

Low-SWaP SWIR ALPD Product Development at SUI

Michael J. Evans*, Sungjin Kim, John Liobe, Paul Bereznycky, Dmitry Zhilinsky, Wei Xu, John Wieners, Andrew Eckhardt, Jinguo Yu, Michael Delamere, John Tagle, Scott Ramsey
Sensors Unlimited Inc., Collins Aerospace, 330 Carter Road, Princeton, NJ 08540 USA

ABSTRACT

As customer demand for infrared laser sensors increases^{1,2}, so too does the need for low cost, readily manufacturable SWIR imaging systems capable of asynchronous laser pulse detection (ALPD). Sensors Unlimited, Inc., an RTX company, presents recent advancements in its SWIR APLD products tailored toward high volume production and broad deployment. Detectors based on SUI's multi-mode tracking (MMT) readout integrated circuit (ROIC)^{3,4} have been adapted for uncooled operation over a wide temperature range, enabling the elimination of costly thermoelectric cooling. A chip-on-board device configuration has also been implemented, obviating the need for a windowed package. Automation of fabrication processes further reduces unit cost and provides improved device uniformity. Results of SUI's latest system performance assessments are also discussed.

Keywords: ALPD (Asynchronous Laser Pulse Detection) InGaAs, SWIR, PDA (Photodiode Array), FPA (Focal Plane Array), Laser, MMT (Multi-Mode Tracking)

1. INTRODUCTION

With strong absorption in the wavelength range from 700 nm to 1700 nm, the InGaAs/InP system is well-suited to the detection of short-wave infrared (SWIR) lasers, including the primary battlefield wavelengths of 850 nm, 1060 nm, and 1550 nm. Two-dimensional focal plane arrays (FPAs) comprising an InGaAs photodiode array (PDA) grown on an InP substrate and a silicon readout integrated circuit (ROIC) have historically been used for imaging in the SWIR region of the electromagnetic spectrum.⁵ Imagery from such devices can be used for asynchronous laser pulse detection (ALPD), but the addition to the ROIC of dedicated pulse monitoring circuitry allows the laser detection to be decoupled from the imaging function. Sensors Unlimited, Inc. (SUI) introduced its first ALPD SWIR cameras with such multi-mode tracking (MMT) in 2017 on a commercial platform, with demonstrated capability of tracking up to 3 pulsed laser spots simultaneously in the field of view.² Adaptation of this technology to broader military applications, however, requires high volume production at low unit cost and enhanced laser tracking performance. Recent improvements to SUI's MMT-based ALPD are detailed herein, including increased detection range, greater thermal tolerance, the ability to track a greater number of laser spots, and expanded test and diagnostics of spot-tracking functionality.

2. APPARATUS

2.1. ALPD camera hardware and interface

SUI's ALPD cameras utilize a board set that includes an output board, a digital board, a focal plane array board, and a chip-on-board (COB) FPA package. The FPA format used in the experiments described here is 640 x 512 pixels on a 15 μm pitch. An open-frame test camera equipped with a SWIR optimized lens is shown on the left in Figure 1, and the COB package is shown in isolation on the right.

*michael.j.evans@collins.com; phone 1 609 333-8316

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary

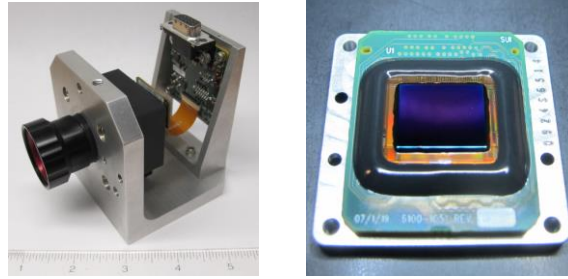


Figure 1. SWIR MMT ALPD test camera (left) and constituent COB FPA package (right).

A graphical user interface (GUI) provides SWIR imagery, a command terminal for camera control, and output of the camera's spot-tracking algorithm. The tracking output includes a list of spots being tracked, the x- and y-coordinates of their centroids in the field of view, and the pulse frequency (or an associated frequency code number) detected for each spot. A real-time map of the tracking output is also selectable. Sample GUI output is given in Figure 2.

