The Advantages of Avalanche Photodiode (APD) arrays in laser-ranging applications

J. D. Strasburg[a], T. W. Murphy Jr.[a], E. G. Adelberger[a], C. W. Stubbs[a],
D. W. Miller[b], J. I., Angle[a]

[a] Department of Physics, University of Washington, Seattle, WA 98195
[b] Department of Physics, Carleton College, Northfield, MN 55057

Abstract

The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) is a new lunar laser-ranging campaign aimed at achieving millimeter precision. At the heart of APOLLO is an integrated array of avalanche photodiodes developed at MIT's Lincoln Laboratories. These devices are capable of detecting the arrival of a single photon with high temporal precision (< 30 ps) at detection efficiencies as high as 50%. The integrated array format allows one to create a range profile with each laser shot by detecting multiple return photons, thereby eliminating the strong-signal biasing encountered with a single-photon detector. The array format also preserves spatial information, facilitating target acquisition and tracking. We are currently using a 4 × 4 array, but the timing system can easily be expanded to handle arrays of 10 × 10 elements or larger. Lincoln Labs is presently testing 32 × 32 devices.

Introduction

Lunar laser-ranging (LLR) has a distinguished history and is the only continuing legacy of NASA's Apollo program.[1,2] After more than 30 years, the corner cube arrays left on the surface by American astronauts are still providing scientifically relevant data without any measurable degradation in their performance. Dedicated LLR began in 1970 using the 2.7 m telescope at the McDonald Observatory near Fort Davis, Texas. The early 250 mm resolution drastically improved knowledge of the lunar orbit, previously known to only a few hundred meters, providing for the first time a lunar test of General Relativity. In the mid-1980s the 2.7 m operation was decommissioned and the McDonald Laser Ranging System (MLRS) was initiated at the same site using a dedicated 0.8 m telescope.[3] Even though the light collecting area was much smaller, technological improvements led to an increase in resolution to the 20–30 mm level. At the same time, two other LLR stations came on-line: the Observatoire de la Côte d'Azur (OCA) in Grasse, France using a dedicated 1.5 m telescope, and the Haleakala station located on Maui, Hawaii.[4] MLRS and OCA are currently the only operational LLR sites achieving a typical range precision of 18–25 mm.

The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) is a next generation lunar laser-ranging campaign. We seek to substantially improve lunar range measurements with the goal of one-millimeter precision.

APOLLO Return Rates

One-millimeter range precision corresponds to 7 ps temporal resolution in the roundtrip time-of-flight. The overall uncertainty is determined by the retroreflector array orientation, laser pulse width and detector/timing electronics jitter. Most of the time, the orientation dominates with a worst-case RMS range spread of 400 ps. To determine the centroid of this range spread to a precision of 7 ps requires the collection of $(400/7)^2 \sim 3000$ photons. Clearly, high-precision LLR will require high photon-return rates. If APOLLO receives even one photon per pulse at 20 Hz, it would take less than three minutes to collect the necessary photons.

The high photon rate expected from APOLLO is the key to achieving substantial gains in precision. The principal factors enabling APOLLO to accomplish its millimeter goal are the large telescope aperture and the excellent atmospheric seeing experienced at the site. The median net image quality of the APO 3.5 m telescope for long exposures is 1.05 arcseconds. A crude scaling of APOLLO to OCA (1.5 m, 2.5 arcsecond image quality) and MLRS (0.78 m, 4 arcsecond image quality) indicates a signal gain of 35 and 300, respectively. A gain of this magnitude (roughly 10^2) is necessary for a single order-of-magnitude improvement in random range uncertainty.

