APOLLO Performance and Data Quality

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Abstract

The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) has entered its tenth year of a steady observation campaign, primarily in pursuit of improved tests of gravitation. APOLLO achieves millimeter-level range precision, routinely ranges to all five reflectors on the Moon, and has seen strong evidence for degradation of reflector performance.

1 APOLLO Overview

APOLLO is an LLR (lunar laser ranging) station situated on the 3.5 m astronomical telescope at the Apache Point Observatory (APO) in southern New Mexico at an altitude of 2800 m. APOLLO obtains approximately 60 hours per year of telescope time (1.7% share), broken into sessions typically lasting about one hour each. Weather and other factors permit successful operation just over 50% of the scheduled time.

APOLLO uses a Nd:YAG laser frequency-doubled to 532 nm, emitting 100 mJ pulses 100 ps in duration 20 times per second. The laser is collimated to emerge from the telescope with sub-arcsecond ($< 5\,\mu$rad) divergence, so that atmospheric seeing—typically 1–2 arcsec at APO—is the limiting factor in signal return rate. At this divergence, accurate telescope pointing becomes a significant challenge. The detector employed by the APOLLO apparatus is a 4×4 avalanche photodiode (APD) array fabricated by Lincoln Laboratory. The detector currently installed has 40 μm circular APD elements on a square grid spacing having a 100 μm pitch. Photon detection efficiency is approximately 50%, and timing jitter is in the neighborhood of 50 ps in our current electronics implementation. A lenslet array in front of the detector recovers the fill-factor of the otherwise sparse (13%) coverage. More details on the apparatus may be found in Murphy et al. (2008) [1].

APOLLO also hosts a superconducting gravimeter mounted on the concrete pier of the 3.5 m telescope. Noise performance is better than 1 nm s^{-2} in one-second intervals. For reference, raising the gravimeter away from the center of the Earth by one millimeter affects a 3 nm s^{-2} change in the strength of gravity. Using the gravimeter, we may not only constrain Earth tides at the station, but also measure loading phenomena from ocean, atmosphere, and local hydrology.

2 APOLLO Data

APOLLO began acquiring science-quality data in April 2006, and began a steady observation campaign in October of that year. Table 1 presents the performance statistics for the entire period. For

Table 1: APOLLO Data Collection Statistics

year	sched. nights	sched. hours	actual nights	NP	A11	Lk1	A14	A15	Lk2	1×	2×	3×	4×	5×
2006	60	113	22	84	9	0	8	67	0	14	3	5	0	0
2007	92	100	45	161	29	0	32	96	4	14	7	22	2	0
2008	91	91	47	303	60	0	64	156	23	10	7	17	13	0
2009	68	73	29	163	36	0	34	82	11	6	3	12	8	0
2010	64	57	39	293	56	31	58	133	15	8	1	14	12	4
2011	60	57	40	366	73	50	75	139	29	2	3	6	13	16
2012	67	57	50	295	47	30	49	149	20	14	4	11	9	12
2013	66	53	35	198	37	19	37	90	15	6	0	8	13	8
2014	59	63	27	234	49	22	53	100	10	4	1	8	8	6
2015	15	13	8	56	10	9	11	20	6	0	1	1	2	4
	642	677	342	2153	406	161	421	1032	133	78	30	104	80	50

each year, the total number of scheduled nights and the corresponding number of hours allocated are given, along with the *actual* number of nights for which successful ranges were acquired. The number of resulting normal point measurements is given, along with a breakdown by reflector. The final five columns present the number of nights for which ranges were obtained to one, two, three, four, or five reflectors. In recent times, APOLLO typically measures to 4 or 5 reflectors in each session—providing a strong constraint on lunar orientation.

Other highlights from Table 1 include the statistic that APOLLO typically delivers about seven normal points per night (about seven per hour). Apollo 15, which dominated the APOLLO normal point measurements in early years, now constitutes less than half of the measurements.