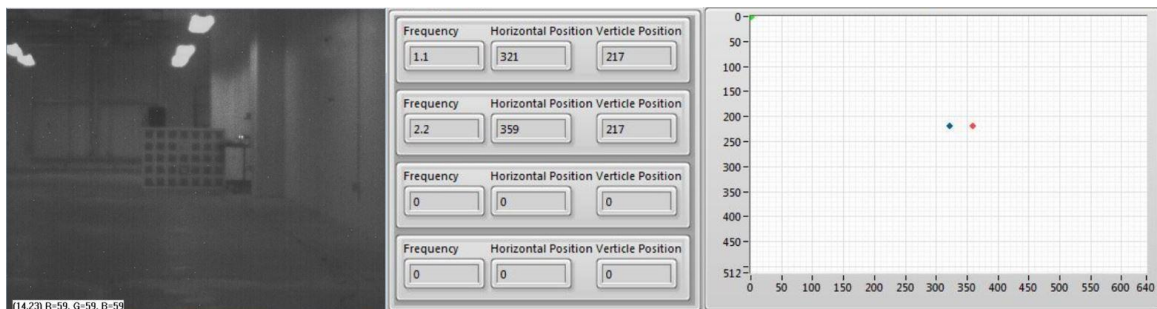


Figure 2. ALPD camera sample GUI output including SWIR image (left), tracked spot list (middle), and tracked spot map (right).

2.2. Pulsed spot generation

Pulsed spots were produced in some instances by directing the output of a 1550 nm laser module at a target in the field of view as in Figure 2 above. Primarily, however, spots were generated using SUI's multi-laser pulse simulator (MLPS) units, hand-held 1550 nm light-emitting diode (LED) sources with adjustable frequencies, directed at the camera. Size and shape of the MLPS spots were manipulated using foil masking of the LEDs, variation of distance to the camera, and deliberate defocusing of the camera lens. The MLPS units can also be programmed to output multiple frequencies simultaneously, simulating co-located but asynchronous spots. A photo of a MPLS unit and a SWIR camera image showing units both during and between pulses are shown in Figure 3(a) and (b) respectively.

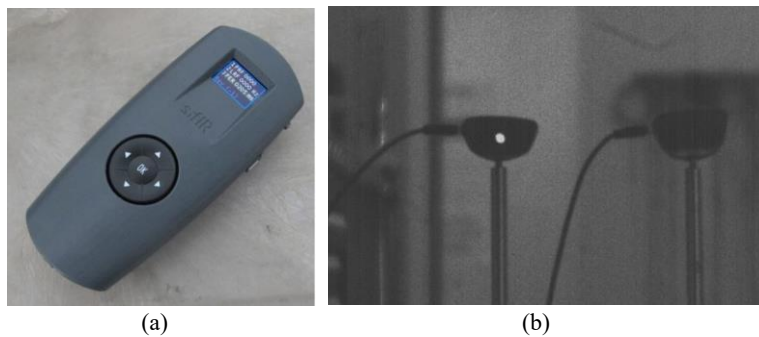


Figure 3. MLPS 1550 nm spot source (a) photo and (b) SWIR image of lit and unlit units.

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary

3. THERMAL TOLERANCE AND MANUFACTURABILITY IMPROVEMENTS

The initial implementation of the COB FPA package and the concomitant elimination of thermoelectric cooling provided significant reductions in the size, weight, and power (SWaP) of SUI's MMT ALPD products.⁶ Those modifications, however, have implications for the thermal requirements and large-scale manufacturability of their FPAs. The absence of the thermoelectric cooler (TEC) allows an additional COB package temperature swing of approximately 15 °C over an environmental temperature range of -40 °C to 70 °C. The wire-bonds connecting the ROIC to the printed circuit board (PCB) (see Figure 4) are protected from the environment by an encapsulation epoxy that was applied manually in two stages (see Figure 5) to cover the wire-bonds completely.

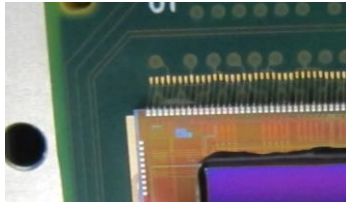


Figure 4. Bare wire-bonds between ROIC and PCB in packaged FPA.

