
APOLLO SPRINGS TO LIFE: ONE-MILLIMETER LUNAR LASER RANGING

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Abstract

The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) obtained its first lunar ranges in October of 2005, achieving over 2000 photons in a 30-minute period. Subsequent operations have seen as many as 2500 photons in less than ten minutes, with a peak photon rate of 0.6 photons per pulse, or 12 per second. The major elements of the system are described, with performance examples and a look at the data precision.

Introduction

Lunar Laser Ranging (LLR) has long provided many of the best tests of gravity, currently claiming the best limits on:

- the weak equivalence principle, to $\Delta a/a < 1.4 \times 10^{-13}$;
- the strong equivalence principle to $\eta < 4.5 \times 10^{-4}$;
- time-rate-of-change of the gravitational constant, G , to $< 10^{-12}$ (fractionally) per year;
- gravitomagnetism to $< 0.1\%$;
- geodetic precession to $< 0.7\%$;
- inverse square law to 10^{-10} times the strength of gravity at $\approx 10^8$ m scales.

Many of these latest results are presented by Williams et al., (2004) [1]. The gravitomagnetic effect produces six-meter deformations in the lunar orbit at two different frequencies [2], each determined by LLR to sub-centimeter accuracy. Though the phenomenologies of gyroscopic precession (frame dragging) outside a rotating body, orbital (Lense-Thirring) precession of the LAGEOS satellites, and orbital distortions of the lunar orbit may appear to represent distinctly different physics, they all stem from the same term in the equation of motion. This is analogous to the seemingly different rotation of a draining tub and trajectory deflection due to the Coriolis force, though both stem from the same root physical cause.

The APOLLO Apparatus

The APOLLO apparatus is situated at the Apache Point Observatory in southern New Mexico, at 2780 m elevation. The laser is permanently affixed to the 3.5 m telescope, so that a rotation of the telescope tertiary mirror allows efficient sharing with other astronomical programs. The median atmospheric seeing at the site is 1.1 arcseconds (at zenith). The telescope is flexibly scheduled, so that APOLLO is able to get 1.5-hour time slots every few days during the accessible part of the lunar month.

Laser

APOLLO's laser is a Leopard SS-20 model from Continuum Lasers. It is a flashlamp-

pumped Nd:YAG system delivering 120 ps infrared pulses via acoustic mode-locking and cavity dumping, operating at 20 Hz. The infrared is frequency-doubled to 532 nm, delivering about 100 mJ per pulse at a pulse-width < 100 ps.

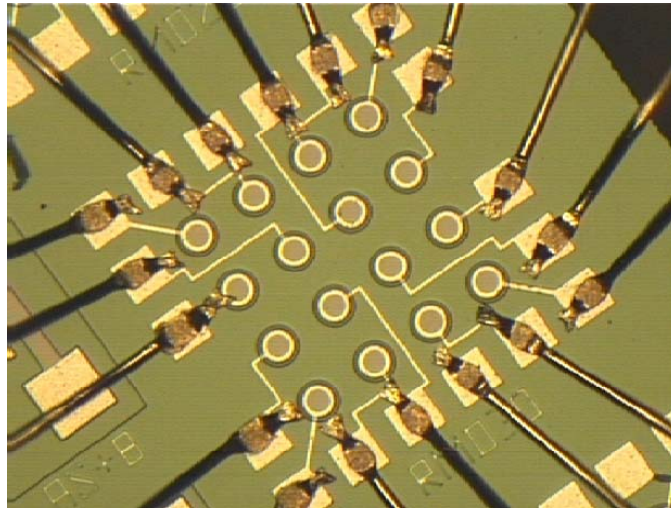


Figure 1: 4×4 APD array with 30 μm elements on a 100 μm square grid.

APD Array Detector

APOLLO uses a 4×4 format avalanche photodiode (APD) array at the re-imaged focal plane (Figure 1). In this way, multiple return photons can be accommodated in a given pulse, each generating a timing signal that is separately time-stamped. A lenslet array placed in front of the detector recovers the fill-factor loss of the bare array. Besides providing multiple “buckets” for the multi-photon return, the resulting 1.4 arcsecond field of view (0.35 arcsec per pixel) yields spatial information about where the telescope is pointing, so that we may maintain tracking lock based on the spatial distribution of the lunar return.