Figure 1 shows the data campaign graphically. It is thus apparent that APOLLO has continued to produce LLR data throughout its campaign.

Range precision is estimated as illustrated in Figure 2. In short, we have a good understanding of the instrumental response and can construct a functional fit to the lunar return that matches observation well. The key round-trip-time information therefore stems from how much one must slide the constructed functional fit in time to overlay the lunar return. APOLLO normal point reported uncertainties are just the statistical uncertainty in this parameter fit, combined in quadrature with 10 ps to represent digital steps in the GPS-disciplined clock frequency.

Plotting the raw uncertainties as a function of observation night number gives a visual impression of APOLLO data quality—shown in Figure 3. Note that almost all nights produce uncertainties less than 1 cm. The median for the five reflectors (in the order presented in the legend) are: 2.4, 2.7, 2.3, 1.6, and 3.4 mm, respectively. If we combine all reflectors for one night, we get a 1.2 mm uncertainty as a measure to the Moon as a whole (center of mass, effectively). We can see the effects of a detector change around night 180, a software fix around 255, and a detector/electronics upgrade around 295.

The numbers just presented are not entirely fair. Because APOLLO uses a 16-element detector, we can produce independent normal point measurements for each channel—accompanied by uncertainties produced in the usual manner—and then compare the results to see if they are consistent with each other within estimated uncertainties (Figure 4). In short, they are not. During the period up until 2010.12.01, we typically saw an inflation of a factor of 2, or alternatively a root-sum-square (RSS) uncertainty contribution of 17 ps (2.5 mm). During the period from 2010.12.01 to 2012.04.06, the scale factor was about 6 (or RSS 60 ps; 9 mm). From 2012.04.07 to 2013.09.01 we saw a factor of

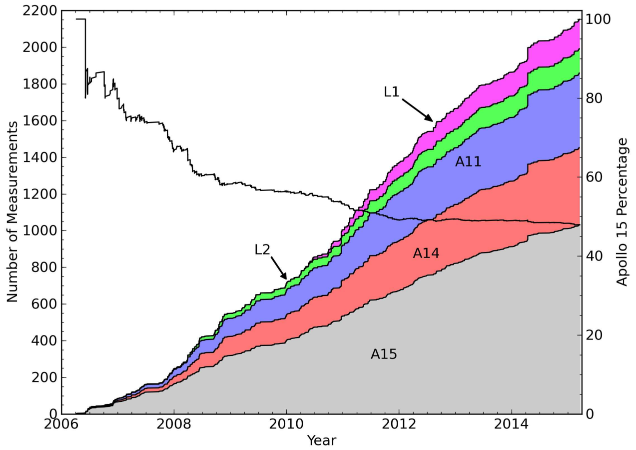

Figure 1: Steady accumulation of APOLLO data over the years, showing Apollo 15 as the most ranged reflector, although decreasingly important (trend line; right axis). The re-discovery of Lunokhod 1 in 2010 is also apparent in this graph. Extended observations during eclipses in December 2010 and April 2014 produce visible surges in the number of ranging points. Summer shutdowns during monsoon season are also somewhat evident.

