Recent Developments at the Apache Point Lunar Laser Ranging Station

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Abstract

The Apache Point Lunar Laser Ranging Station (formerly the Apache Point Observatory Lunar Laser-ranging Operation, or "APOLLO") became part of the NASA Space Geodesy Network at the beginning of 2021. In conjunction with the former APOLLO team, best practices were established regarding observation and processing of data into normal points. A quality control process to identify centimeter-level biases was introduced, archival procedures were adjusted to match version 2 of the Consolidated Range Data format, and a fully reduced 2021 dataset was published to the Crustal Dynamics Data Information System's database.

The APOLLO experiment has achieved median range precision at the (1-3) millimeter level for many years, yet comparisons of measurements against models are nearly an order-of-magnitude larger. Model-measurement disagreement raises the question of whether APOLLO suffers from gross systematic inaccuracies or if models are incomplete in some manner. In 2016, the APOLLO team added an Absolute Calibration System (ACS) consisting of a high-repetition-rate (80 MHz) short-pulsed (< 10 ps) laser that is locked to a cesium clock. The ACS delivers "truth" photons to the APOLLO detector at well-known time intervals which provides an independent assessment of the accuracy of the APOLLO system and an avenue for correcting range data in-situ. ACS results suggest systematic errors are reduced to ≤ 1 mm such that both the accuracy and precision of the data are at the ~ 1 mm level.

1. Introduction

Modern physics is built upon two primary pillars: general relativity and quantum mechanics, which describe nature at its largest and smallest scales, respectively, yet are fundamentally incompatible with each other. Gravitational tests are challenging to perform given many require studying astronomically sized objects. However, in our local region, the Earth-Moon system provides a convenient laboratory for probing gravity using lunar laser ranging (LLR).

Many leading constraints on gravity (such as the strong equivalence principle) have historically been tested in this natural laboratory, and the goal of modern-day LLR experiments is to improve upon these constraints [1, 2]. Gravitational tests aside, LLR is additionally sensitive to Earth orientation parameters [3], secular evolution of the Earth-Moon distance [4], and the physical properties of the Moon [5]. A more detailed overview of LLR science deliverables can be found in Reference [1].

1.1 APOLLO Apparatus

This section serves as a brief overview of the ranging system to better understand the application of the more recently developed timing calibration system. A more detailed description of APOLLO instrumentation, operation and sequence of events can be found in Reference [6]. The range laser is an Nd:YAG that is frequency doubled to 532 nm with pulse energies of 115 mJ, pulse widths of 90 ps FWHM at a 20 Hz repetition rate.

A small portion of the outgoing light is reflected by a local corner cube attached to the secondary mirror of the telescope (3.5 m primary aperture at Apache Point Observatory). The relative timing of the “fiducial” (FID) photons from the local corner cube and the returning “lunar” (LUN) photons yield a differential measurement, effectively determining the separation of the local and remote corner cubes using the same detector and timing electronics. After each laser pulse (or “shot”), the 100 ps resolution 4x4 avalanche photodiode (APD) detector array is turned on (in associated detector activation events called “gates”) once for the fiducial returns and once for the lunar returns. Raw APOLLO data products are referred to as “runs” and are the result of photon collection periods spanning 3-10 minutes (~ 3000 – 10000 laser shots) on a single lunar reflector.

Photon events are timed using a custom state machine referenced against a 50 MHz clock train and a 12-bit, 25 ps resolution time-to-digital converter (TDC) event timer with 100 ns range. TDC calibrations are obtained from a process called CALTDC that is performed once before and once after each data collection period. During CALTDC, the TDC sends common START and STOP signals to all channels 1000 times for five different START positions. This allows us to then fit a quadratic function to each channel’s results to provide a conversion between digital timestamp (TDC number) and an actual timestamp for any photon event. More information on this process can be found in Reference [6].

2 Transition to NASA

At the beginning of 2021, stewardship of APOLLO was handed to NASA. Operations have continued as normal, excluding hardware failures and weather. Best practices were established regarding observation/operation, and documentation organization has been ongoing. A replacement for the 2001 control computer APOLLO uses for operation is being investigated, to better protect against unforeseen computer failures.

NASA released the first APOLLO dataset under its stewardship in early 2022, now in consolidated range format (CRD) version 2. There now additionally exists a standardized quality control process that allows us to quickly identify centimeter level biases in APOLLO normal points, courtesy of the NASA GSFC ILRS LLR analysis center.

3 Timing accuracy assessment

LLR science is achieved by comparing range results to complicated solar system models that incorporate all relevant physical effects that can influence a range timing measurement, of which there are only a few in the world. The Jet Propulsion Laboratory develops a model that is believed to be the most complete, yet produces model “residuals” (the difference between measured results and predicted results) with a weighted RMS of 15-20 mm. Other models produce residuals with weighted RMS values two to three times the scale of JPL model residuals [7].

While one cannot determine from the residuals alone whether the data or model is primarily to blame, there has been evidence that points to model deficiencies in the form of missing physics or errors in the implementation of the model. One indication is that model residuals are expected to follow a linear trend over very short timescales (~ 1 hr.), which was found to be true from a previous study of APOLLO range measurements. Furthermore, the scatter in residuals about the linear trend was consistent with the scale of range measurement uncertainties, providing additional evidence that APOLLO data is less likely to blame for the spread in model residuals [7].

