INVESTIGATION OF COMPONENT TECHNOLOGIES FOR SWIR CAMERAS

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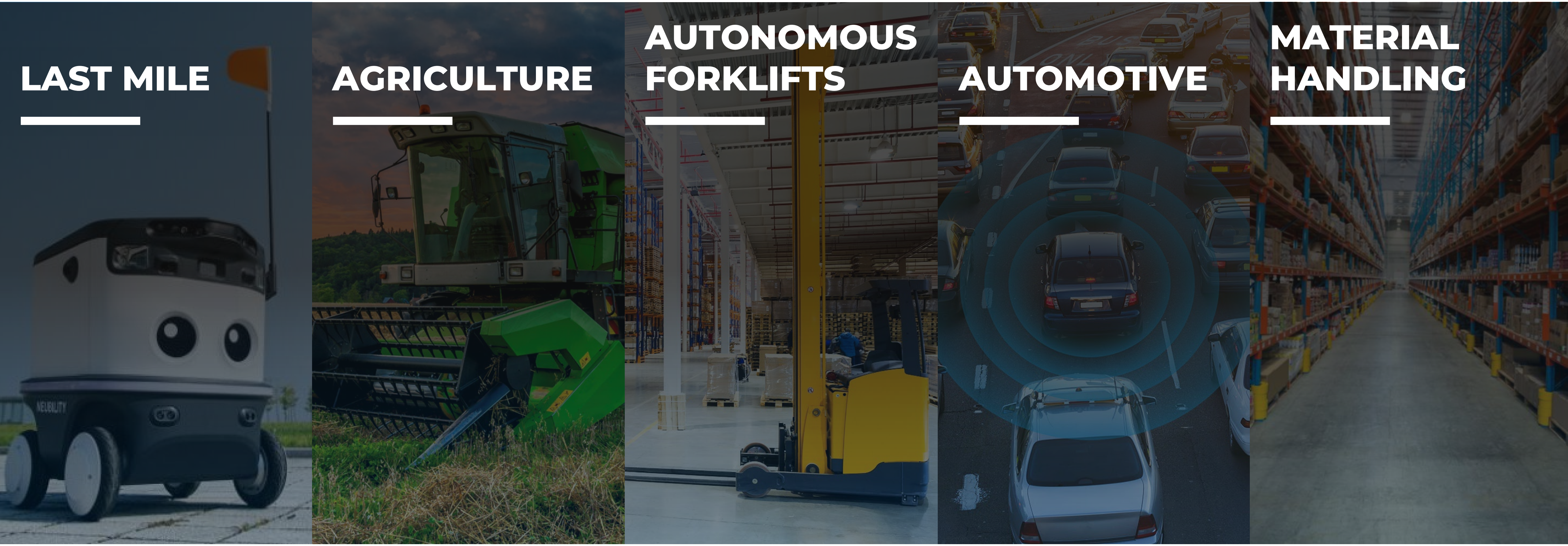
DEMAND FOR NEW SENSORS



LIMITED NUMBER OF OFF-THE-SHELF SOLUTIONS FOR THE 2M-20M OPERATING RANGE

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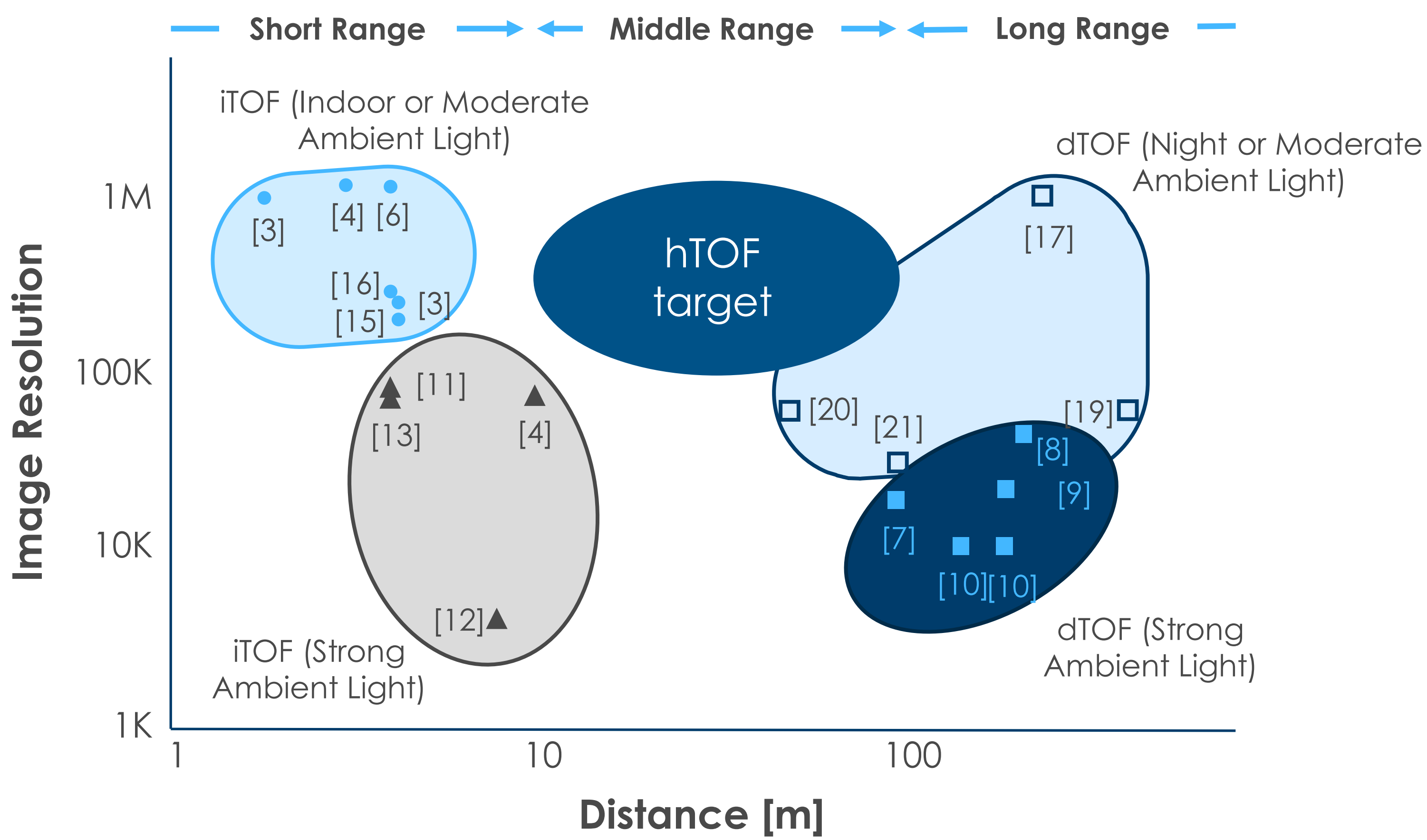
SHORT-RANGE SOLUTIONS	SOLUTION GAP	AUTOMOTIVE SOLUTIONS
intel REALSENSE, SONY, Azure Kinect DK, Luxonis		LeddarTech, Aurora, ibeo automotive, INNOVIZ TECHNOLOGIES, LUMINAR
• Operating range: <10m with many <5m • Majority fail to work in ambient light • Simple system integration • Low-cost	• Range: 2-20m • Ambient light • Resolution: VGA+ • Simple integration	• Operating range >>20m too long • Expensive • Large volume • Typically, lower resolutions • Complex system integration