The expected return photon rate is dominated by the signal loss from divergence of both the outgoing and return beams. The outgoing beam, even if perfectly collimated, is limited by the atmosphere to a divergence of one to a few arcseconds. At one arcsecond, the beam makes a footprint about 2 km in diameter on the lunar surface. The small corner cubes comprising the Apollo arrays are 3.8 cm in diameter and because they are not diffraction limited devices and, in addition, are susceptible to thermal deformations, the effective beam divergence is 7-10 arcseconds creating a beam footprint of about 18 km on the earth's surface. If Φ is the atmospheric divergence, ϕ the corner cube divergence, D the diameter of the collecting telescope, and d the diameter of the n corner cubes in the array, then the link efficiency is

$$\varepsilon = \eta^2 f Q \left(\frac{n\, d^2}{r^2\, \Phi^2} \right) \left(\frac{D^2}{r^2\, \phi^2} \right).$$

Here r is the distance to the moon, η is the telescope/atmospheric transmission efficiency (experienced both ways), f is the receiver throughput—dominated by a narrow-band filter, and Q is the detector efficiency. With one arcsecond seeing, 40% telescope efficiency, 25% receiver efficiency and 30% detector quantum efficiency, the APOLLO link efficiency (to the smaller of the Apollo arrays) is only 1.7×10^{-17}. However, a 115 mJ laser pulse at 532 nm contains 3.1×10^{17} photons placing APOLLO squarely in the regime of 5–10 detected photons per pulse. We have been intentionally pessimistic with regard to optical efficiencies, but nonetheless calculate a detection rate of 5 photons per pulse. This return rate exceeds that routinely experienced at OCA and MLRS by a factor of roughly 1000—at odds with the simpler scaling discussed earlier.

Although the link efficiency equation as applied to current LLR stations yields photon rates roughly an order-of-magnitude too optimistic for current LLR stations, this is not the case when applied to the LLR system that once operated on the 2.7 m telescope at McDonald Observatory.[5]

At roughly 0.8 photons per pulse, this system had a high enough photon return rate to enable real-time optimization of the system. APOLLO will likewise operate in this regime. Even a factor of 100 degradation in efficiency (due to pointing, focus, etc.) will produce one photon per second—enough to carry out real-time adjustment of pointing, focus, transmit/receive misalignment, and beam collimation. All of these adjustments are actuated in APOLLO, allowing an automated optimization routine to find the parameters that will yield peak performance.

Another indication that this expectation may be reasonable comes from the best historical performance of the MLRS and OCA LLR stations. Without the ability to fine-tune performance in a closed-loop, algorithmic manner, the idealized system capabilities are perhaps best characterized by the lucky occasions when the systems happened to be tuned to optimum performance. MLRS, for instance, reports receiving 120 photons in 41 minutes on the Apollo 15 reflector.[6] Considering the time spent steering the telescope, one might estimate a peak instantaneous rate of one photon every 10 seconds, or 0.01 photons per pulse. For OCA, a return rate of 0.1 photons per pulse was obtained on the Apollo 15 reflector.[7] Blindly scaling these rates by the factors computed above based on aperture and seeing alone, one predicts a peak photon rate for APOLLO of about 3 photons per pulse.

Avalanche Photodiode Arrays

Multi-photon returns introduce new complications in terms of detection. Traditionally, laser ranging has operated in one of two modes: single-photon mode, where photons could be detected using a single device such as an avalanche photodiode or microchannel plate, or in the large-signal mode, where the detector (such as a photomultiplier tube) response represents the shape of the return pulse. APOLLO's expected return of 5–10 photons per pulse does not fit either of these modes, requiring a new approach. A single-photon detector would only detect the first photon, biasing the data to shorter times and thus shorter ranges. In order to measure a lunar range we need a way to either time-tag every individual return photon, or determine the centroid of the return pulse. Many techniques could be devised to meet this need. For instance, a chain of beam splitters that would enable each detector to statistically receive some fraction of the incident light would be capable of detecting multiple photons. Another technique could involve spatially spreading the return pulse across an array of detectors so that each detector receives a certain fraction of the input. APOLLO has chosen to adopt the latter technique using an array of avalanche photodiodes (APDs).