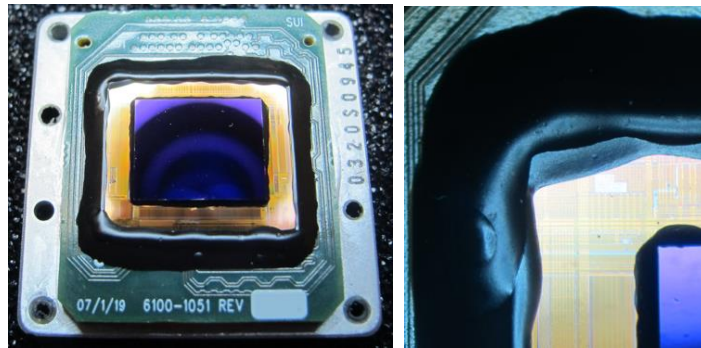


Figure 5. Packaged FPA wire-bonds encapsulated with manually applied epoxy.

The type of epoxy and the application method contributed to failures in those connections when exposed to repeated thermal cycling. The epoxy was found to crack and/or delaminate from the PCB surface in some instances as shown in Figure 6, pulling apart the wire-bonds in the process.

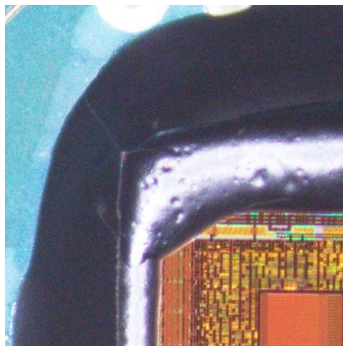


Figure 6. Cracked encapsulation epoxy in corner of FPA.

A series of experiments was undertaken to eliminate the latent defects resulting from the existing encapsulation process. Multiple candidate epoxies were dispensed onto test vehicles including glass slides, dummy PCBs, and fully functional,

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary

packaged FPAs. The epoxy beads on glass slides were evaluated for adhesion, shape, wire coverage, and cross-sectional uniformity. Down-selected candidates were applied to test devices which underwent thermal cycling, humidity exposure, fungus exposure, vibration testing, and destructive physical analysis. Two of the candidate epoxies passed all performance evaluations, exhibiting no cracking or delamination. The candidate epoxy with the simpler curing procedure was implemented for production. An automated dispensing process was also developed that served to make the application more uniform and repeatable with a marked reduction in manufacturing time. Packaged FPAs fabricated using the new encapsulation epoxy and process are shown in Figure 7, and a close view of a new epoxy bead following thermal, humidity, and vibration testing is shown in Figure 8.

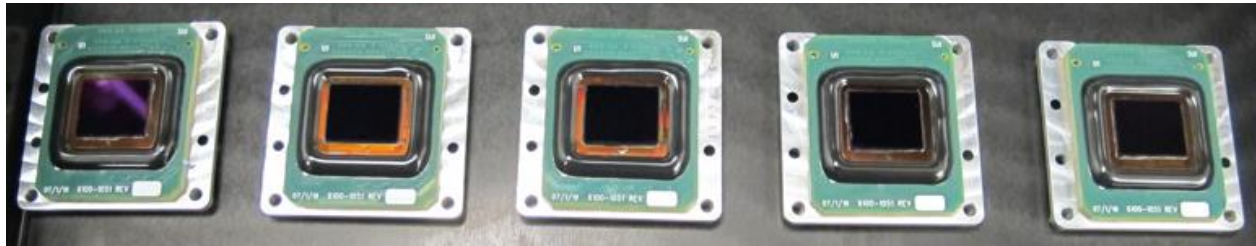


Figure 7. Packaged FPAs fabricated with new encapsulation epoxy and automated application.

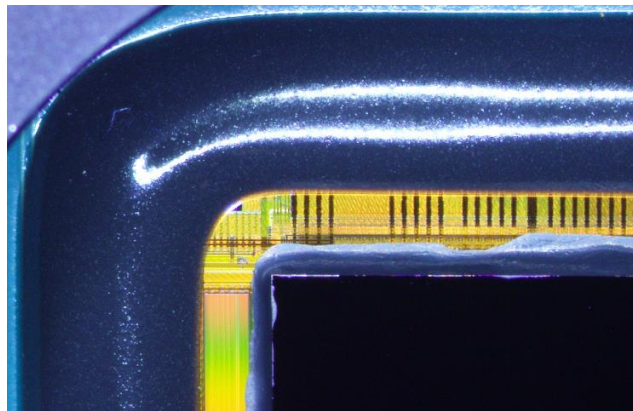


Figure 8. Corner of FPA showing new encapsulation epoxy bead after environmental testing.

