The C-SPAD as a single-photon detector

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Abstract

We have successfully used a C-SPAD as the principal detector at Herstmonceux since 1999. This paper outlines the reasons we chose to buy one; the results from initial testing; the need to re-tune to match our pulse length; and the results from tests after the re-tuning (including dependence on return energy and temperature). We conclude with a critical assessment of the C-SPAD's performance and explain why, for "best" results from both calibration and satellite ranging, we continue to maintain a single-photon detection regime using the C-SPAD output which is not compensated for return energy dependent time-walk.

Introduction

We have used Single-Photon Avalanche Diode (SPAD) detectors at the Herstmonceux SLR station since 1992. Their principal advantages over the traditional photo-multiplier tubes (PMTs), which they replaced, are the fast rise time of the avalanche to give good epoch timing, and the fact that they are compact, stable and robust. But they do have some disadvantages: they are intrinsically noisier than PMTs; there is time-walk (the response time is dependent on both light pulse energy and the temperature of the device); and the tiny chip can make alignment difficult. However, the effects of these drawbacks can be minimized at the telescope by using neutral density filters to attenuate the energy of return pulses at the level of single photons, and by frequent calibration, especially when the temperature is changing rapidly. In routine operation the advantages far outweigh the drawbacks.

At the end of 1998 we purchased a time-walk compensated version of the SPAD, the so-called C-SPAD (Kirchner *et al.* 1998), which has several improvements over previous SPAD detectors:

- A larger chip makes for easier alignment;
- The detector chip itself is cooled to -60°C and is much less noisy;
- The electronics are temperature stabilized to minimize response time variations with temperature (particularly important for us since our detector is exposed at the Cassegrain focus of the telescope); and
- A second output channel has been added for which the timing of the emitted electrical pulse is delayed by an amount equal to the time-walk induced by the particular energy of the incoming photon pulse.

Testing the C-SPAD Performance

The C-SPAD was installed on our telescope and successfully aligned. We immediately noticed a reduction in the level of background noise. We conducted an extensive series of tests to investigate how the range to a local calibration target varied with the energy of the return pulse reaching the detector. The return energy was estimated by monitoring the rate of true returns (Appleby & Gibbs 1994) detected by the C-SPAD. All experiments were carried out on days when the outside temperature varied very little. Each experiment consisted of ranging to a ground target for the same length of time and controlling the return rate as closely as possible using neutral density filters. At high pulse energies (where the simple relationship between return rate and photon energy breaks down) photon numbers were estimated by extrapolation from lower energies, using the accurately known ratios between the attenuations of different neutral density filters and irises.

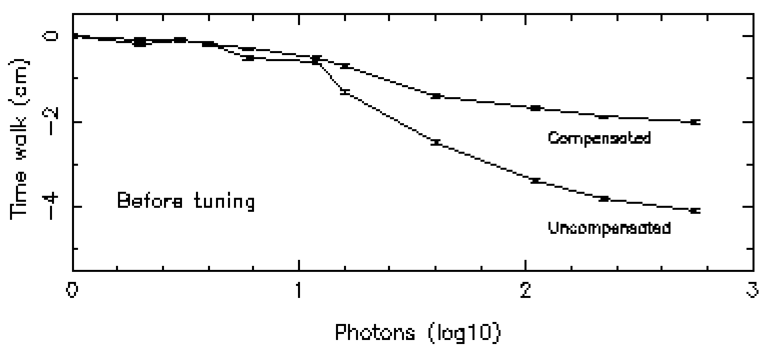

Figure 1a
Shows some time-walk for both output channels of the C-SPAD

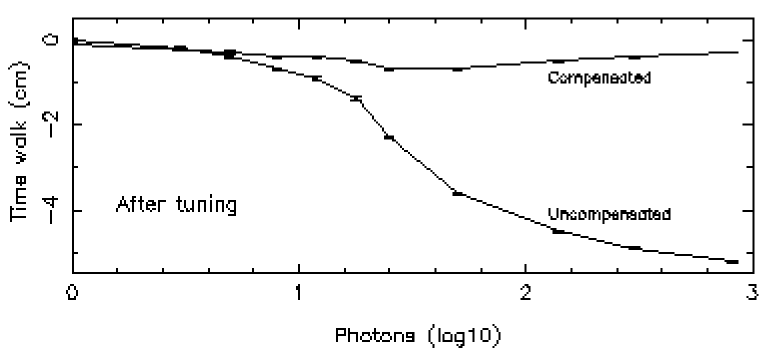

Figure 1b
Shows very little time-walk after the compensation was tuned for the correct laser pulse length.