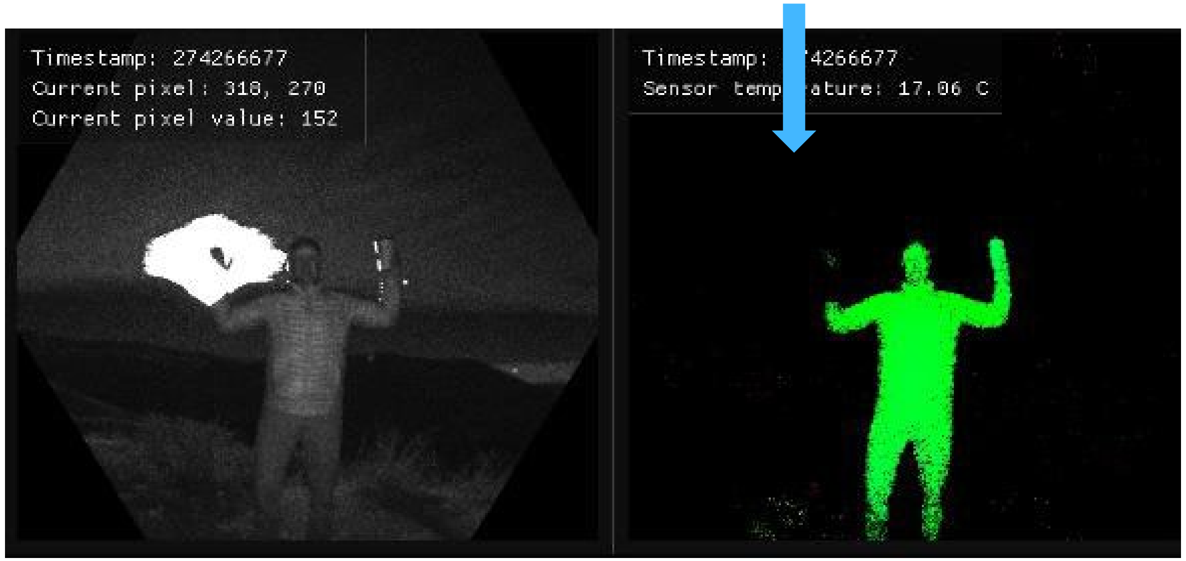
ANOTHER DEFINITION OF THE OPERATING RANGE GAP IS DEFINED IN LITERATURE



Hybrid Time-of-Flight Image Sensors for Middle-Range Outdoor Applications
S. Kawahito, Fellow, IEEE, K. Yasutomi, Member, IEEE, and K. Mars, Member, IEEE

AMBIENT LIGHT ALSO POSES A CHALLENGE

940nm iTof Camera



940nm iTof Camera

IT ISN'T JUST TOF CAMERAS CHALLENGED BY THE SUN

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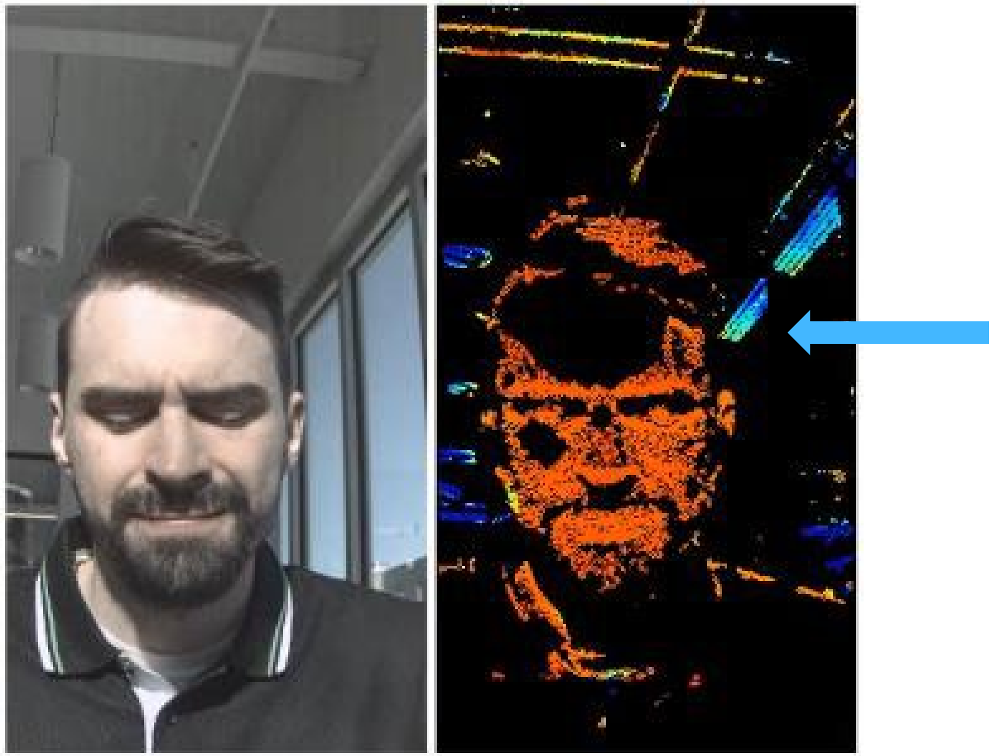
850nm Active Stereo Camera



