3D Flash LiDAR Fusion on a 640x512 SWIR FPA: Depth Calibration, TOF Characterization, and Path to Next-Gen ROICs

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ABSTRACT

Integration of 3D Flash LiDAR technology with a 640×512 short-wave infrared (SWIR) focal plane array (FPA) enables real-time, eye-safe, depth and imaging fusion, with superior performance in obscured and low-light conditions. This work delves into the methodologies deployed in depth sensing, system-level calibration, and time-of-flight (TOF) characterization; all essential for achieving high-precision, real-time 3D imaging. Key aspects such as depth accuracy, temporal resolution, and signal-to-noise optimization are explored to highlight the system's current state. This paper also outlines a roadmap to next-generation readout integrated circuit (ROIC) architecture, emphasizing innovations in pixel-level TOF, power efficiency, and high-frame-rate data throughput, to meet the demands of advanced defense, aerospace, and autonomous systems for complex operational environments.

Keywords: SUI, SWIR, Depth sensing, TOF, 3D Imaging, Flash LiDAR, SU640AM2

1. INTRODUCTION

Scanning Light Detection and Ranging (LiDAR) uses a moving laser beam that is mechanically or optoelectronically steered across the target area, capturing data point-by-point to generate a detailed 3D map. This approach is known for its high resolution and long-range capabilities, making it suitable for applications such as autonomous vehicles, topographical mapping, and infrastructure inspection. In contrast, flash LiDAR illuminates an entire scene or area simultaneously using a wide-angle laser pulse, capturing 3D data in a single snapshot. This method eliminates the need for mechanical scanning, offering faster data acquisition and increased robustness to motion, which is advantageous in dynamic environments such as aerial imaging or obstacle detection in robotics. However, flash LiDAR typically has a shorter range and lower resolution compared to scanning LiDAR [1].

SWIR TOF depth sensing with Flash LiDAR enjoys many of the same advantages as traditional SWIR imaging:

- Penetration through atmospheric obscurants. SWIR LiDAR can penetrate through fog, smoke, haze, and other atmospheric particulates better than visible light.
- Covert operations compatibility. SWIR LiDAR is not detectable by the human eye.
- Improved eye safety with SWIR lasers. SWIR light operates in a wavelength range that is safer for human eyes compared to shorter wavelengths like visible or ultraviolet light, allowing for eye-safe laser-based applications.
- Enhanced imaging through glass. Unlike many other wavelengths, SWIR LiDAR can capture 3D scene data through glass.
- Compact and lightweight systems. SWIR is a relatively mature technology. The addition of flash LiDAR as a core capability will enable the integration of flash LiDAR into portable or aerial platforms, such as drones or robotics.

This paper presents the initial system level verification of the SU640AM2 ROIC from Sensors Unlimited, Inc. (SUI). The SU640AM2 ROIC comprises a unique multi-mode signal processing approach which allows for pulse detection, TOF measurement, and image integration to occur simultaneously on a per-pixel basis.

Applications: Defense, Aerospace, Autonomous systems, Complex operational environments

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2. SYSTEM DESCRIPTION

The SUI SU640AM2 Readout Integrated Circuit (ROIC) is a 640×512 array with a 15 µm pixel pitch. This is a first-in-class device to combine the following three technologies within each pixel unit cell:

- SUI's Multi-Modal Tracking (MMT) laser pulse tracking technology,
- State of the art SWIR imaging based on SUI's Buffered G-Mod (BGMOD) architecture,
- And a new pulsed TOF measurement technique within each unit cell floorplan.

Figure 1 shows a pixel functional block diagram for the SU640AM2 ROIC. The result is a world-first Tri-Modal ROIC. This ROIC establishes a critical baseline of performance and provides a platform to validate tri-modal imaging, Asynchronous Laser Pulse Detection (ALPD), and initial TOF/Distance measurement capabilities. SUI's vanguard MMT ROIC technology, the SU640AB7, also has a 15 µm pixel pitch, and is considered the gold standard of VGA ALPD-capable sensor designs. In the same pitch, the SU640AM2 includes a collocated TOF circuit and supporting readout [2]. Lessons learned and performance metrics from the SU640AM2 will directly inform the advancements integrated into future ROIC designs. The following summarizes some of the TOF specific test and characterization results of the SU640AM2 ROIC to date.