APDs are semi-conductor devices capable of detecting single photons when biased beyond their breakdown voltage in "Geiger mode". In this mode, a single electron-hole pair generated by an incident photon creates an avalanche of charge that produces a detectable current pulse with rise times of a nanosecond or better and durations of 10–20 ns. Detectors a few tens of microns thick achieve visible photon detection efficiencies in excess of 60%, time resolution in the tens of picoseconds, and have break down voltages around 20–40 V.[8] The high photon detection efficiency and lower operating voltages make these detectors more favorable than other fast single-photon detectors.

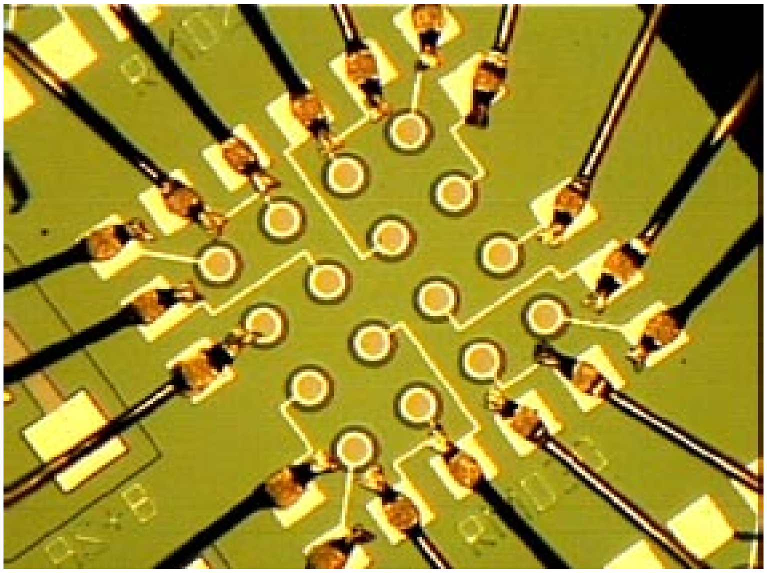


Figure 1: The 4 × 4 APOLLO APD array produced by Lincoln Labs. The individual elements are the circular pads 30 μm in diameter, separated by 100 μm in each dimension. We may ultimately employ a much larger array in APOLLO.

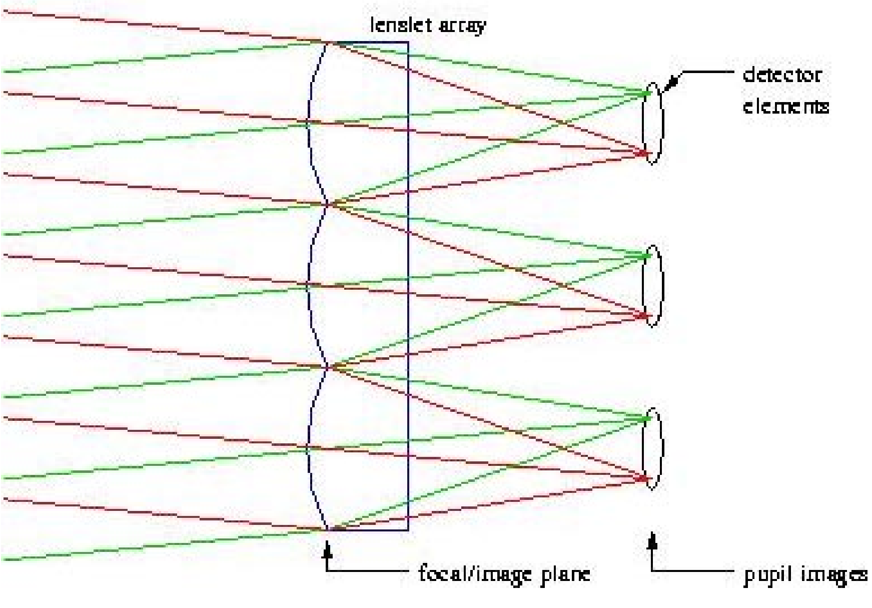


Figure 2: A lenslet array located at the focal plane will produce an array of pupil images. Spatial information is preserved by the array, and may be used to perform real-time guiding on the return signal. The array is pictured being fed an *f*/5 beam, though it will actually see a gentler *f*/20 beam.