4. ALPD PERFORMANCE ENHANCEMENTS

4.1. Pulsed spot multiplicity

The number of pulsed spots in the field of view simultaneously that could be tracked by SUI's first ALPD cameras was limited to three.² With the development of new camera firmware and user interface software, simultaneous tracking of four different spots has been successfully implemented. Photographs of the experimental configuration of the spot sources is shown in Figure 9, and the GUI output showing tracking of four simultaneous spots is illustrated in Figure 10.

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary



Figure 9. MLPS sources used for 4-spot tracking.

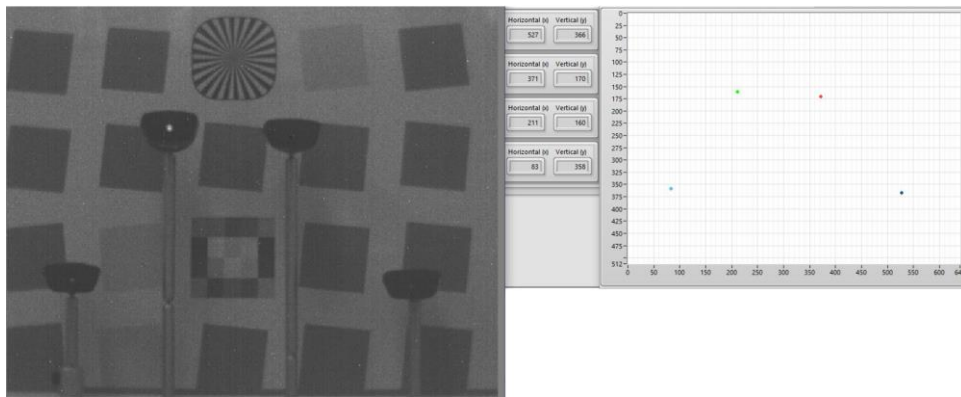


Figure 10. Four-spot tracking (NOTE: only one spot is captured during a pulse in the SWIR image frame at left).

4.2. Detection range

Earlier products in SUI's ALPD line detect and track a pulsed spot in the field of view if the spot illuminates a 2 x 2 or larger array of pixels to a threshold level.⁶ Detection range for a uniform spot was maximized when the spot sits at the intersection of four pixels, as shown schematically in Figure 11(a), such that irradiance from the spot is divided equally among the four. New firmware requires that a minimum of only a single pixel be illuminated to the threshold level in order to initiate a spot-track. Detection range is now maximized when a spot is centered on a pixel as shown in Figure 11(b), thereby increasing the maximum detection range versus the prior firmware for a spot of the same radiance.

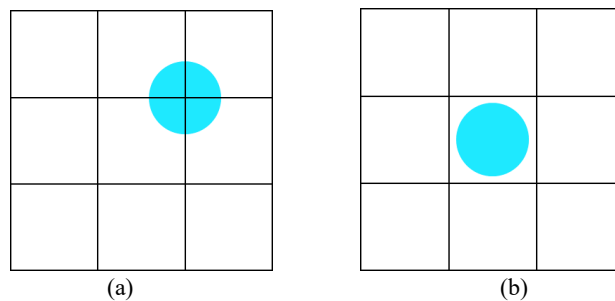


Figure 11. Schematic of spot positions on pixel grid for maximum tracking range under (a) original algorithm and (b) new, single-pixel algorithm.

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary

5. SPOT-TRACKING ALGORITHM DEVELOPMENT

5.1. Pulse map

The initiation and maintenance of a spot-track entail complex algorithmic processing.⁴ Pixel output in response to a laser pulse must be distinguished from output arising from noise or other detector anomalies, for example, and determinations must be made as to which pixels are to be considered part of a single spot. A “pulse map” utility was created that allows the spot-track processing algorithm to be accessed at multiple stages, assisting in the development of the new firmware. The map has the same format (640 x 512 pixels) as the SWIR imagery and can be viewed either separately as binary output (with detecting pixels white and non-detecting pixels black), or as an overlay atop the image output where the detecting pixels are displayed at the maximum response level. The left-hand side of Figure 12 shows a raw SWIR image of a high-power 1550 nm laser spot projected on a wall in a large room with reflective surfaces. The right-hand side of Figure 12 shows the first-stage pulse map from the same scene. Multiple reflections from the main spot are present in the map prior to the execution of the pulse-processing algorithm required to yield a single spot.