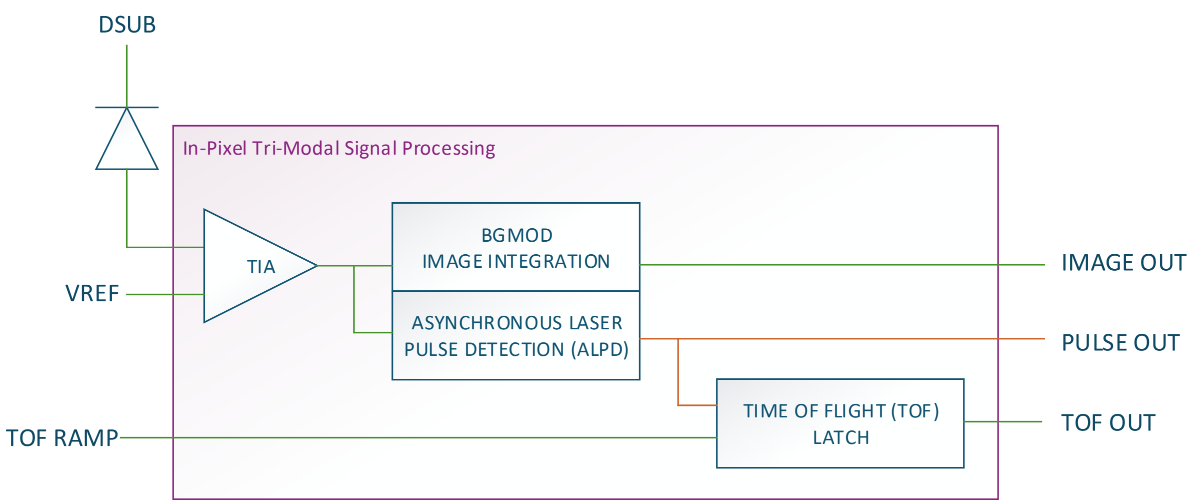

Figure 1. SU640AM2 Pixel Functional Block Diagram

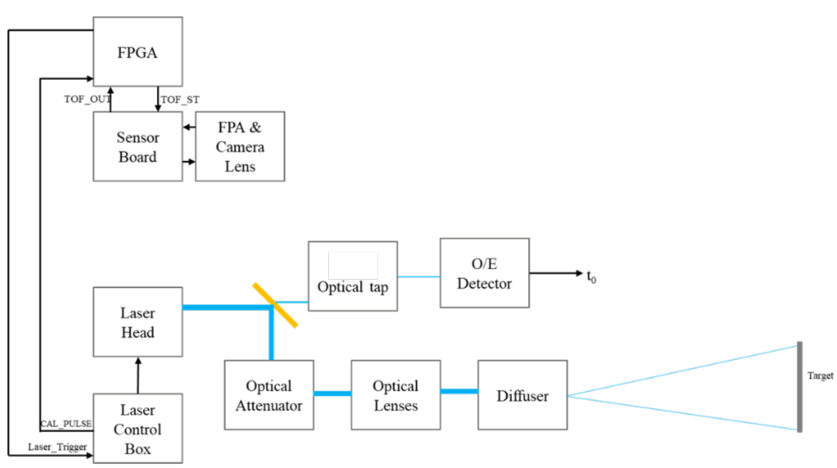

Figure 2. SU640AM2 System block diagram

Figure 2 shows the depth sensing system block diagram and consists of a high-energy pulsed SWIR laser that is synchronized, calibrated and controlled from an FPGA chip along with the 640X512 SWIR FPA and custom designed lens. The laser was synchronized using an optical tap from the laser beam and using a pulse output from an avalanche photodetector that is fed back to the sensor board. The optical path includes an optical attenuator, aspheric lens and diffuser to uniformly illuminate the target. The intensity variation correction and walk error correction co-efficient were measured and used in the distance measurement algorithm. The region of interest (ROI) can be selected from few pixels up to a full frame. Both the intensity image and TOF time stamp images can be collected simultaneously using the dual output path from the read out integrated circuit (ROIC). The measured simultaneous intensity image and TOF image using a 3D chair as a target is shown in Figure 3.

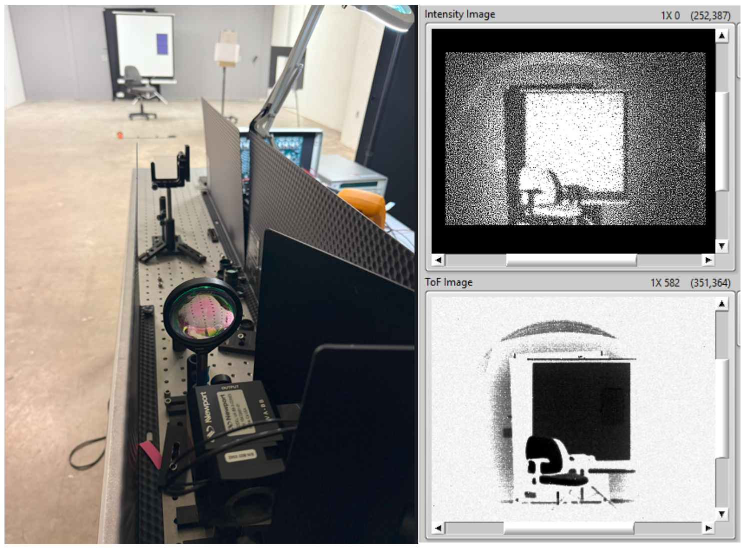

Figure 3. Flash LiDAR depth sensing Measurement using a chair as a target: Left picture taken with visible camera and the right picture with TOF and intensity images