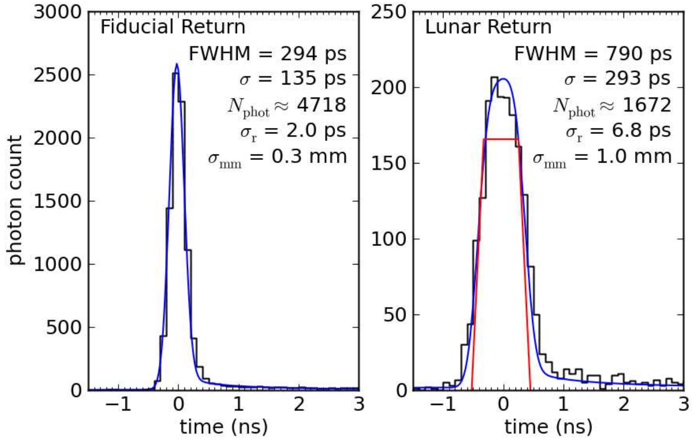

Figure 2: APOLLO normal point data utilizes interleaved fiducial measurements from a local corner cube (mounted to the telescope secondary mirror). From the fiducial measurement (left), we fit a physically-motivated response curve that incorporates laser, detector, and electronics influences (blue fit). The temporal influence of the reflector is known from its orientation and lunar libration at the time of measurement (red trapezoid, right). We simply convolve the APOLLO instrumental reponse with the trapezoid to get a functional fit to the lunar return (blue curve, right). Constraining this to have the correct total flux and background, the only free parameter is the temporal location of said function that best fits the data. In this case, the parameter is fit to 6.8 ps (1 mm), which is slightly better than the overall RMS divided by $\sqrt{N}$ owing to the squared-off shape of the return.

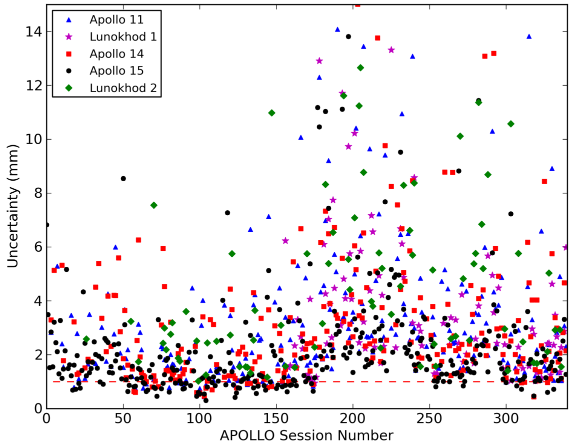

Figure 3: APOLLO raw normal point uncertainties for each night of observation for each reflector. The dashed line at bottom is at 1 mm, for reference. The 10 ps clock contribution to normal point uncertainty is removed here for better visibility of intrinsic data quality trends.

2.5 (or RSS 20 ps; 3 mm). Following the installation of a new detector electronics scheme, we have seen perfect compliance with estimated uncertainties, so that the recent period (2013.09.30 to present) shows no need to scale uncertainties or apply a root-sum-square contribution. This is very good news for APOLLO.

Figure 5 shows what we now think to be an accurate representation of APOLLO uncertainties across time. We have no explicit preference for whether scaling errors by a multiplicative factor or combining in quadrature with a RSS term is best. They have roughly equivalent impacts, but only one method should be applied—not both together. The website posting APOLLO data (`http://physics.ucsd.edu/~tmurphy/apollo/norm_pts.html`) has a table of the suggested scalings or RSS factors.

3 Findings

APOLLO's main goal is to probe gravitational physics more deeply than has been possible before. The data quality now appears to exceed modeling capability, where post-fit residuals tend to have a root-mean-square (RMS) scatter in the 15–30 mm range, depending on the model. Thus APOLLO's data precision has not yet significantly advanced gravitational constraints, as yet. It is, however, reassuring that APOLLO data alone at this point provides comparable limits on the equivalence principle to those from the entire LLR dataset (Müller et al., 2012 [2]).

On other fronts, APOLLO has opened up a new reflector (Lunokhod 1) for LLR, which we find to be a reliable and responsive reflector [3]. The stronger signal offered by APOLLO has permitted robust observation of degradation in the reflectors, seen as a striking signal deficit at full moon [4]. This led to detailed characterization of corner cube prisms and their sensitivity to thermal gradients [5, 6], culminating in smoking-gun observation of signal strength recovery during lunar eclipse [7]. We conclude that the reflectors likely have a dust coating with a covering faction around 0.4–0.5.

