube, showing a 120 ps standard deviation. A functional fit to the fiducial is convolved with the trapezoidal response from the lunar array (shown superimposed on the lunar return) to form a fit-function for the lunar return. Note that the Apollo 11 array is obviously physically smaller than the Apollo 15 array.

For example, the 5000-shot Apollo 15 observation pictured in Figure 1 resulted in 702 shots with zero photons, 1062 shots with one photon, 471 shots with two photons (thus 942 photons), 225 shots with three, 98 with four, 47 with five, 27 with six, 13 with seven, 3 with eight, and finally 1 shot returning nine photons. This adds to a total of 3592 photons (selection criterion slightly more restrictive than the one that produces estimate of 3731 photons used above). This means over 70% of detected photons arrived in bundles of more than one photon. If the distribution followed a Poisson behavior, a return of 3592/5000, or a mean of 0.718 per pulse would deliver only 51% of photons in multi-photon returns, and would not be expected to produce more than one return with as many as 5 photons, out of 5000 trials. Strictly speaking, the proper distribution in an APD detector is binomial, because any given element will either report a detection or not, but is not capable of reporting the detection of more than one photon in a single element.

We can ask the question: Does APOLLO have *enough* detector elements—are we missing any events? Figure 2 addresses this question. It is clearly seen that the lunar distribution does not adhere to either Poisson or binomial statistics, being “top-heavy” with strong returns from speckle. But even for the strong run pictured, where 81% of the lunar returns arrived in multi-photon packets, the distribution terminates naturally before we run out of detector elements. Thus we can be reasonably assured that we are catching all the detectable photons with APOLLO, and therefore can anticipate being able to correct for multi-photon bias. Note also the remarkable adherence of the fiducial data to binomial statistics. At every data point (save the cross-over at $n = 3$), the data identifies with the binomial point rather than the Poisson point. This provides additional reassurance that we understand our device statistics.

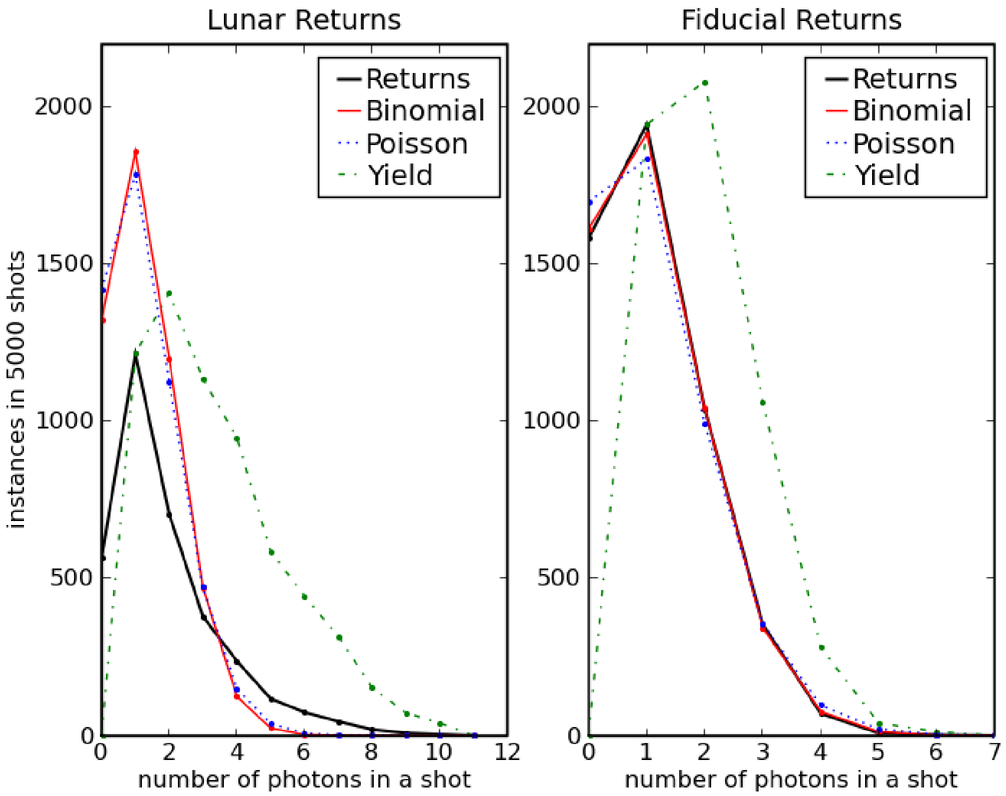

**Figure 2.** Study of photon count statistics for both the lunar and fiducial returns. In the lunar case, the return rate average was 1.26 photons per shot, with 81% of photons in multi-photon packets. For the fiducial, the average was 1.08 photons per shot, 64% in multi-photon clusters. In each, measured returns (number of shots with that number of photons) are thicker black lines, and comparative binomial and Poisson distributions are shown in red solid and blue dotted lines, respectively. The green dash-dot line is a multiplication of the return (black) line by the number of photons, to represent the total photon number as a function of photons per shot. While the binomial and Poisson distributions are very similar, the fiducial data clearly picks out the binomial distribution as correct (in fact, the black line is largely hidden by the red one).