3. ALGORITHM – CALIBRATION AND MEASUREMENT RESULTS

Depth sensing

Depth sensing is performed in the SU640AM2 utilizing a unique combination of the ALPD pulse detection circuitry and an in-pixel analog TOF latch. An analog TOF ramp is shared across the entire pixel array. During a flash LiDAR frame, a laser pulse is emitted into the scene and the TOF ramp generator begins to increment. Each pixel latches its instantaneous TOF ramp voltage as the laser pulse reflects off the environment and returns back to the ROIC. The amplitude of this latched TOF voltage is the raw data used to calculate the distance that light travelled from the pulser, to the target, and back to the ROIC.

System level calibration

There are several sources of uncertainty within this system that must be carefully accounted for. In addition to the obvious jitter, quantization, and Johnson-Nyquist contributors, it was experimentally realized early on that this architecture is susceptible to a time-of-detection error that is related to the intensity of the reflected laser pulse. For simplicities sake, all testing thus far has been conducted in the dark – though there are plans to implement and characterize a background subtraction algorithm during future testing. The result of these tests is a robust, per-pixel correction algorithm that utilizes the intensity of the returned light as one of its inputs, and whose uncertainty increases as reflected intensity decreases in a known way as discussed below.

Depth accuracy

The following are the results of SUI's initial experiments to demonstrate Flash LiDAR system operability with the SU640AM2. Table 1 shows the actual target distance and distance measured using the SU640AM2 in a laboratory environment with a uniform, stationary target and in the dark. As seen from Table 1, the measured distance corresponds to the actual distance to target. The SU640AM2 is designed to comfortably work with distances between 0 m and 25 m, although further distances are achievable with range gating. We expect the accuracy of these measurements to improve substantially via further refinement to our experiment environment.

True Distance (m)	Mean Meas Distance (m)	Median Meas Distance (m)	StdDev (m)
10.00	10.48	10.44	0.69
9.00	9.12	9.06	0.51
8.00	8.17	8.13	0.43
7.00	7.08	7.06	0.41
6.00	5.74	5.75	0.42
5.00	4.91	4.91	0.47

Table 1. Measurements vs. Distance, Center 25x25 Region of Interest

The following are real world Depth images from the SUI laser lab. Pixel brightness is proportional to the distance from the aperture. Some artifacts of note include the disparity in distance between the background and foreground, very clean lines of demarcation between objects at various distances, as well as the "shadow" of area behind the objects where flashed light is unable to penetrate. The histogram data to the right of the image is binned distance information from the green rectangle Region of Interest (ROI). Shown in Figure 4 the target at 10 m is a COTS projector screen, and in Figure 5 the object at 6 m is a flat cardboard target on a movable stand. The distribution of abnormally light and dark pixels is mostly due to a combination of pixel-to-pixel variation and ROIC-to-Focal Plane hybridization imperfections. This is something that will improve as development continues.