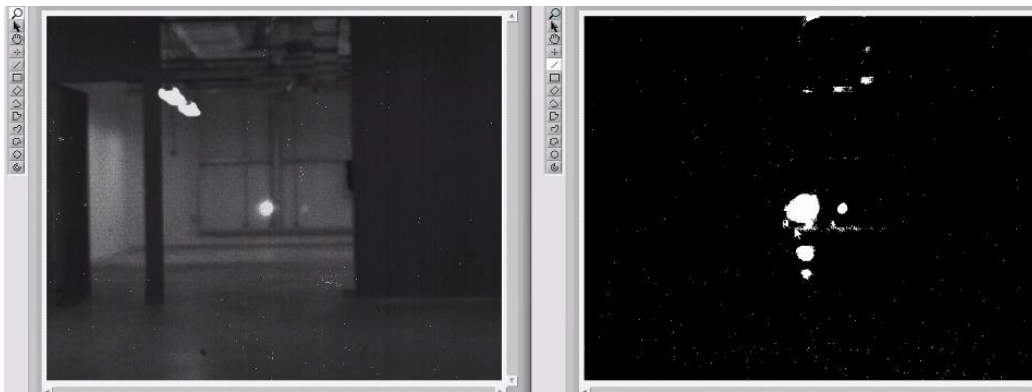


Figure 12. SWIR image (left) and pulse map (right) from high-power laser spot showing main spot and multiple reflections.

5.2. Spot configuration and variation

The default shape of the 1550 nm spots generated by both the MLPS units and the laboratory lasers is approximately a filled circle, as shown in Figure 13.

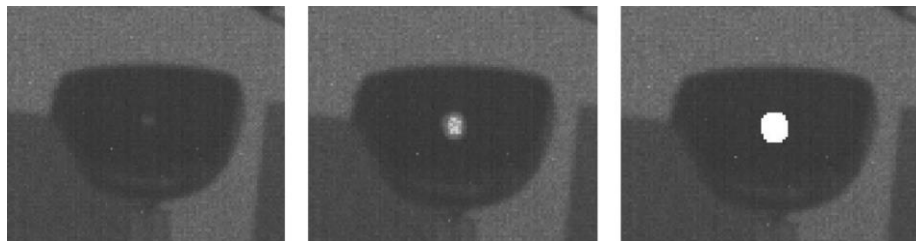


Figure 13. SWIR images of MLPS between pulses (left), during pulse (center), and with pulse map overlay (right)

In battlefield scenarios, however, laser spot shape may be affected by such factors as atmospheric obscurants, uneven surfaces, or anomalies in the laser source output. It is therefore desirable that the ALPD camera accommodate a wide variety of spot shapes and sizes. Masking the output of a MLPS unit was used to produce irregular spot types for evaluation of the new spot-tracking algorithm. An example is shown on the left in Figure 14, where pinholes in a foil mask were used to create multiple circular spots in proximity pulsing at the same frequency. The initial pulse map is shown on the right. Additional examples of pulse maps from tested spot configurations are shown in Figure 15.

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary

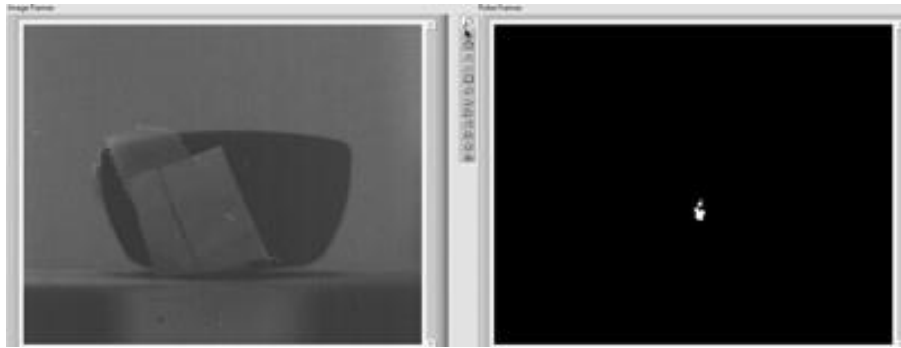


Figure 14. SWIR image of masked MLPS and corresponding pulse map.