However, more definitive tests to address the above concerns was desirable which prompted the development of a calibration scheme that would allow us to independently assess the accuracy of APOLLO data. This calibration scheme involves injecting very short pulses of light onto APOLLO’s detector at well-understood intervals to investigate timing inaccuracies and systematic errors. The concept then evolved to deliver calibration photons to the detector simultaneous to ranging measurements, allowing us to establish an “optical ruler” of photon tick marks against which we can calibrate ranges directly without needing to investigate and eliminate various sources of systematic error [8]. The rest of this document is intended to briefly review the design of the Absolute Calibration System (ACS) and describe how timing corrections are established as well as present some results from the ACS.

4 Absolute Calibration System (ACS)

4.1 ACS overview

The final design scheme uses a fiber cavity SESAM laser whose cavity length is modulated by a phase-lock-loop with a cesium standard. The ACS laser produces pulses with ~ 10 ps width at an 80 MHz repetition rate; while this negates the “pulse-on-demand” style originally desired, a custom pulse selection system utilizing an electro optic modulator is able to deliver a series of pulses to the detector that coincide with the FID and LUN photon returns. This overlays the aforementioned “optical ruler” of ACS (or “truth”) pulses atop the lunar range measurements, allowing us to calibrate APOLLO’s timing response at the time of ranging. A detailed description of the ACS hardware and integration into the rest of the APOLLO apparatus is provided in Reference [8].

4.2 Calibration concept

While ACS pulses are 12.5 ns apart, the 80 MHz pulse train can appear in five possible locations relative to the 50 MHz pulse that forms the STOP signal for the TDC, as can be seen in Figure 1. ACS photons and lunar range (or fiducial) photons arrive in a single gate of the APD, and timing within the gate can be used to judge which photons are ACS or LUN or FID photons. An example of this can be seen in Figure 2.

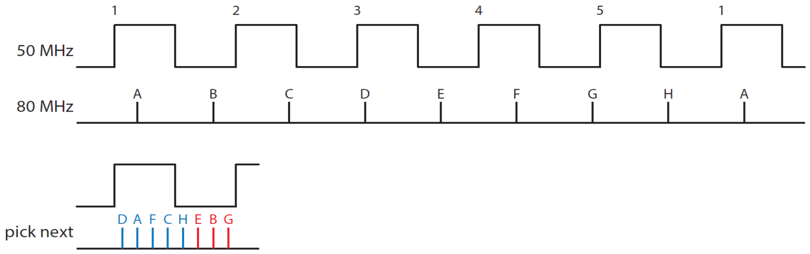

Figure 1. Relative timing between 50 MHz APOLLO clock train and 80 MHz ACS laser pulse train. Five possible positions of the ACS pulse train relative to any 50 MHz rising edge are demonstrated before repeating. The comb produced has teeth spaced at 2.5 ns.

Figure 2's top panel displays the FID and LUN range return "slugs" of 20-ns-wide uniform distributions, aggregated over all channels; range returns are asynchronous relative to the 50 MHz clock used to schedule APOLLO events given the range laser's large (~ 1.6 microsecond) jitter. A timing "anchor" in the form of a fast photodiode is used to obtain a low-jitter (~ 20 ps) measurement of laser fire time which is present for every laser shot and is used to schedule detector timing gates.

The middle panel of Figure 2 overlays the ACS combs (one for each gate type) atop the FID and LUN signals. The ACS comb "teeth" appear broad because relative timing corrections between channels have not been accounted for; the bottom panel shows a set of tightened-up ACS teeth after accounting for the relative channel timings. We may then compare the measured separation of ACS teeth against the known "truth" separation of $n \times 2.5$ ns, where n is an integer, to obtain a calibration of the APOLLO system.

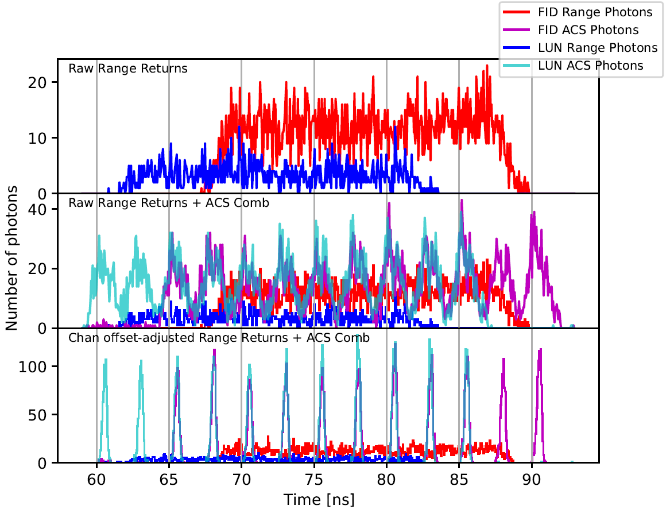

Figure 2. Histograms of time-converted ACS and range photons. The top and middle plots do not contain relative channel timing corrections, while the bottom subplot does.