Element spacing	100 μm
Active diameters	20, 30, 40 μm
Device thickness	~ 20 μm
Formats produced	4 × 4 and 32 × 32
Breakdown voltage	~ 25 V
Photon detection efficiency	30% (> 50% with AR coating)
Dark count rate	~ 2400 $e^{0.106T}$, T in °C
Effective resistance	25 kΩ
Effective capacitance	< 2 pF

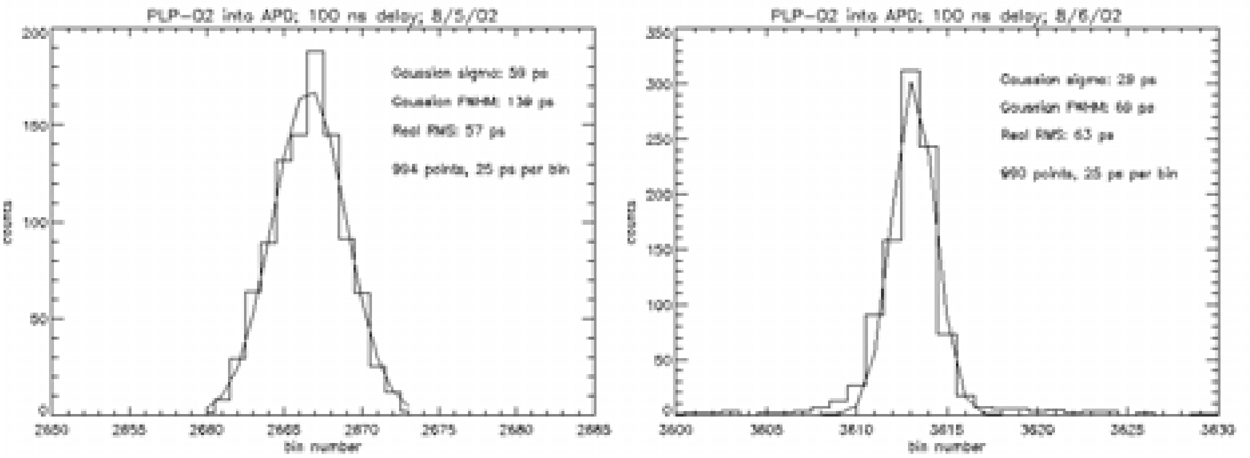
Table 1: Lincoln Labs APD array characteristics

MIT Lincoln Laboratories has recently begun exploring integrated APD arrays, with elements arranged in square patterns with 100 micron spacing. These arrays have small active areas 20–40 microns in diameter with breakdown voltages typically 25–30 V. In addition, they have photon detection efficiencies as high as 50% when anti-reflection coated. The timing resolution of the devices is typically 50–100 ps. Lincoln Labs has also examined the cross-talk between neighboring elements and found no correlated pulses between neighboring detectors in over 600 observations.[9] One of these arrays will be used at the focal plane of our LLR receiver in such a way as to oversample the point-spread-function across a handful of elements (e.g., via 0.3 arcsecond pixels). A lenslet array in front of the detector recovers a nearly 100% fill factor, compared to the 3–12% fill-factors of the arrays as fabricated.

By locating the lenslet array at the focal plane, sections of the image are partitioned and individually concentrated onto the detector array elements (themselves in a pupil plane). Each element is presented with an image of the telescope primary mirror as is shown in Figure 2. In this way, spatial information is preserved on the array in a way that chained beam-splitters would not achieve. Because of this, tracking errors may be unambiguously corrected based on the location of the signal within the array. However, one must use a very small field of view, comparable to the seeing size, in order to gain the full benefit of the multi-photon sampling. This is simply because one wants the point source return to cover a large number of detector elements (pixels) in order to achieve the multiplex capability.

