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Beyond sensing

Noise and stability analysis of an asynchronous SPAD camera operating in space at low Earth orbit

Introduction

Single-photon avalanche diode (SPAD) cameras are increasingly relevant in space missions due to their ability to detect extremely low photon fluxes, making them valuable for applications such as space-based imaging, optical communication, and scientific experiments requiring high sensitivity. In the space environment, however, SPAD detectors are exposed to conditions that can significantly influence their noise characteristics and long-term stability, including temperature variations, radiation exposure, and elevated background illumination from sunlight. Understanding the behavior of SPADs in space is therefore essential for assessing system reliability and ensuring mission performance.

This report summarizes the noise and stability performance of an asynchronous 64×48 SPAD camera, first evaluated under terrestrial laboratory conditions and subsequently after final integration into a satellite system on the ground. The device was then characterized during its operation in low Earth orbit (LEO). The primary objective is to verify whether the noise characteristics, specifically the dark count rate (DCR) and hot pixel percentage, remain stable throughout launch preparation and in-orbit operation.

Measurement Results

Initial characterization was performed in the laboratory to establish baseline noise metrics. The primary parameter assessed was the per-pixel DCR, measured across the full array at room temperature under various integration times and frame-count settings. After the camera was integrated into the satellite, the same noise metrics were re-evaluated following the final shake test, during which the camera module was subjected to launch-level vibration levels, and the subsequent thermal vacuum (TVAC) test, which simulated the vacuum conditions and temperature variations expected in space. Finally, the photon count distribution over the array was measured while the camera was operating in orbit and imaging a region of the Earth through the onboard optics.

The normalized DCRs, accounting for the different integration times and frame counts, recorded for single-frame measurements obtained on the ground and in orbit are shown in Fig. 1 as pixel population curves. Before the camera was integrated into the satellite, DCR maps were obtained using 50 ms and 500 ms integration times. After the final shake test and subsequent TVAC test performed on the integrated satellite, the measurements were repeated with an 80.5 ms integration time. An additional measurement was obtained in orbit, where the camera captured an Earth scene using the same 80.5 ms integration time. In each population curve, saturated pixels were classified as hot pixels and removed from the analysis, along with zero-count pixels.

The resulting population curves show no significant change in noise following the shake and TVAC tests, as indicated by the consistent slope and shape of the high-DCR regions. For the in-orbit data, the measurement was not taken in darkness but during imaging of a scene; therefore, photon arrivals dominate the overall curve shape. Nonetheless, no signs of pixel damage or an increase in the hot pixel percentage were observed after several months of operation in space. The measured hot-pixel percentages were **9.4%** before satellite integration, **9.1%** after the shake test, and **8.9%** for the in-orbit measurement.

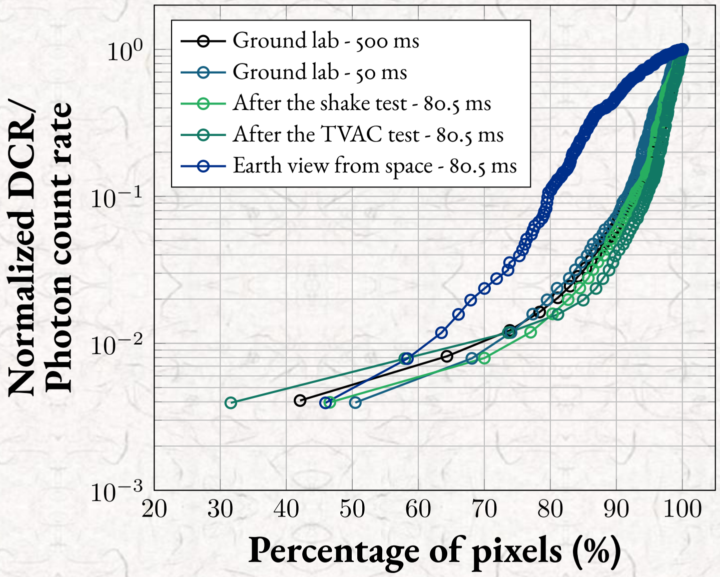

Figure 1. Single frame pixel population curves recorded during the phases of the operation.

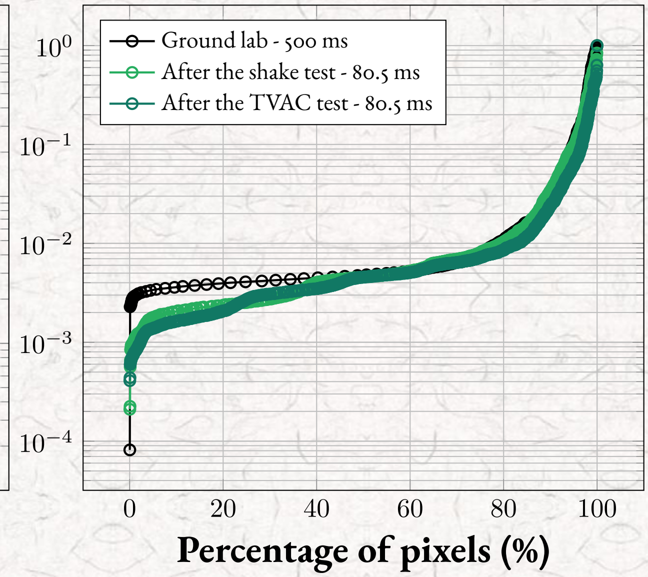

Figure 2. 50-frame pixel population curves recorded or reconstructed during the phases of the operation.