Figure 15. Pulse maps of various spot shapes used for spot-tracking firmware development.

6. TEST RESULTS

Following the validation of the new encapsulation epoxy and the environmental tolerance of the updated camera design, the new firmware was evaluated in multiple scenarios for its ability to track four simultaneous pulsed spots. Figure 16 shows an image of the tracking of four pulsed 1550 nm spots, each with a unique size, frequency, and position. The spot in the lower left quadrant of the image is closer to the camera than the other three and thus larger and defocused. The upper left and lower right spots are masked, with the upper left the smaller of the two. The upper right spot is in focus and unmasked. An early-stage pulse map associated with the same scene is shown overlaid on the image in Figure 17.

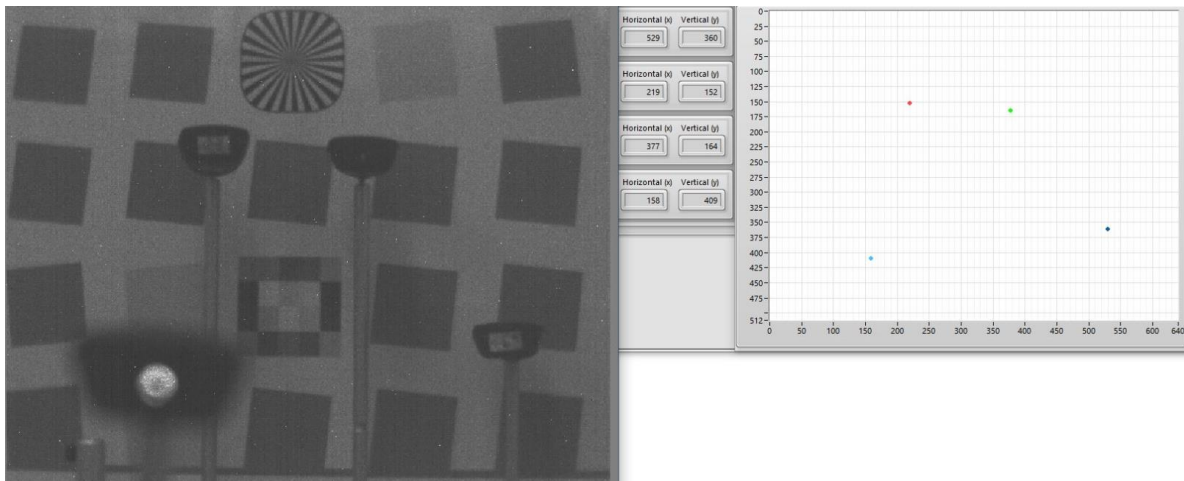


Figure 16. Spot-tracking of four 1550 nm spots of varying size, frequency, and position.

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary

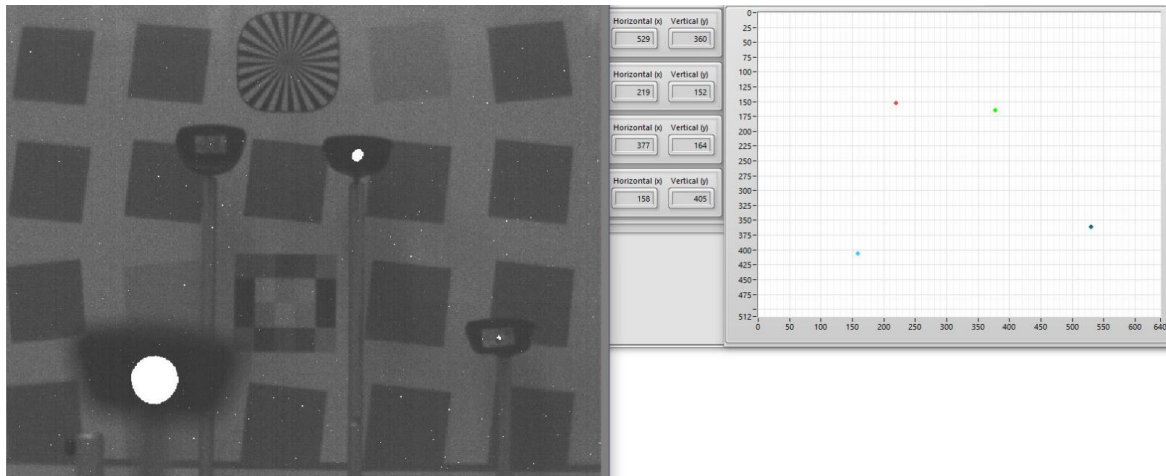


Figure 17. Image with Pulse map overlay of 4 different tracked spots.