Optical Layout

Figure 2 shows the APOLLO optical layout. Starting at the laser output, the green pulse emerges as a ~ 7 mm diameter ($1/e^2$) beam with an approximately Gaussian profile, centered 61 mm off of the optical bench. A beam expander (TL1 and TL2) expand the beam to 16 mm diameter prior to the rotating transmit/receive (T/R) optic. Following the T/R optic, the beam encounters a plano-concave lens (L3) that introduces a roughly $f/10$ divergence to the beam so that it may fill the telescope aperture. After L3, the beam experiences two 90° turns on M5 and M4—both of which are multi-layer dielectric coatings for high-efficiency reflection at 532 nm. After this are the telescope’s aluminum-coated tertiary, secondary, and primary mirrors (M3, M2, M1). The beam emerges from the primary mirror collimated to well below 0.5 arcsec.

Incoming light from the telescope is brought toward a focus, following the inverse path of the transmit beam, becoming collimated at L3. From here, the path through the T/R optic experiences two 90° turns on M6 and M7, in the process being elevated to ~ 115 mm off of the optical bench so that it may cross the transmit path. M7 is tip-tilt actuated so that the receiver may be aligned relative to the transmit beam direction. The collimated beam enters the receiver tube via an uncoated glass window, tilted to send the reflected light toward a CCD camera that aids acquisition and alignment. The clear aperture up to this window is maintained to be at least 35 mm so

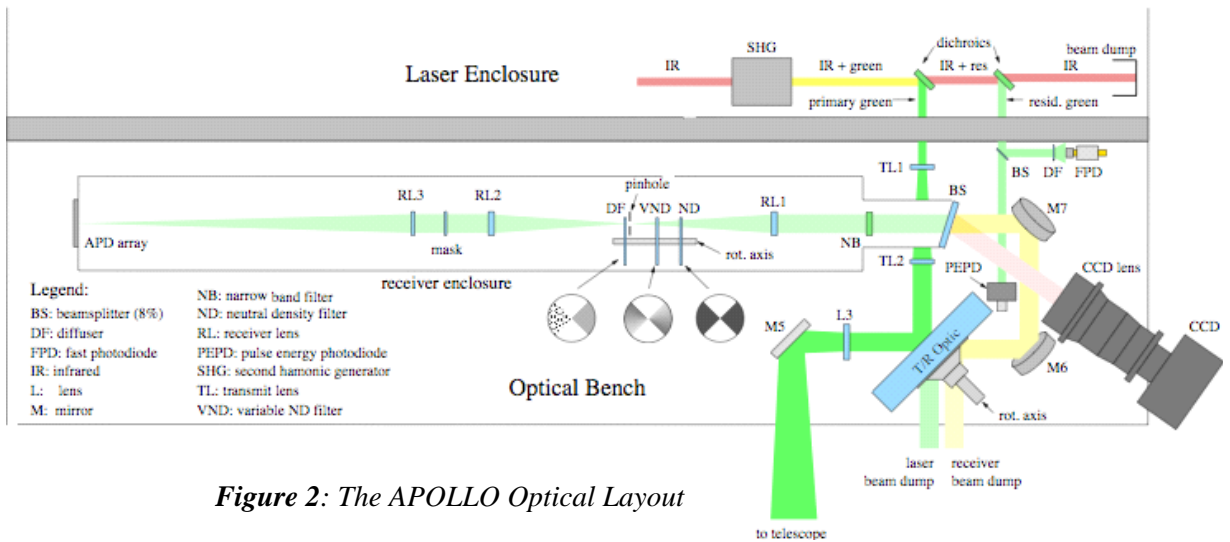


Figure 2: The APOLLO Optical Layout

that a 40 arcsec field of view is preserved for the CCD camera. Past this window, the optics are 25 mm in diameter, which is suitable for the small field of the APD detector array.

A narrow passband filter sits at the front of the receiver tube, with a 1.5 nm FWHM passband centered at 532 nm, and 35% transmission at the center wavelength. Beyond this, a doublet lens (RL1) concentrates the collimated beam to a focus, where a pinhole is placed to act as a spatial filter. The 400 μm hole corresponds to 3 arcsec on the sky. An identical lens (RL2) is placed opposite the pinhole, re-forming the collimated beam. An optional mask in the collimated beam prohibits light originating outside the telescope aperture to proceed. A final lens (RL3) focuses the light onto the detector at the end of the receiver tube. The receiver tube is closely baffled at 50 mm intervals along its entire length so that scattered light from the laser fire is unlikely to survive a trip to the photon-sensitive detector.