Visible Spectrum Depth Camera

TRICKS TO REDUCE THE IMPACT OF AMBIENT LIGHT

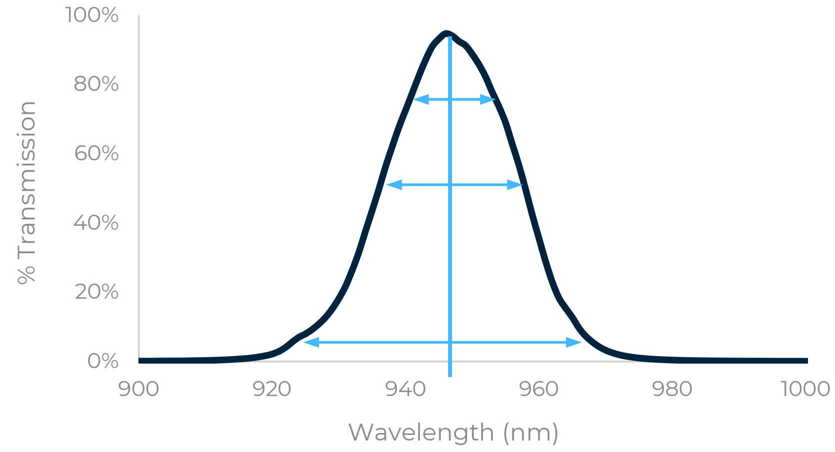
BACKGROUND SUBTRACTION

$$\varphi(phase) = tan^{-1}\left(\frac{Q_{270} - Q_{90}}{Q_{180} - Q_{0}}\right)$$

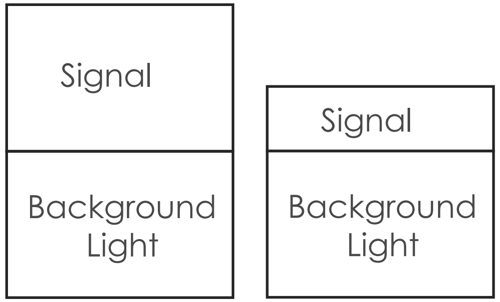
$$Amplitude = \sqrt{(Q_{180} - Q_0)^2 + (Q_{270} - Q_{90})^2}$$