The largest spot comprises approximately 2200 detecting pixels and the upper right spot comprises approximately 250. The lower right spot comprises approximately 25 detecting pixels, and the upper left spot produces only a single detecting pixel. Magnified views of the masked MLPS units with the pulse maps overlaid are given in Figure 18.

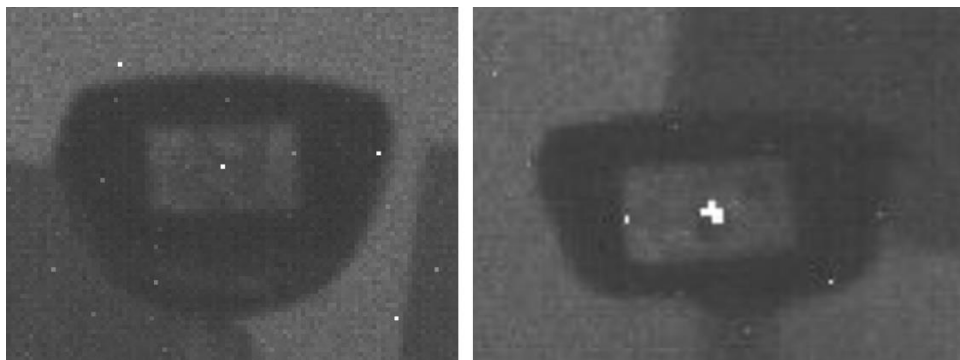


Figure 18. Magnified views of masked MLPS spot sources with pulse map overlays, including tracking based on a single-pixel detection (left).

Tests of the camera's ability to accommodate motion of the spots in the field of view were also conducted. Figure 19 shows three video frames taken over approximately four seconds as the camera was rotated relative to the spot sources. The tracking output map associated with each frame is shown to the right of the image. All four tracks were maintained throughout the movement of the camera.