The results from these initial tests for both output channels are shown in Figure 1a. Time-walk in centimeters is plotted against the logarithm of the number of photons estimated to be hitting the C-SPAD at each detection. The shape of the curve for the uncompensated channel follows theoretical expectation (*e.g.* Appleby & Gibbs 1994), but we were puzzled that the compensated channel also exhibited time-walk effects. It was quickly realised that this was because the compensation had originally been set up using a short pulse, very different from the 100ps pulse of the Herstmonceux laser. The C-SPAD was returned to Graz where the electronics were re-tuned to match our longer pulse length.

Tests after tuning the C-SPAD

On its return the C-SPAD was re-installed on the telescope and the above experiments repeated as closely as possible. From the results plotted in Figure 1b it is immediately clear that the time-walk behaviour of the compensated channel is greatly improved (now as advertised!) while that of the uncompensated channel is virtually unchanged. The totality of the results from these tests gave us great confidence in the performance of the C-SPAD and we adopted it as our principal detector. Since then we have routinely gathered data from *both* output channels, but continued to submit to Data Centres only those from the uncompensated channel (operated in the single photon regime, return rate ≤ 16%). The reasons for this choice are outlined below.

Temperature effects

We already knew from our experience with previous SPADs that the calibration range showed a clear correlation with ambient temperature. Figure 2 shows 8-day time series of calibration range and outside temperature, using data from the uncompensated channel, and there is clear evidence that the two are again correlated.

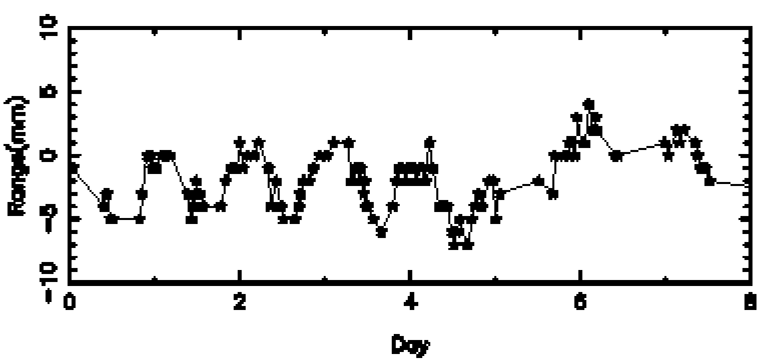

Figure 2a
Shows the daily variation in calibration range in mm

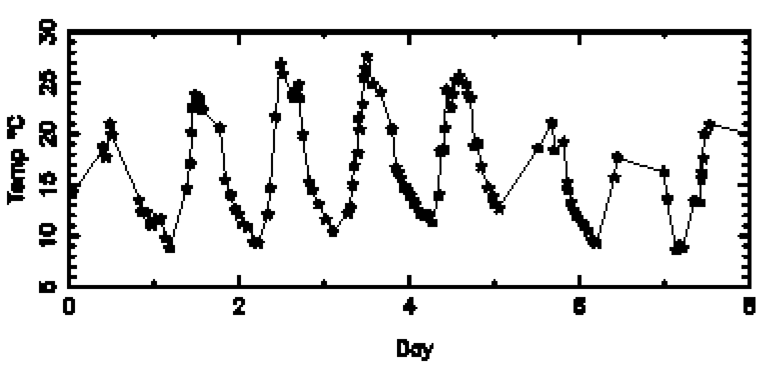

Figure 2b
Shows the daily variation in the outside temperature

The upper panel in Figure 3 reveals a linear relationship with a slope of about 0.6mm/°C, approximately half the slope of the same plot for the “old” SPAD. When we plotted the corresponding data (lower panel Figure 3) for the compensated channel (recorded *simultaneously* with the data plotted in the upper panel) we were somewhat surprised to find an equally good correlation but with the opposite slope! This immediately tells us that the effect cannot be due to expansion of the telescope or the target, but must be intrinsic to the detector itself. It can be seen from the time series that the measured range varies only relatively slowly as the temperature changes, and so any contribution to satellite ranges can easily be eliminated by frequent calibration, especially when temperatures are changing fast.