$$Z(depth) = \frac{c}{2f_m} \times \frac{\varphi}{2\pi}$$

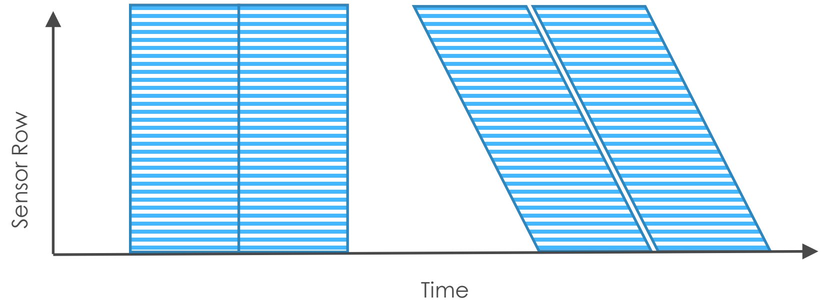
NARROW BANDPASS FILTER



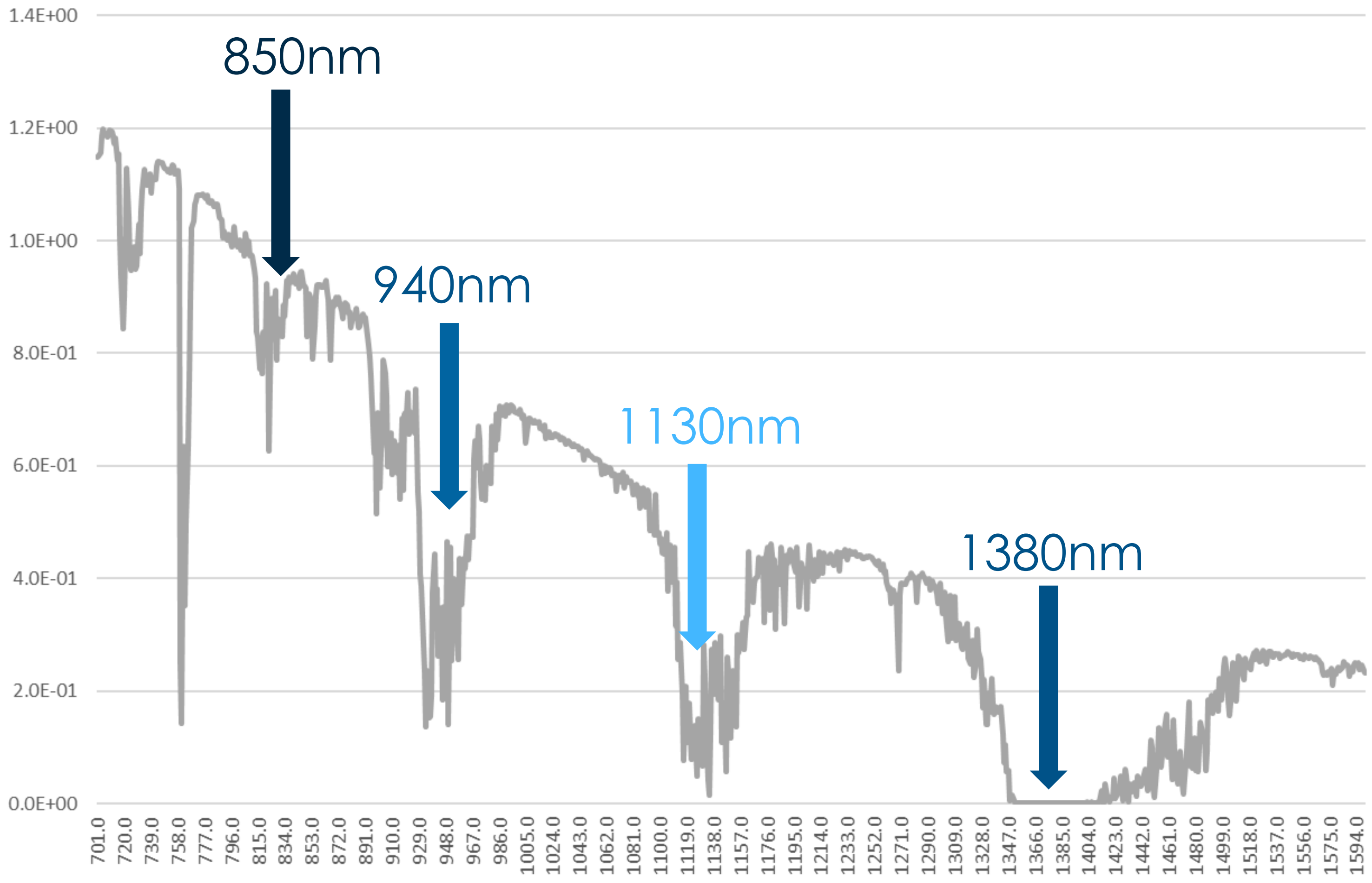
LARGE FULL WELL CAPACITY



GLOBAL SHUTTER VS ROLLING SHUTTER



SOLUTION: TARGET ALTERNATIVE GAPS IN THE SPECTRAL CURVE (1130NM, 1380NM)



Wavelength (nm)	**W*m-2*nm-1** (Ave +- 20nm)
850	0.8983
940	0.3928
1130	0.1784
1380	0.000146

Data from ASTM International: ASTM-G173 › Standard Tables for Reference Solar Spectral Irradiances

SWIR ALLOWS FOR INCREASED RANGE WITHOUT VIOLATING CLASS 1 LASER EYE SAFETY

ISSUE
Active illumination propagates at $1/r^2$ limiting range

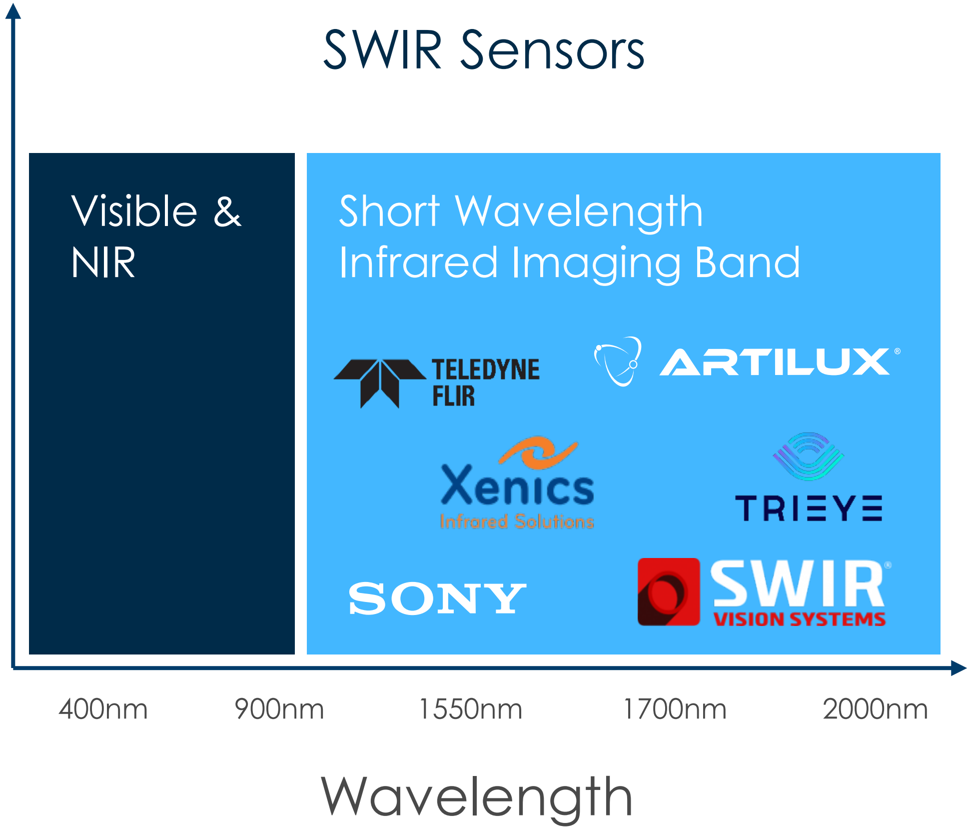
CONSTRAINT
Laser eye safety limits the amount of laser power at 940nm