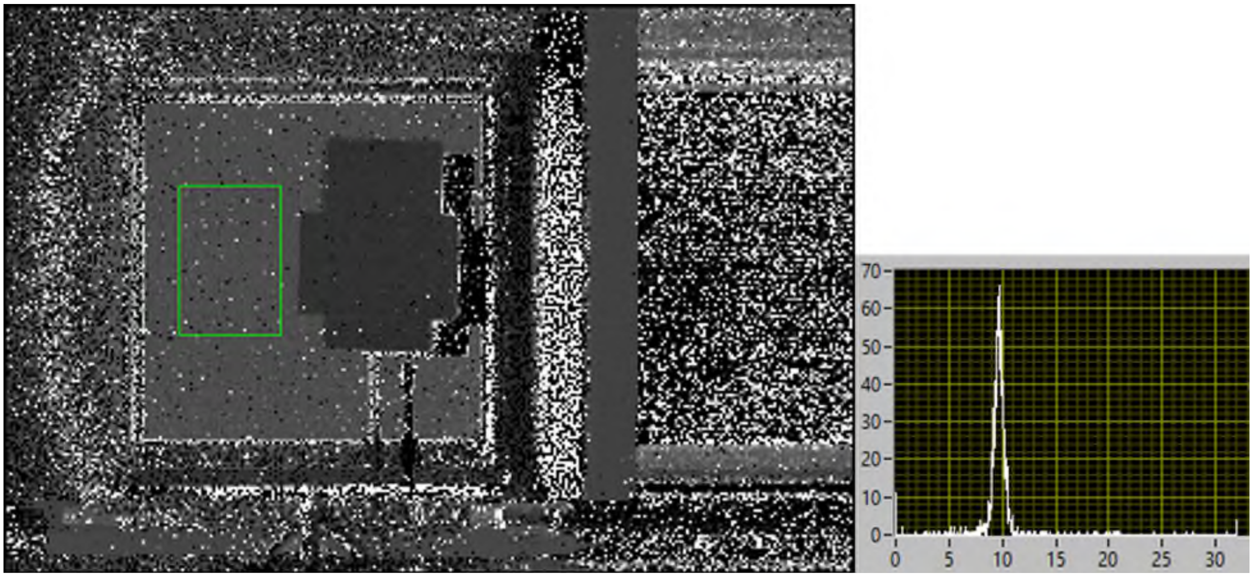

Figure 4. Flash LiDAR Distance Measurement on a 10 m Target

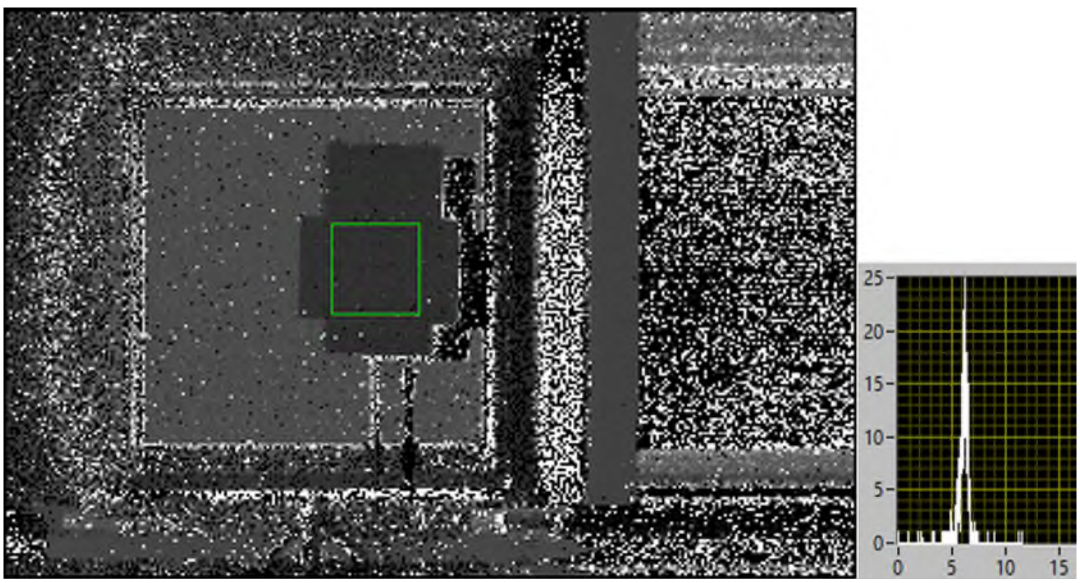

Figure 5. Flash LiDAR Distance Measurement on a 6 m Target

The technical demonstration and system bringup work that was achieved to date will serve as a critical foundation for our enhanced device characterization initiatives, which will underpin our product offerings incorporating this ROIC. Additionally, ongoing efforts are leveraging lessons learned to inform the development of our next-generation ROIC, designed to deliver improved sensitivity, enhanced uniformity, and more precise control over TOF measurements and range gating capabilities.

4. SUMMARY

This work highlights recent advancements in characterizing the SU640AM2 ROIC and its first-in-class Tri-Modal ROIC which combines laser pulse tracking, SWIR imagery, and TOF range measurements. The ROIC outline has been reviewed, and calibration and measurement results are presented. This paper discusses lab imagery highlighting the results of the ROIC TOF capability. Finally, the roadmap to the next-generation ROIC is discussed herein, noting improvements to TOF capabilities and imagery.

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REFERENCES

[1] Corneliu Rablau, "Lidar: a new self-driving vehicle for introducing optics to broader engineering and non-engineering audiences," Proc. SPIE 11143, Fifteenth Conference on Education and Training in Optics and Photonics: ETOP 2019, 111430C (2 July 2019); https://doi.org/10.1117/12.2523863

[2] Krishna Linga, Michael Evans, Wei Huang, Paul Bereznycky, Scott Endicter, William Gustus, John Tagle, John Liobe, "InGaAs-based devices for laser spot tracking and long-range remote sensing," Proc. SPIE 13469, Infrared Technology and Applications LI, 134690A (29 May 2025); https://doi.org/10.1117/12.3053729