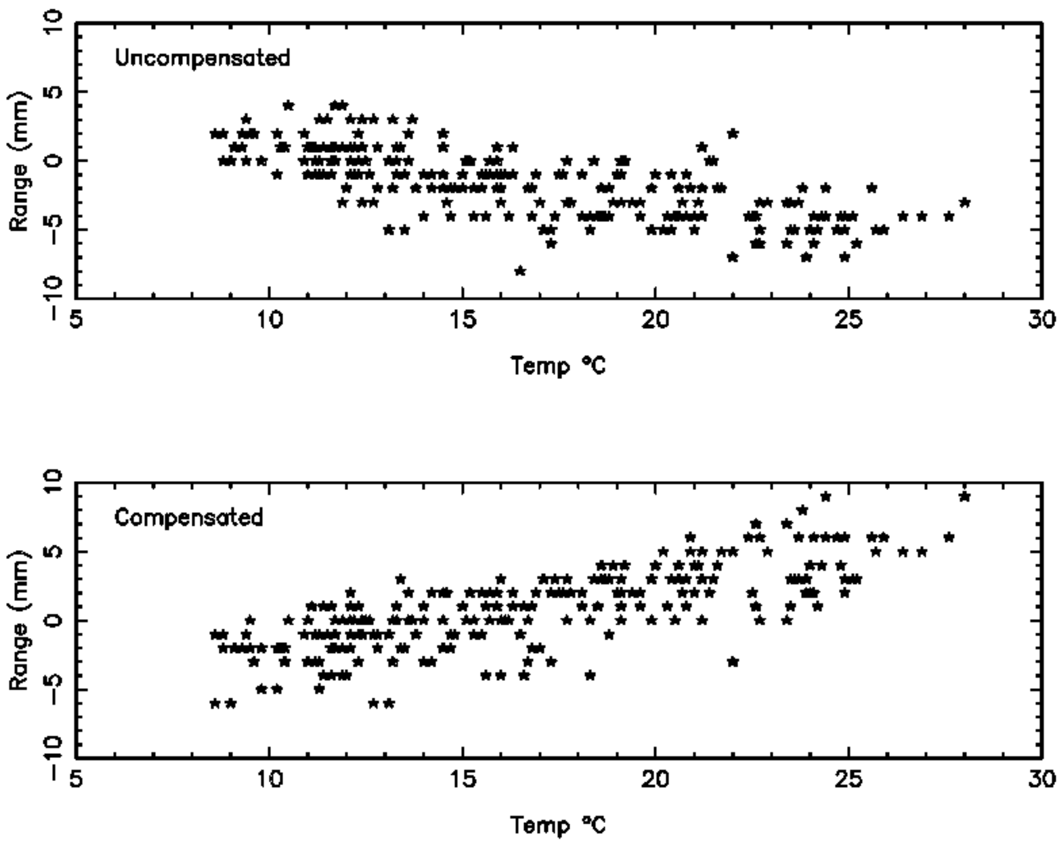

Figure 3
Shows the calibration variation with temperature for both compensated and uncompensated channels of the C-SPAD

Summary and Statement of Herstmonceux Policy

With the C-SPAD you get: low detector noise; less temperature variation; easier alignment; and choice of time-walk compensation. At low return energies (single-photon detection) the two output channels are essentially equivalent. But at higher energies it is not clear whether the compensation, tuned for the Herstmonceux laser, will be appropriate to the 'stretched' pulse returning from the satellite reflector arrays. In the absence of accurate measurements of the return energy on a shot-by-shot basis it would be difficult to monitor such effects, and to ensure that the appropriate centre of mass correction is applied to the range measurements when the data are analysed. Thus, in order to maintain the best possible data consistency on the longest possible time-scale, we choose to operate at low return energies (single-photons). By doing so we are setting out to ensure that we observe in exactly the same manner for *all* satellites and ground targets, and under *all* the different types of observing conditions that we encounter. Strict adherence to this way of working necessarily implies higher formal errors of measurement because of the contributions from satellite signature and pulse length; and the low return rate results in fewer points per normal point bin. However, we believe that these effects are more than compensated by the achievement of a long-term dataset which is independent of the nature of the detection system, consistent across the whole constellation of satellites, and uniform with respect to satellite signature and absence of time-walk.

For the time being, therefore, we will continue to observe with the uncompensated channel of the C-SPAD in single-photon mode. For selected satellites with very small reflector arrays we plan to investigate the use of the compensated channel output. For example the Westpac satellite, during the course of a given pass, often has periods where there is no reflector visible from the observing station. In our system the default action of the automatic return rate control software is to remove neutral density during such intervals in the hope of re-aquiring the track. When another reflector does come into view the return rate is suddenly huge and it takes a little while for the system to adjust to the required return rate again, and the recorded returns will suffer time-walk. This could be avoided (without compromising the satellite signature information – negligible in this case) by taking the compensated channel output instead. Similar considerations might apply to CHAMP and other satellites with particularly compact reflector arrays.

Acknowledgements

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References

Appleby, G.M. & Gibbs, P. *Monitoring Potential Range Biases in Single-Photon SLR Systems,* Proc. 9th International Workshop on Laser Ranging Instrumentation, Canberra 1994, pp 92-102.

Kirchner, G., Koidl, F., Prochazka, I. & Hamal, K. *SPAD Time Walk Compensation and Return Energy Dependent Ranging,* Proc. of 11th International Workshop on Laser Ranging, Deggendorf 1998, pp 521-525.