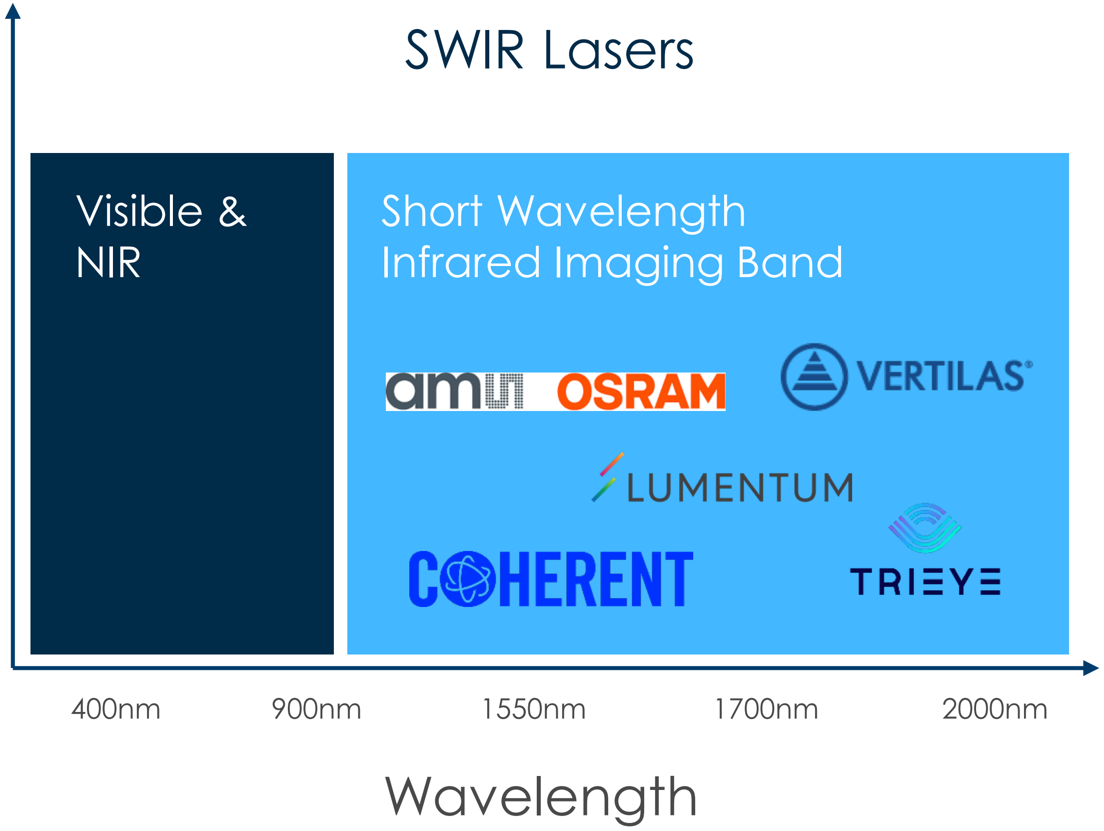
SOLUTION
Use a wavelength that can increase the magnitude of the signal while remaining below laser eye safety / skin safety limits (MPE)

1380nm
Potential for order(s) of magnitude more laser power than 940nm(1)

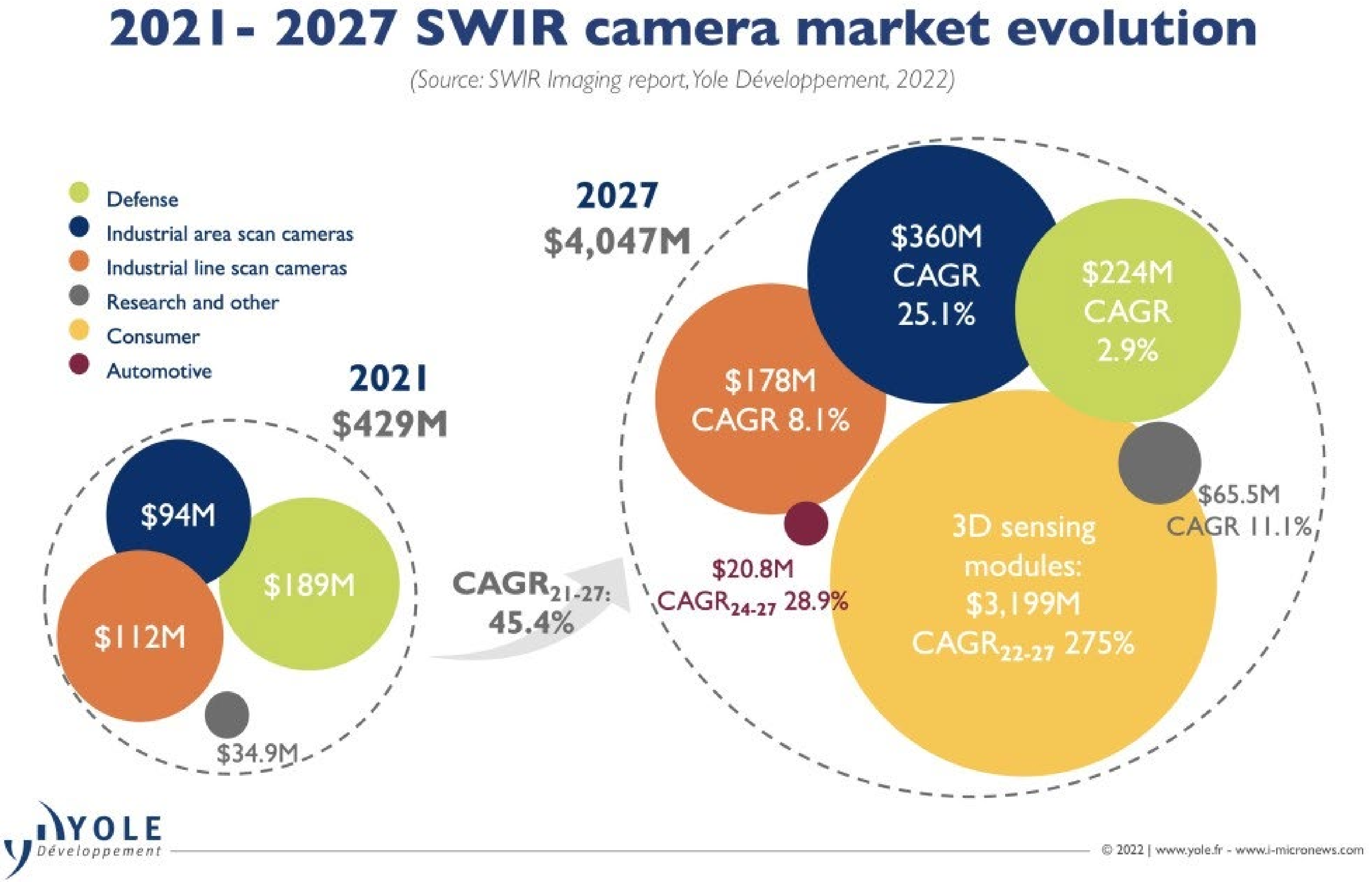
(1) Depends on many factors

THE TECHNICAL THEORY IS SOUND, WHAT ABOUT THE SUPPLY CHAIN?