Differential Measurement Scheme

APOLLO, like many laser ranging systems, implements a differential timing scheme, referencing its photon arrival times against returns from a local corner cube. This **fiducial** signal (note: often called “calibration” in the SLR community) follows *exactly* the same optical path as the lunar return photons, and is processed by the same timing electronics in the same configuration. The only difference is that optical coatings on the T/R mirror and on the disks near the spatial filter pinhole rotate into

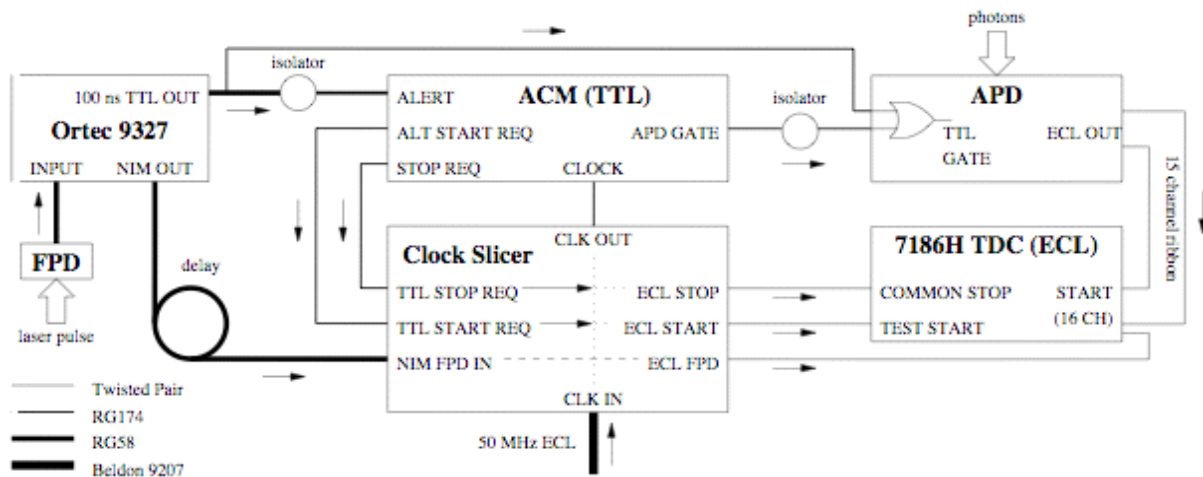


Figure 3: The APOLLO Timing System

the beam to provide an attenuation of $\sim 10^{10}$, adjustable over about one order-of-magnitude. The result is a signal level of approximately one photon per pulse (distributed among the APD elements). The disks in the receiver rotate at half the rate of the T/R optic (which itself triggers laser fire events), one side diffusing the fiducial photons to have a roughly uniform distribution within each pupil-imaging APD element. The other side has matching attenuation, but allows the fiducial to be concentrated on each APD element in accordance with the corner cube's spatial location within the telescope entrance aperture. In this way, we can explore the timing bias associated with illumination position within the APD element. See [3] for details on this scheme.

Timing Scheme

The multiplexed timing system for APOLLO is capable of ~ 20 ps timing on 16 independent channels (common STOP) at rates as high as 4 kHz. The timing system is comprised of:

- a 16-channel time-to-digital converter (TDC): Phillips Scientific model 7186H;
- a Truetime XL-DC GPS-disciplined clock with low phase noise 10 MHz output;
- a $5\times$ clock multiplier producing a 50 MHz ECL clock, preserving low phase noise;
- a custom “clock slicer” module that extracts selected clock pulses out of the train;
- a custom CAMAC module that coordinates gate events and requests clock pulses;
- an Ortec 9327 amplifier/discriminator establishing laser fire time to high precision.

The timing system is depicted in Figure 3. A secondary feature of our setup is the ability to calibrate the TDC by sending pulse pairs based on the 50 MHz clock to the TDC. In this way, we get START/STOP pulse pairs that are integral numbers of 20.00 ns apart. Even so, by arranging the lunar and fiducial photons to use the same 20 ns part of the TDC range (we have control of gate placement up to the clock period), we make the need for this calibration secondary. Running the calibration at 1 kHz at five pulse-pair separations yields 1000 measurements per setting in a five second period.

Example Data Runs

We present here example data from recent APOLLO runs to illustrate the system performance and capabilities.

Figure 4 shows the result of a 10,000 shot (500 second) run on Apollo 15—an array of 300 3.8-cm-diameter corner cubes. The first half of the run was spent optimizing pointing and beam offset. More than three quarters of the return photons fell within the last half of the run, producing an average rate of 0.33 photons per shot.