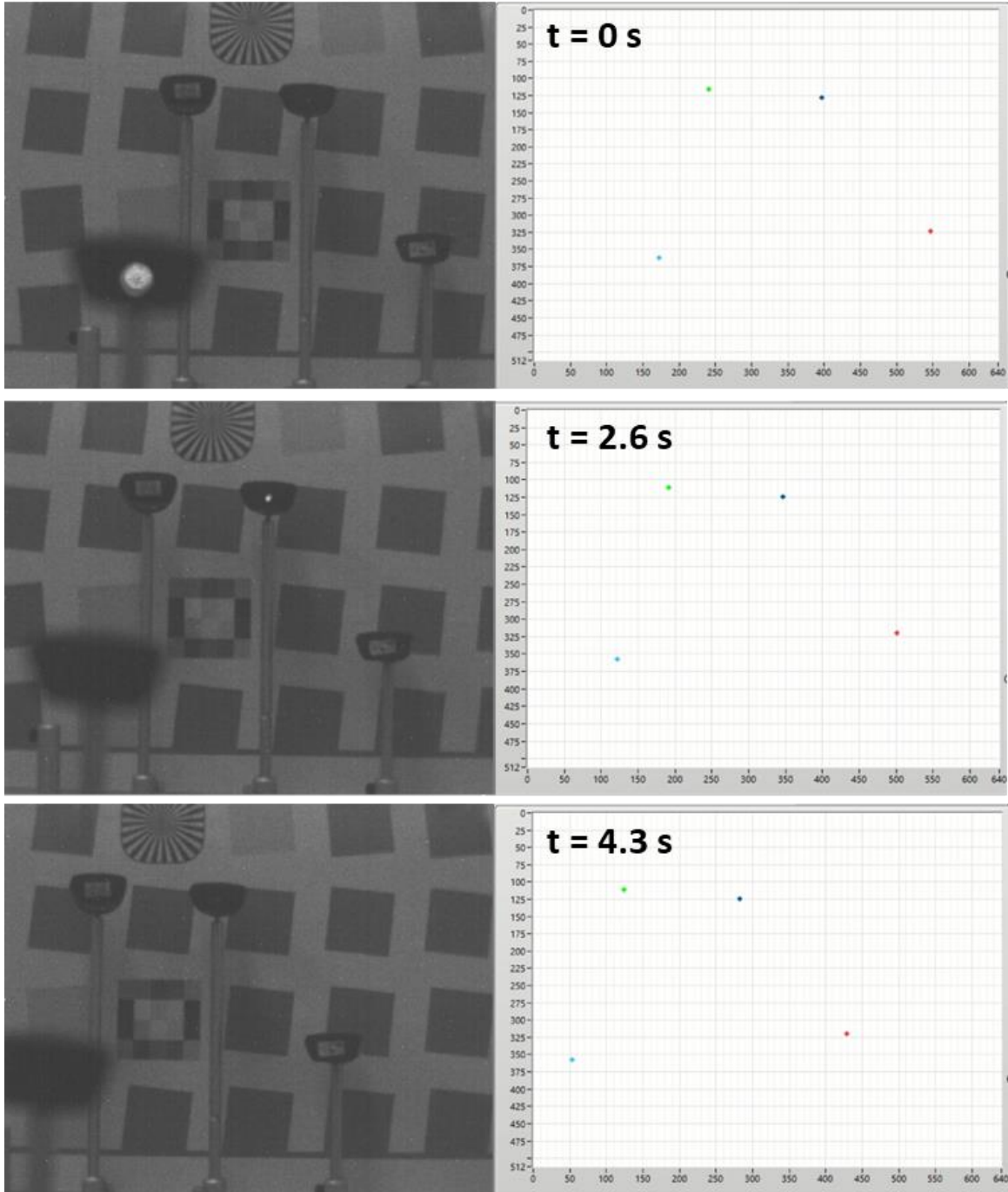


Figure 19. Images and tracking output maps taken during motion of camera relative to four spot sources.

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary

7. SUMMARY

Updates to the hardware and firmware of SUT's MMT ALPD cameras have been implemented to enhance their suitability for military applications. The COB FPA package has been modified to support environmental exposure without the need for thermoelectric cooling, and automation has been added to the wire-bond encapsulation process. Successful tracking of four different, simultaneous 1550 nm spots, including that of a single-pixel-sized spot, was verified under a variety of illumination levels and over a range of temperatures. The capability to track four moving pixels in the field of view was also demonstrated.

REFERENCES

- [1] R. Fraenkel, E. Berkowicz, L. Bykov, R. Dobromislin, R. Elishkov, A. Giladi, I. Grimberg, I. Hirsh, E. Ilan, C. Jacobson, I. Kogan, P. Kondrashov, I. Nevo, I. Pivnik, and S. Vasserman "High definition 10 μm pitch InGaAs detector with asynchronous laser pulse detection mode", Proc. SPIE 9819, Infrared Technology and Applications XLII, 981903 (20 May 2016); <https://doi.org/10.1117/12.2222762>
- [2] https://www.army.mil/article/269184/army_awards_up_to_1_9_million_for_low_cost_laser_sensors
- [3] John Liobe and Douglas S. Malchow "Advancements in multi-mode ROIC design for SWIR detectors (Conference Presentation)", Proc. SPIE 11407, Infrared Technology and Applications XLVI, 114070B (5 May 2020); <https://doi.org/10.1117/12.2560707>
- [4] John C. Liobe, Krishna Linga, Wei Xu, and Andrew Eckhardt "Hostile detection using multi-mode SWIR sensors", Proc. SPIE 12534, Infrared Technology and Applications XLIX, 1253409 (15 June 2023); <https://doi.org/10.1117/12.2664032>
- [5] Tara Martin, Peter Dixon, Mari-Anne Gagliardi, Navneet Masaun, "320x240 pixel InGaAs/InP focal plane array for short-wave infrared and visible light imaging," Proc. SPIE 5726, Semiconductor Photodetectors II, (7 April 2005); <https://doi.org/10.1117/12.596409>
- [6] John C. Liobe, John Wieners, "Low SWaP SWIR cameras for multi-mode applications," Proc. SPIE 12107, Infrared Technology and Applications XLVIII, 121070A (27 May 2022); <https://doi.org/10.1117/12.2624016>

This document does not contain any export-controlled technical data. RTX, Raytheon Technologies Proprietary