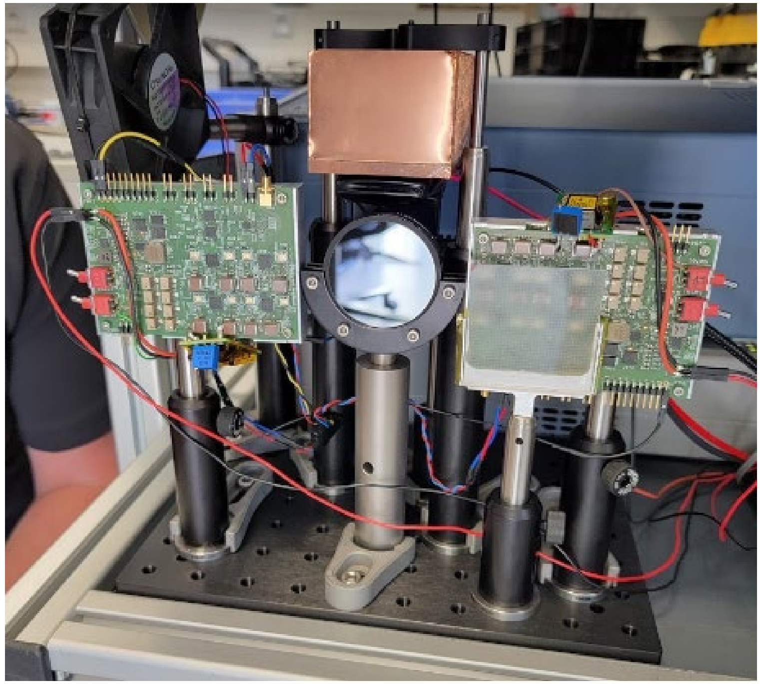




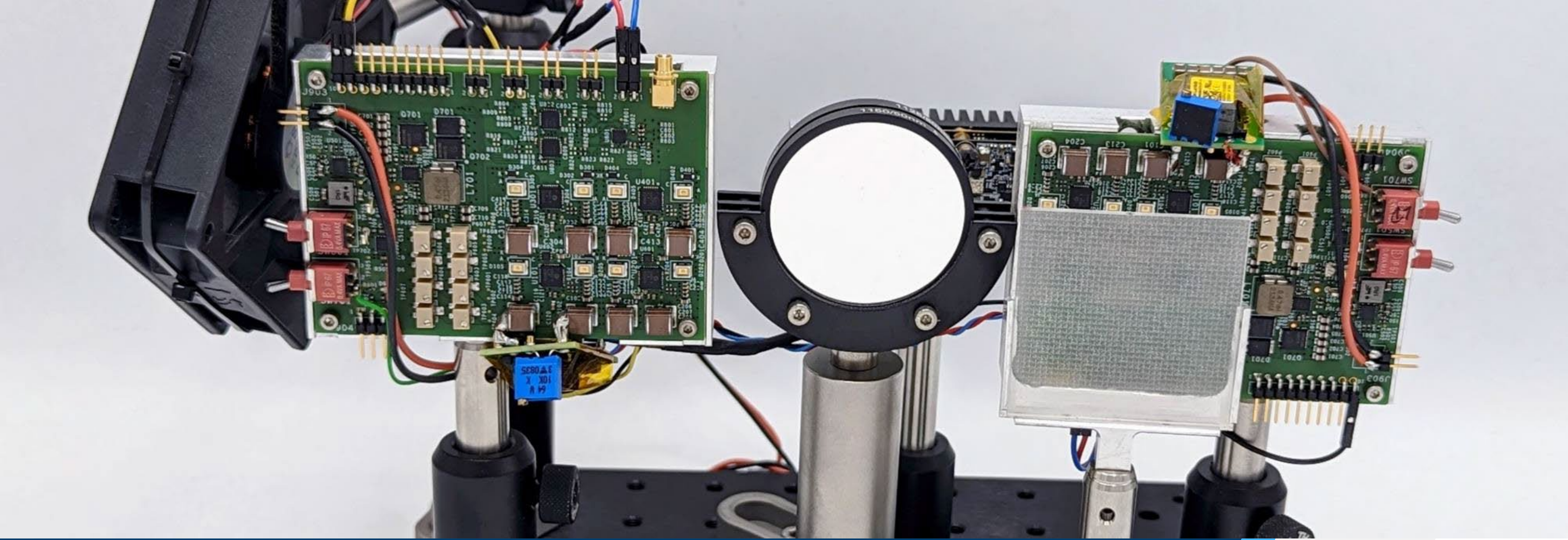
YOLE DEVELOPMENT SWIR FORECAST



CHALLENGES OF ARCHITECTING A 3D CAMERA BASED ON SWIR COMPONENTS



Component	Key Limitations	Suppliers
Image Sensor (Rx)	Component selection, cooling, noise	Artilux, Trieye, SWIR Vision Systems
Band Pass Filter (Rx)	OTS Selection	Viavi, Edmund, etc.
Lens (Rx)	OTS selection, F#, AR coatings	Many companies
Laser (Tx)	Power, laser efficiency, maturity	Coherent, ams OSRAM, Lumentum
Diffuser (Tx)	OTS Selection	Viavi, Edmund, etc.