When the array is oversampled, the multi-photon return is spread across many detector elements so that individual elements are statistically unlikely to detect more than one photon in a given pulse. As a consequence, one obtains a range "profile" of the target object with each shot. By preserving the two-dimensional information of the return laser pulse, one may apply real-time guiding corrections based on this information.

Systematics such as beam focus, transmit/receive co-alignment, etc. may be evaluated based on the two-dimensional footprint of the return. Imaging standard stars with the array can also perform flux calibrations, enabling the long-term tracking of the system throughput.



(a) (b)

Figure 3: APD timing results. (a) Gaussian response with RMS of 57 ps, (b) Non-Gaussian response with RMS of 63 ps but a Gaussian core with RMS of 29 ps.

We are currently working with two 4 × 4 arrays from LL, the appearance of which is shown in Figure 1 and the characteristics listed in Table 1. Eventually, we hope to upgrade to a larger format, possibly as large as 10 × 10 elements. Larger arrays do not require a redesign of our current timing scheme, but only an expansion of the multiplexing.[10] This would provide much greater oversampling so that the likelihood of getting more than one photon per element becomes very small, eliminating the need to correct for strong signal biases. LL has successfully fabricated 32 × 32 devices with an architecture designed for bump-bonding to the back of the array.

Timing Results

Time resolution data was taken using a short-pulsed laser, a single APD channel and associated readout electronics, and a Phillips Scientific Time-to-Digital Converter (TDC).[11] A trigger signal from the laser biased the APD beyond breakdown (effectively turning it on) for 100 ns. There was a user specified delay of 20–100 ns between the trigger signal and the actual laser fire. The APD was placed close to the laser head so that when the laser fired, the chances of detecting an outgoing photon were very high, making the effective laser pulse width less than 15 ps. The 15 mV signal from the APD readout electronics was compared with a 5–10 mV threshold and the output of the comparator acted as the STOP for the TDC. The trigger signal from the laser also acted as the START for the TDC. Each run consisted of 1000 TDC START/STOP pairs. Extreme outliers (dark counts, noise, etc.) were removed and the remaining data was analyzed to determine RMS jitter.

Figure 3a shows a Gaussian pulse shape with a Gaussian RMS of 59 ps and a real RMS of 57 ps while figure 3b shows a pulse with a Gaussian core but with much wider wings. The RMS of the core is only 29 ps as compared to the full RMS of 63 ps. The wings are not a common feature of the data and the vast majority of runs had responses similar to Figure 3a. The source of the wings is unclear, but the inner core suggests that the detectors and timing electronics are capable of 30 ps or better timing resolution.

We found that sequential 1000 START runs returned RMS results varying from 50–70 ps RMS. This is likely the result of the low signal-to-noise level. The lack of robustness discouraged us from trying to optimize the system's many degrees of freedom and encouraged us to explore other options. A new design is currently underway for an electronics scheme involving a series of diodes and transistors that will produce 100 mV signals.[12] It is hoped that the system will be much more robust and not produce the wide variation observed with the previous electronic design, and will consistently deliver the 30 ps performance glimpsed in our earlier attempts.

Simulations

Figure 4 shows three screenshots from a simulator intended to realistically represent the operating performance of APOLLO. These highlight the advantages inherent in using array detectors in laser ranging applications. On the left, the simulator shows the moon phase, with the target retroreflector designated by a green cross. In the middle, the top ten arrays represent ten consecutive calibration returns spanning 0.5 s followed by a sum of the ten frames. Below this, is a similar set showing the lunar returns and sum over the same 0.5 s interval. The returns are colored according to the type of detection they represent—calibration, scatter, background, or lunar. On the right is a histogram of calibration return times and 1, 5, and 10 second sums of the lunar returns. Note that the calibration return is much higher and easily distinguished from other sources of noise. A 5 or 10 second sum could be used as part of a closed-loop tracking and guiding system for the telescope.