It is also worth noting that by routinely ranging to three or more reflectors per session (Table 1), APOLLO is able to provide tight constraints on lunar orientation, exposing the need for models to

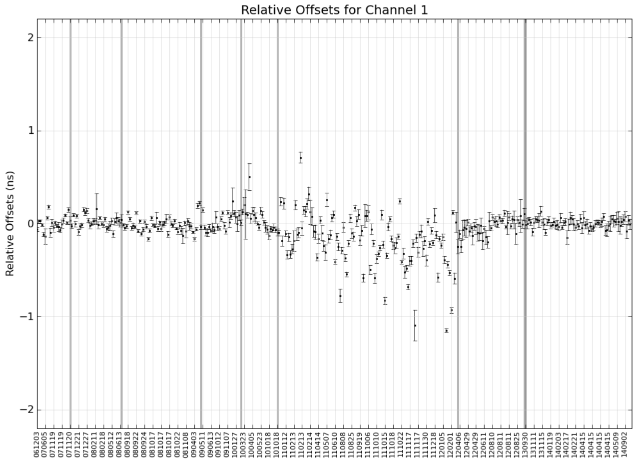

Figure 4: Comparison of the LLR round-trip time measured on APD Channel 1 alone to the mean round-trip time measured independently on all channels. The degree of scatter relative to estimated uncertainties determines an appropriate error inflation factor. Vertical lines delimit known changes to the apparatus. The most recent period is very well behaved, with no scatter in excess of estimated uncertainties.

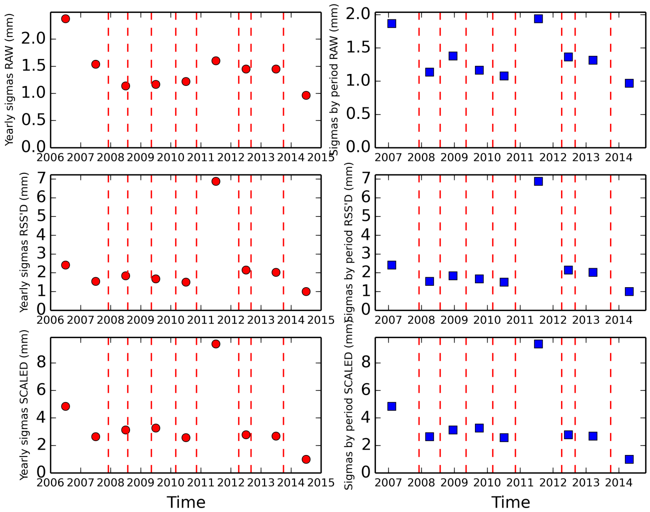

Figure 5: Trends in uncertainties in the raw, root-sum-squared, and scaled scenarios, presenting more realistic assessments of APOLLO data quality. The left-hand set presents yearly measures, while the right-hand set more appropriately assesses quality within known periods of similar instrumental performance (delimited by red dashed lines in all panels). The most recent period—associated with a new detector end electronics readout scheme—appears to be the best.

better capture the dynamics of the lunar interior.

4 Other News

APOLLO spent some time from 2010–2013 ranging to the Lunar Reconnaissance Orbiter (LRO). A small corner cube array was installed on the spacecraft that had a nominal cross-section about 50 times weaker than the Apollo 11 or Apollo 14 reflectors. We attempted two-way ranging on ten occasions (two of which were very good conditions) but never saw a convincing return signal. We practiced pointing/tracking via one-way ranging and were successful on nine out of ten attempts using a very tight (one-arcsecond) beam. Moves away from the nominal track at that scale resulted in loss of signal.

The APOLLO team is working closely with the Planetary Ephemeris Program (PEP) team: John Chandler, Irwin Shapiro, Bob Reasenberg. Our goal is to bring PEP up to modern state-of-the-art standards and ultimately take advantage of APOLLO's millimeter-level precision.

Over the next few years, APOLLO will be building an absolute calibration system (ACS) that will inject light pulses into the apparatus at well-known and completely trusted intervals (primarily around the 2.5 s lunar round trip time). By comparing the APOLLO-reported result to the standard, we may discover sources of systematic error in the instrument.

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