THE CONTENDERS & TEST PROCEDURE

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3D CAMERAS TESTED

Sensor	Technology	Commercially Available	Wavelength (nm)	Resolution	FOV	Indoor / Outdoor	Range
Artilux SR5 (940nm)	iToF	2023	940	640x480	57.7° x 44.9°	Indoor/Outdoor	~12m
Artilux SR5 (1130nm)	iToF	2023	1130	640x480	40° × 30°	Indoor/Outdoor	~23m
Artilux SR5 (1360nm)	iToF	2023	1360	640x480	40° × 30°	Indoor/Outdoor	~23m
TriEye*	SEDAR	2023	13xx	1284x960	100° × 70° (30m) 60° × 45° (50m)	Indoor/Outdoor	0.2m to 30m 0.2m to 50m

* Sensor testing and data processing was performed by TriEye representatives

TEST PROCEDURE FOLLOWS THE PRELIMINARY WK72962 STANDARD

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ASTM INTERNATIONAL
Helping our world work better

E57.23 - Measuring the performance of a 3D perception system across the specified Field-of-View

Partial List of Members

NIST National Institute of Standards and Technology

SENSE

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AIRY:3D

TRIEYE

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DEPTH METRICS FOR DEPTH SENSOR EVALUATION

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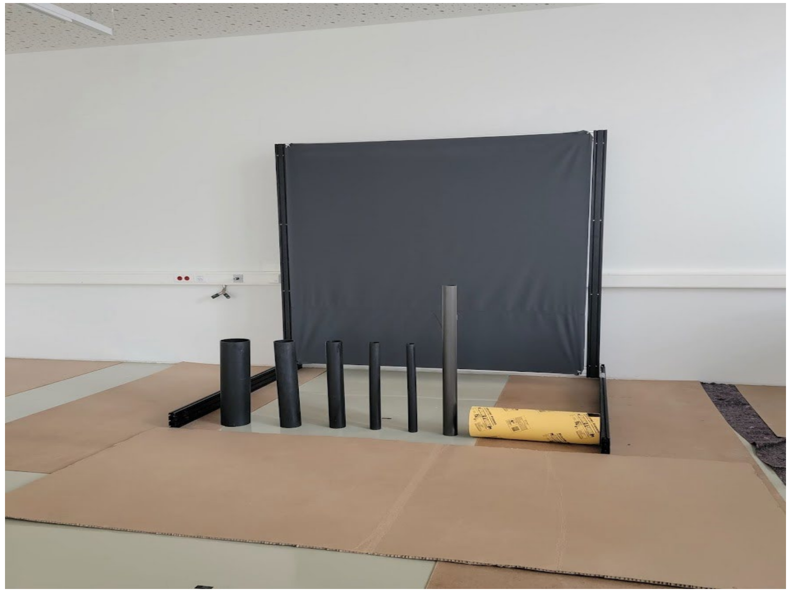
- **Fill Ratio**: Percentage of “valid” (w/non-zero depth) pixels over ROI
- **Z-Accuracy**: Offset of mean/median depth from ground truth
- **Spatial Noise** (RMS Error): variation in depth over ROI
- **Temporal Noise**: Variation in depth per pixel over time (frame-to-frame). Determine # of frames to reach steady-state z-accuracy.

Note: In testing, some of the manufacturers pre-processed / filtered the output data.

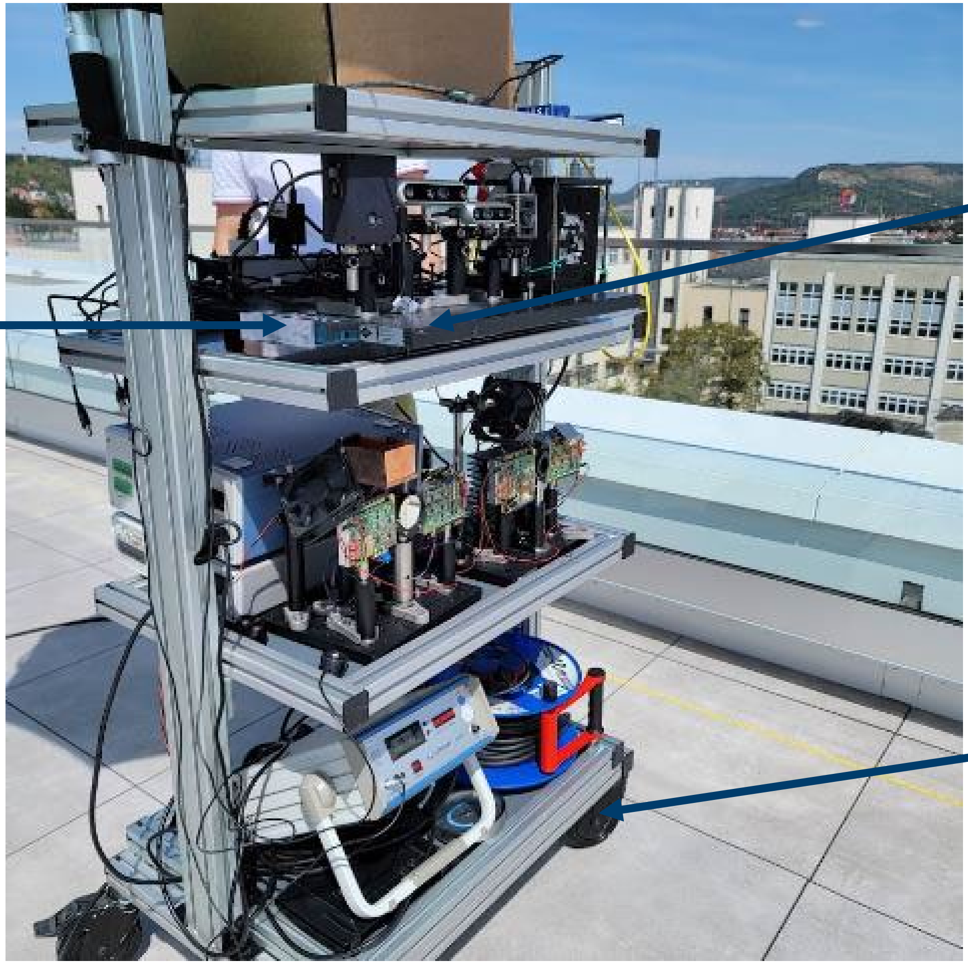
4 flat planes (2m x 2m) of known reflectivity (6%, 24%, 56%, 80%). Targets were fabricated from Type-822 fabric and measured with a spectrophotometer. (www.group8tech.com)