Figure 4a shows Apollo 15 near full moon with one arcsecond seeing. The return is well centered. Figure 4b again shows Apollo 15 near full moon with arcsecond seeing, but now there is an introduced pointing error that produces an offset of about half an arcsecond. This offset is clearly seen in the 1, 5, and 10 second sums. Figure 4c shows Apollo 14 in the dark with a centered return but only 1.5 arcsecond seeing. Now the center of the return is not as obvious in the 1, 5, or 10 second sums.

It should also be noted that lunar and twilight background is very low, even near full moon or early evening. This is largely due to the very small field of view of less than 1.3 arcseconds. This low background rate should enable APOLLO to collect data uniformly throughout the lunar cycle with the exception of two or three days on either side of new moon.

Conclusion

APOLLO is an exciting new LLR endeavor that stands to significantly improve lunar range precision. Access to a large telescope with excellent seeing conditions allows for significant improvement in the signal strength and is the key to the project's success. In order to fully make use of this high return rate, we are employing new technology in the form of avalanche photodiode arrays. The APD arrays fabricated by Lincoln Labs have high timing resolution of better than 30 ps. The array format also allows for the detection of multiple photons while preserving the spatial information, facilitating closed-loop tracking and acquisition as well as permitting the evaluation of systematic errors based on the two-dimensional footprint.