It should be noted that in normal practice there is an aggregation of ACS combs across long timespans to improve the quality of the ACS calibration relative to the typical uncertainty of an APOLLO normal point. However, this aggregation is outside the scope of this document, and we will proceed as if aggregation does not take place. More information can be found in References [9, 10].

4.3 Range timing calibration with contemporaneous ACS data

APOLLO runs with sufficient contemporaneous ACS information allow us to calibrate individual FID and LUN timings. Photon timing corrections are extracted by determining the position of range photons relative to an ACS comb (one for each gate/channel combination). This section discusses the photon-by-photon calibration procedure. More detailed information can be found in an upcoming publication: [10].

We assert the teeth of the comb should have a fixed pitch of 2.5 ns relative to a chosen reference tooth of the comb (same reference tooth for every channel/gate combination). Each range photon has a measured position in TDC space which can be used to compute the corresponding ACS-derived timing calibration based on their proximity to comb teeth. Interpolation between comb teeth allows calibration of photon events falling anywhere within the span of the comb.

At the end of each run's data processing, we summarize the scale of timing inaccuracies into a single representative differential estimate for further study. In absence of ACS calibration, the CALTDC calibration is used. Therefore, we define an ACS timing correction for an individual range photon (FID or LUN) as the difference between its ACS-calibrated timestamp and its CALTDC-calibrated timestamp: $C_i \equiv t_{ACS,i} - t_{CALTDC,i}$. The mean timing corrections to FID and LUN range photons are obtained separately for those range photons considered to be contributors to the actual signal, and differenced such that $C_{differential} \equiv C_{FID} - C_{LUN}$, where C_{FID} and C_{LUN} are the mean FID and LUN timing corrections, respectively.

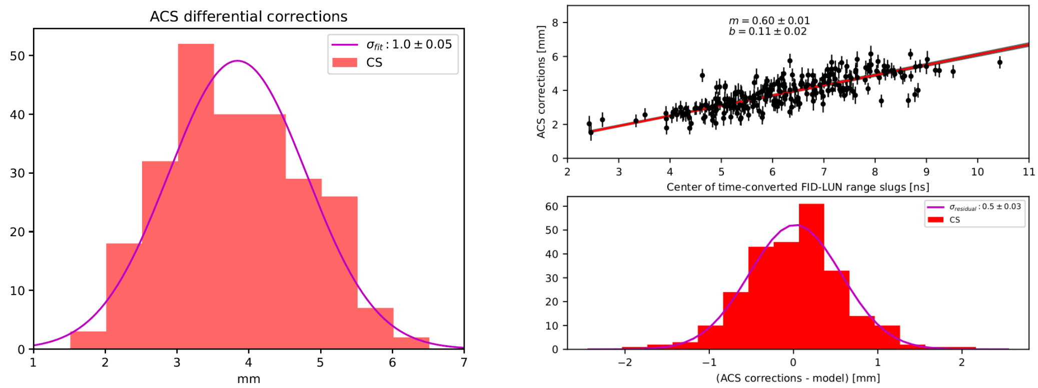

Figure 3. Left: distribution of differential ACS corrections between 2017 February 21 and 2019 August 14. A best-fit gaussian is overlaid, with standard deviation of 1.0 mm. Right: the upper subplot shows the relation between ACS corrections and the difference between FID and LUN slug positions in TDC space. The lower subplot displays the distribution of ACS corrections after removing the trendline in the upper subplot.

Figure 3's left panel shows a distribution of ACS corrections ($C_{differential}$) for APOLLO data between 2017 February 21 and 2019 August 14. A gaussian fit suggests APOLLO's range bias to systematically be around 4 mm of one-way range. The fitted standard deviation of 1.0 mm is indicative of APOLLO's timing accuracy once range bias is removed, and agrees with the scatter in model residuals about the linear trend discussed earlier in Section 2.

5 Range timing calibration without contemporaneous ACS data

When the lunar signal is weak, delivery of ACS photons onto the detector is disabled so as not to interfere with telescope pointing feedback derived from APD event rates. We observe a strong correlation between derived ACS corrections and the differential positioning of FID and LUN signals within TDC space and recognize we may use that correlation to "look-up" what a run's ACS correction *would have* been if it had contemporaneous ACS data.

Figure 3's right panel is an example of the relation between ACS corrections and the difference in the mean location of the FID and LUN slugs. The FID and LUN signals are not necessarily fully overlapped, as can be seen in the upper subplot of Figure 2. This makes sense in that if FID and LUN signals were sampling significantly different regions of the TDC, the more range error is likely to be present, and this is corroborated by the upper subplot of **Error! Reference source not found.**. The fitted trendline slope of 0.6 mm/ns indicates that the TDC adds about 0.4% range error for imperfect overlap of the range signals – this is a systematic never-before-seen for APOLLO and is very useful to understand. While outside the scope of this document, we additionally believe there is an avenue to use this strong correlation to predict what an ACS correction would have been for runs that came before the installation of the ACS as well, since the same event timer (TDC) has been used for the duration of the experiment.

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