Figure 5 shows a 10,000-shot run on Apollo 11 (100 3.8 cm corner cubes) that followed the Apollo 15 run shown in Figure 4. Having optimized the signal in the previous run, the signal rate is steady in the Apollo 11 run. The 0.11 photon-per-pulse average return rate is consistent with the 0.33 result from Apollo 15, given the difference in array sizes.

The APOLLO error budget is dominated by the temporal spread arising from the libration-tilted finite-sized corner-cube arrays. Typically contributing about 20–50 mm root-mean-square (RMS) spread (less for the smaller arrays), we need approximately 400–2500 photons to achieve 1 mm random uncertainty. The above examples show that APOLLO is capable of achieving this in few-minute timescales.

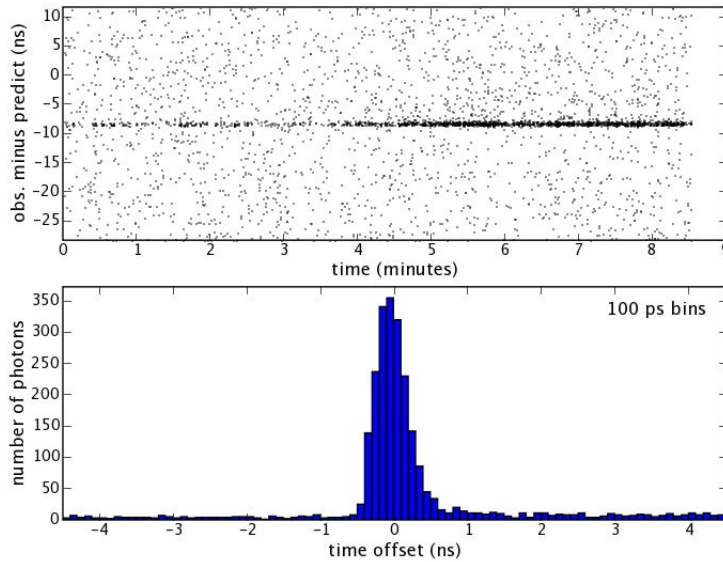


Figure 4: Apollo 15 run: 10,000 shots, 2000 lunar returns, 1670 of those in last half (following system optimization). Photon rate average in last half: 0.33 per pulse.

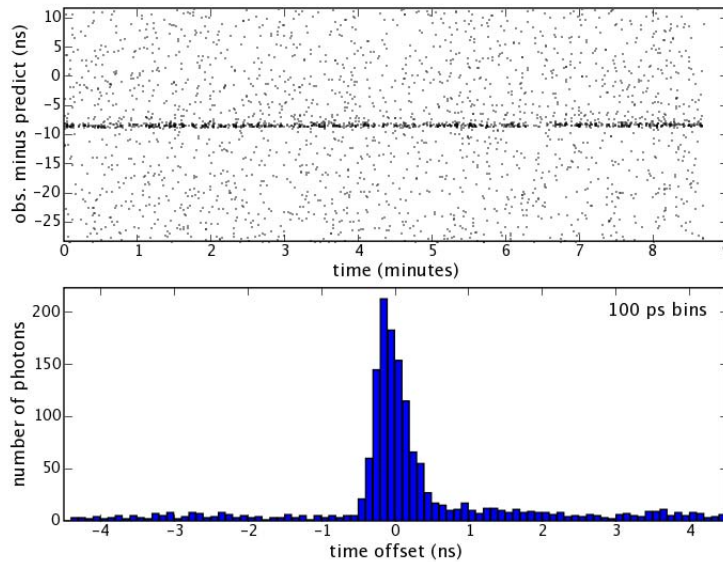


Figure 5: Apollo 11 (3 times smaller than Apollo 15) run: 10,000 shots, 1100 lunar returns

Fiducial Data

An example of APOLLO fiducial data is shown in Figure 6. This particular set coincides with the lunar data presented in Figure 4. Shown here are the time histograms between the arrival of the cable-delayed fast-photodiode signal and the fiducial corner cube APD signal for the various APD channels. The absolute value (about 6 ns on average) is not fundamental, being affected by the cable delay between these signals. The offsets between channels *is* relevant, however, as this information is needed to properly register the lunar return photons among the various APD channels. The consistent shapes indicate that all channels behave similarly in the time domain (channel 8 is an exception). Channels 3 and 5 are inactive. The channel 15 input on the TDC is used to mark the fast photodiode (laser start) reference time. This is expected to fall at a random time relative to our 50 MHz clock, thus producing a uniform histogram 20 ns wide. The time axis is reversed in these histograms