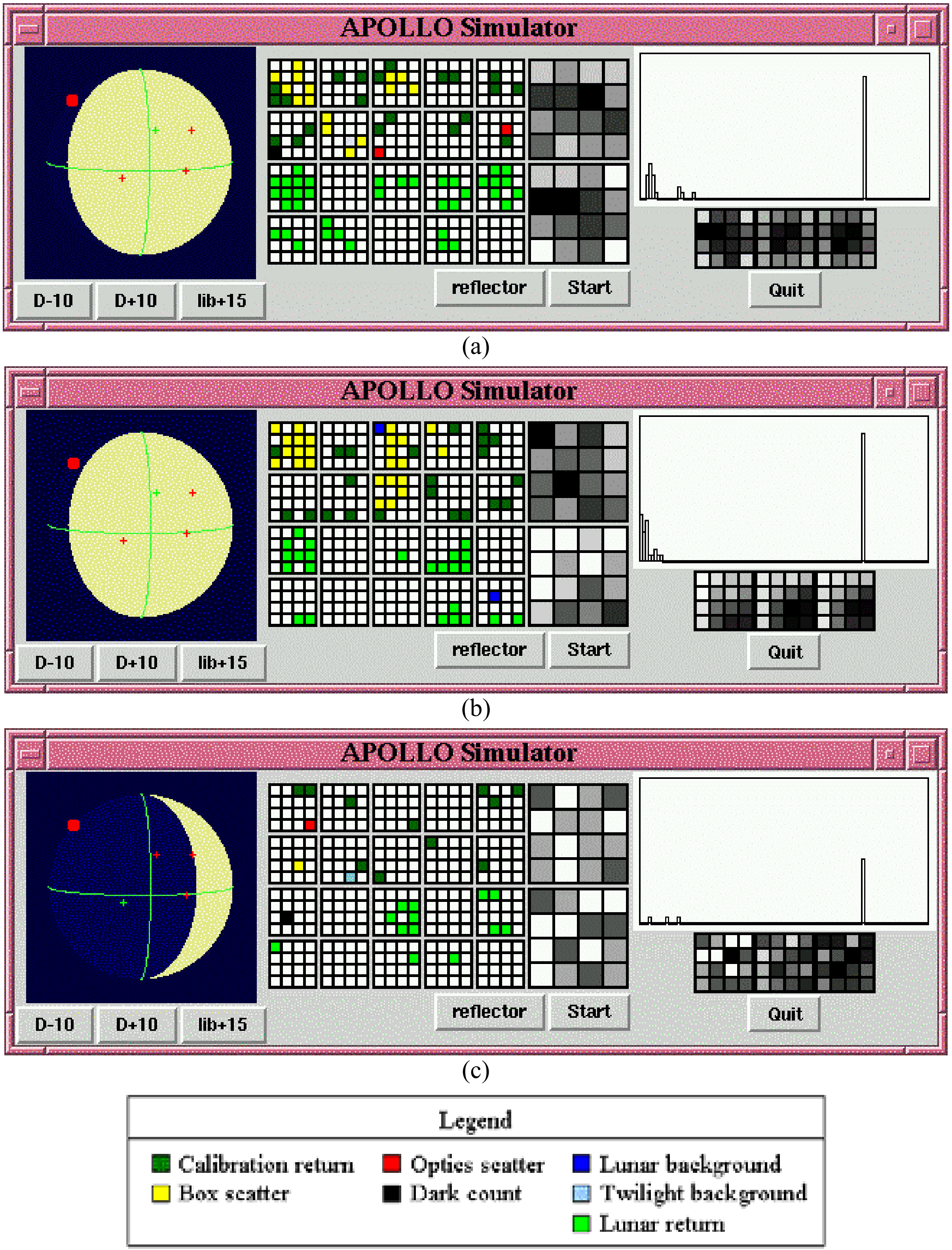


Figure 4: APOLLO simulator screen shots: (a) Apollo 15 near full moon with one arcsecond seeing and centered return, (b) Apollo 15 near full moon with one arcsecond seeing and offset return, (c) Apollo 14 near new moon with 1.5 arcsecond seeing and centered return.

References

[1] Bender, P. L., Currie, D. G., Dicke, R. H., Eckhardt, D. H., Faller, J. E., Kaula, W. M., Mullholland, J. D., Plotkin, H. H., Poultney, S. K., Silverberg, E. C., Wilkinson, D. T., Williams, J. G., & Alley, C. O., “The Lunar Laser Ranging Experiment,” *Science*, **182**, 229-238, (1973)

[2] Dickey, J. O., Bender, P. L., Faller, J.E., Newhall, X. X., Ricklefs, R. L., Ries, J. G., Shelus, P. J., Veillet, C., Whipple, A. L., Wiant, J. R., Williams, J. G., & Yoder, C. F., “Lunar Laser Ranging: A Continuing Legacy of the Apollo Program,” *Science*, **265**, 482-490, (1994)

[3] http://almagest.as.utexas.edu/~rlr/mlrs.html

[4] Samain, E., et al., “Millimetric Lunar Laser Ranging at OCA,” *Astron. & Astrophys. Suppl. Ser.*, **130**, 235-244, (1998)

[5] Silverberg, E. C., private communiucation (2002)

[6] Wiant, J. R., private communiucation (2002)

[7] Samain, E., private communiucation (2002)

[8] Cova, S., Ghioni, M., Lacaita, A., Samori, C., & Zappa, F., “Avalanche photodiodes and quenching circuits for single-photon detection,” *Applied Optics*, **35**, 1956-1976, (1996)

[9] Heinrichs, R.M., Aull, B.F., Kocher, D.G., Newbury, N., & Primmerman, C.A., “Development of 3D imaging laser radar technology for advanced seekers,” IRIS Proc. Active Systems, Tucson, Arizona, March (1997)

[10] Murphy, T. W., et. al., “APOLLO: Multiplexed Lunar Laser Ranging,” *13th International Laser Ranging Workshop*, Washington, D. C., USA, (2002)

[11] http://www.phillipsscientific.com/phisci1.htm

[12] Lacaita, A., Cova, S., Samori, C., & Ghioni, M., “Performance optimization of active quenching circuits for timing with single photon avalanche diodes,” *Rev. Sci. Instrum.*, **66**, 4289-4295, (1995)