In addition, Fig. 2 shows a DCR measurement acquired over 50 frames with a 500 ms integration time prior to satellite integration, together with reconstructed 50-frame results obtained from the single-frame data collected after the shake and TVAC tests. The reconstruction was performed by deriving a transfer matrix that characterizes the per-pixel mapping between a single-frame DCR map acquired with 50 ms integration and a 50-frame accumulated DCR map acquired with 500 ms integration. This matrix was then applied to the shake and TVAC single-frame DCR data to estimate their corresponding 50-frame distributions expected for a 500 ms integration time. Pixel population curves were then generated from these reconstructed DCR maps. These longer-accumulation results likewise show no significant change in the high-DCR regions.

The DCR maps corresponding to the single-frame lab test and after the TVAC test are presented in Fig. 3 and in Fig. 4, respectively. Table 1 also summarizes the mean and median normalized DCR values including and excluding hot pixels present before and after the satellite integration. It should be noted that zero-count pixels were omitted during the mean and median calculations, as well as in the computations of hot pixel percentage. Hence, both the DCR maps and mean/median DCR values further confirm that no measurable degradation occurred in the camera's noise performance and hot pixel characteristics throughout the operational sequence.

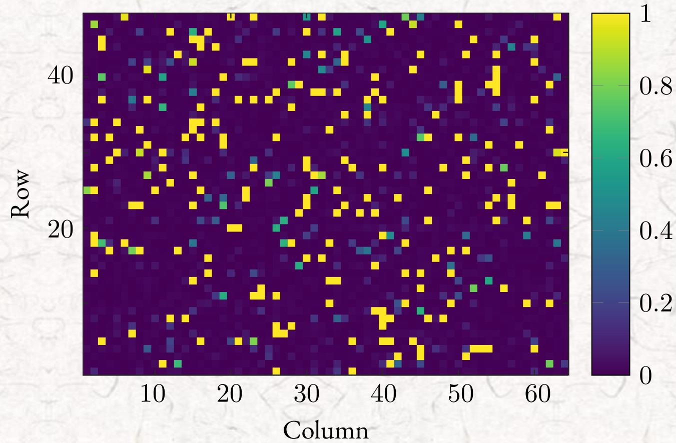

Figure 3. Single-frame 2D DCR map of ground lab measurement with 500 ms.

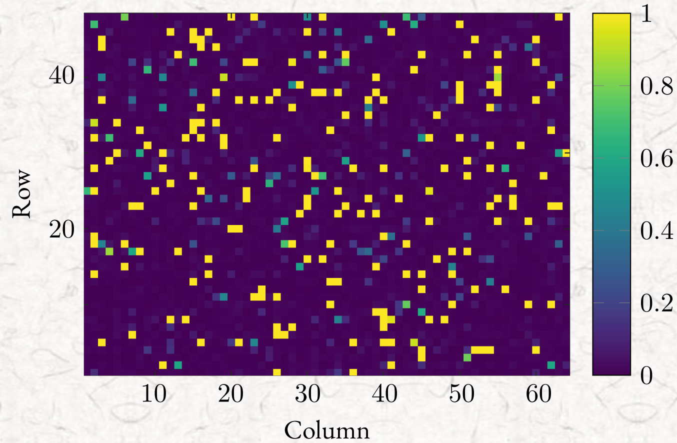

Figure 4. Single-frame 2D DCR map of after the TVAC test measurement with 80.5 ms.

Table 1. Test results summary.

Condition	Exposure	Mean normalized DCR	Mean normalized DCR excluding hot pixels	Median normalized DCR excluding hot pixels
Ground lab	500 ms	0.1283	0.039	0.00816
After the shake test	80.5 ms	0.1255	0.03784	0.00793
After the TVAC test	80.5 ms	0.1012	0.03235	0.00787

Conclusion

This work presented a comprehensive noise and stability assessment of an asynchronous 64×48 SPAD camera from laboratory characterization through satellite integration and extended operation in low Earth orbit. The results demonstrate that the DCR distribution and hot pixel percentage remained remarkably stable throughout vibration, thermal vacuum testing, and several months of in-orbit operation. No measurable degradation or radiation-induced damage was observed. These findings confirm the robustness of SPAD technology under realistic space environmental conditions. To the best of our knowledge, these results represent the first reported in-orbit noise performance characterization of a SPAD camera operated in space, providing an important validation milestone for the future use of SPAD-based imaging systems in space missions.