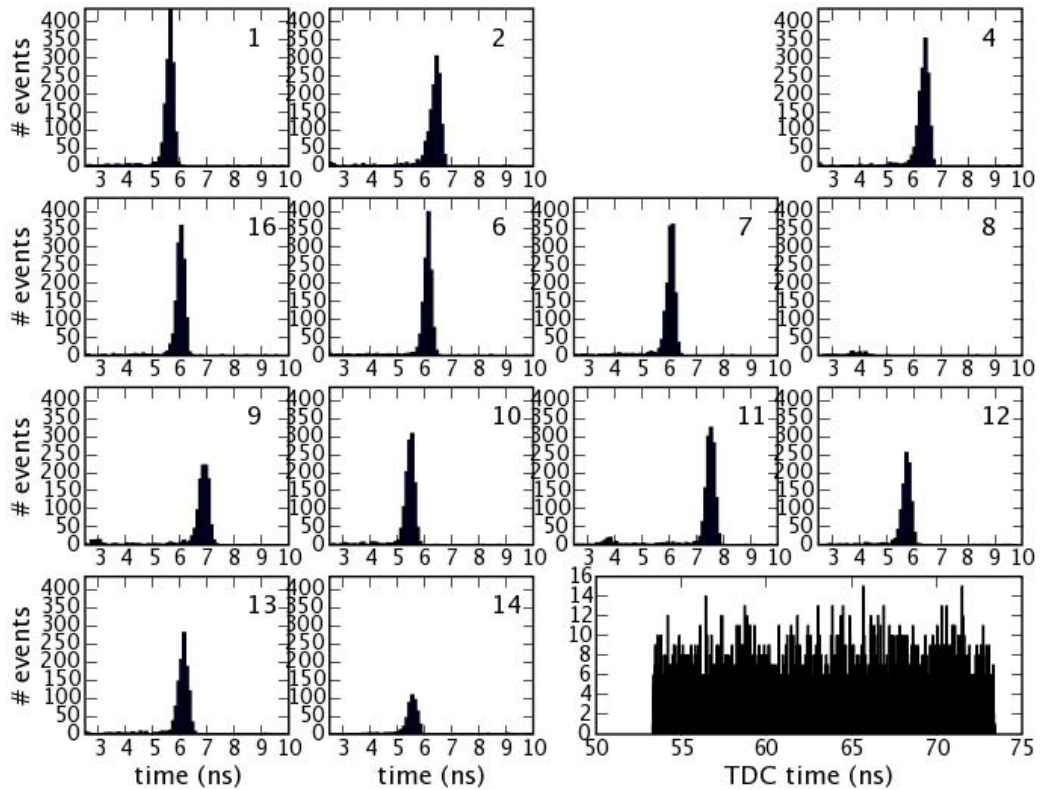


Figure 6: The fiducial events recorded for the run shown in Figure 4 for each APD channel, at 100 ps per bin. The time axis is reversed from the histogram in Figure 4. Channel 15 is used for the fast photodiode/Ortec signal (pictured in the wide panel), and channels 3, 5, and 8 are effectively inoperative.

compared to the one shown in Figure 4. The asymmetry is due to the APD response: some photoelectrons take longer to produce an avalanche than the typical, prompt, photoelectron.

APOLLO Performance Summary

APOLLO has achieved routine operational status, and began to gather scientifically useful data beginning in April 2006, with a regular cadence established in October 2006. More than a year of data is needed to see the impact of APOLLO's ranging capability on gravitational physics, so this should come about late in 2007. At this time, some of APOLLO's first year accomplishments are:

- As many as 2500 photons in a 500 second period
- Peak rates of ~ 0.6 photons per pulse, over 30 second intervals
- Range with ease at full moon (initial October 2005 acquisition at full phase)
- As many as 9 lunar return photons detected in a single pulse
- In strong runs, $\sim 50\%$ of photons arrive in multi-photon groups—even when the average rate is 0.25 photons per pulse

References

- [1] Williams, J. G., Turyshev, S. G., and Boggs, D. H., "Progress in Lunar Laser Ranging Tests of Relativistic Gravity," *Physical Review Letters*, **93**, 261101, (2004)
- [2] Murphy, T. W., Nordtvedt, K., and Turyshev, S. G., "Gravitomagnetic Influence on Gyroscopes and on the Lunar Orbit," *Physical Review Letters*, **98**, 071102, (2007)
- [3] Murphy, T. W. et al., "APOLLO: Meeting the Millimeter Goal," *Proceedings of the 14th International Laser Ranging Workshop*, pp. 165–173, San Fernando, (2004)