## Precision Assessment

High photon yield is *necessary* for achieving high precision, but it is not in itself *sufficient.* In the worst-case libration angle of 10°—resulting in the greatest array-induced spread—the standard deviation of lunar return photons may be 450 ps, as depicted for Apollo 15 in Figure 1. One millimeter one-way determination corresponds to 6.7 ps of round-trip time, which would necessitate approximately a 70-fold increase in precision over that offered by a single photon, requiring 4900 photons. APOLLO can clearly achieve the requisite photon number, but there may be other instrumental errors that preclude APOLLO from reaching its one-millimeter precision goal. Where random uncertainty is concerned, APOLLO appears to me reaching the millimeter mark, as illustrated by Figure 3.

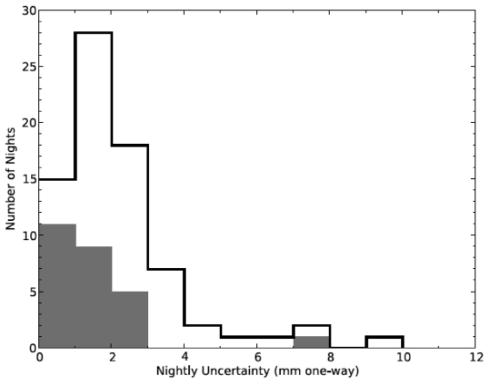

**Figure 3.** Summary performance of APOLLO normal points, averaged per night per reflector. The median is 1.8 mm for all data (2006 April through 2008 February), though for “recent” data (shaded: 2007 September through 2008 February) the median is lower, at 1.1 mm.

Ultimately, one must compare against a model that contains all relevant physics, the parameters of which are determined by a least-squares fit to the data. But no model has yet demonstrated one-millimeter LLR fidelity. So for the short term, we must find alternate means of assessment. One way to explore the data quality is by comparing against the prediction used for data acquisition. The prediction we use is only good to a round trip of about 1 ns (150 mm one-way) over the long term. But within a one-hour observation block, the departure from truth is reduced to a behavior that is almost entirely linear with time. Thus we can look for scatter or otherwise nonlinear departures of APOLLO data from the prediction. Such analysis was extensively pursued in Battat et al., (2009), and here we only summarize the results.

We have applied two methods to seek possible deviations from linear behavior. The first is to break strong runs into segments, applying our data reduction analysis to each segment in turn. The second is to look at the trend of normal points from the same reflector taken over a one-hour observation period. In short, we have not yet seen deviations from linear performance for either method. The scatter we see is consistent with our estimated errors based solely on the standard deviation of the return profile divided by the square root of the number of photons constituting the measurement. This is not a conclusive statement about APOLLO accuracy: the remaining linear trend may not be wholly due to prediction inadequacy, and the night-to-night variations are not probed by this method. At the least, it is a reassuring check on the performance.

A separate indicator that the APOLLO estimated uncertainties are approximately correct is the behavior of the residuals against the LLR model employed by the Jet Propulsion Laboratory (JPL). APOLLO is frequently able to make several rounds among the reflectors within a single one-hour session. When APOLLO data is downweighted to 15 mm uncertainty per normal point, the post-fit residuals show coherent clustering by reflector, the spread of points for a given reflector being consistent with the original normal-point uncertainty estimates, but in disagreement with other reflectors. This is symptomatic of a lunar orientation offset. When APOLLO data is fit at full weight, the model is able to eliminate the spread from one reflector to the next, indicating that the APOLLO data contains true coherence that is useful to the model, well below the 15 mm level. This is a point of further reassurance, but does not in itself address longer-term systematics. For this, we must pursue further model development.

## Unsolved Mysteries

Despite the high photon return from APOLLO, we still have a signal deficit compared to expectations. We reported in the proceedings from the 15th International Workshop on Laser Ranging that a careful attempt to calibrate the signal strength fell a factor of 12–16 short, even with knowledge of the beam footprint on the lunar surface. This work was based on a maximum photon rate of 0.6 photons per pulse—far exceeded by now. But the narrow-band filter used at the time was calculated for 35% transmission, whereas the current filter has a transmission > 90%. The net effect is that we still have a factor of ten discrepancy, though we will continue to look for ways in which we may have misunderstood our system.

Potentially associated with the signal deficit is a pronounced performance gap near full moon. When the moon is within 15° of full, we have difficulty acquiring any signal at all, and not because of increased background. The actual signal level is down by a factor of 15 or more compared to the rates we see away from full moon (we closed the gap somewhat since the Poznan presentation, when the gap was a factor of 100). Meanwhile, the background rate goes from 0.15 photons per gate across 16 channels (thus 0.01 per gate per channel) to about 1.0 photons per gate across all channels (thus < 0.1 per channel per gate). The background trend as a function of lunar phase is smooth and well-behaved, reaching a peak at full moon with no discontinuities in behavior near full moon.

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