Cylinders with known reflectivity (6%) and diameter matching the requirements of objects referenced in ANSI/ITSDF B56.5-2019.

OUTDOOR TEST SET UP

Laser distance measurement tool for measuring ground truth.
2 measurement tools were positioned on both ends of cart to maintain alignment.



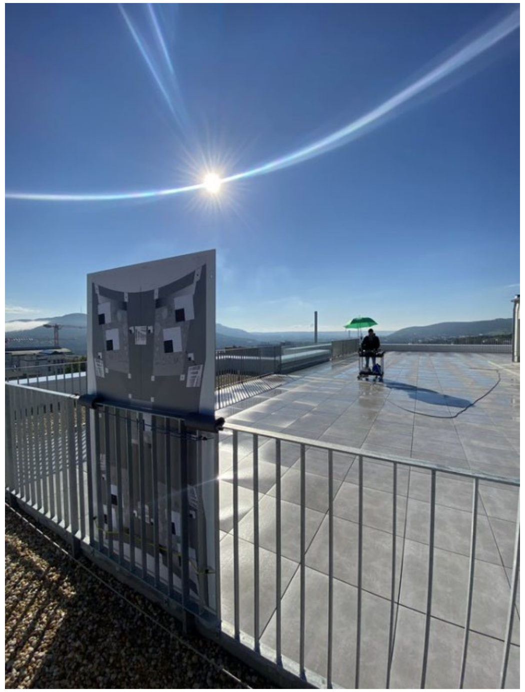
Sensors connected to optical table to maintain positioning and alignment.

Rolling Cart

MEASUREMENT OF ENVIRONMENTAL CONDITIONS

TEST ENVIRONMENTS

Indoor:
Controlled lighting



Outdoor:
Sun Facing Targets

Outdoor:
Sun Facing Camera

1360NM POC: COMPARISON OF INDOOR VS OUTDOOR Z-ACCURACY W/ 80% TARGET

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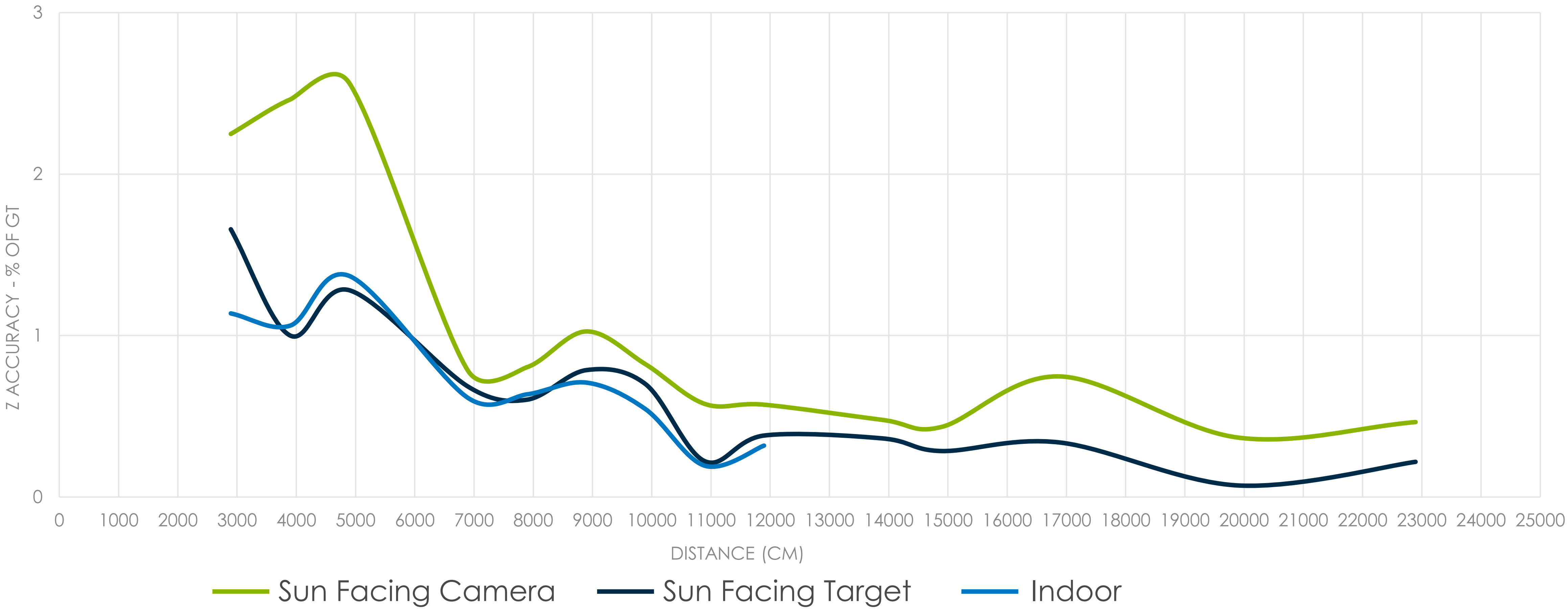
Preliminary testing indicates minimal contributions to depth error from ambient light.



Z-ACCURACY COMPARISON OF SWIR POCS VERSUS 940NM IN AMBIENT LIGHT

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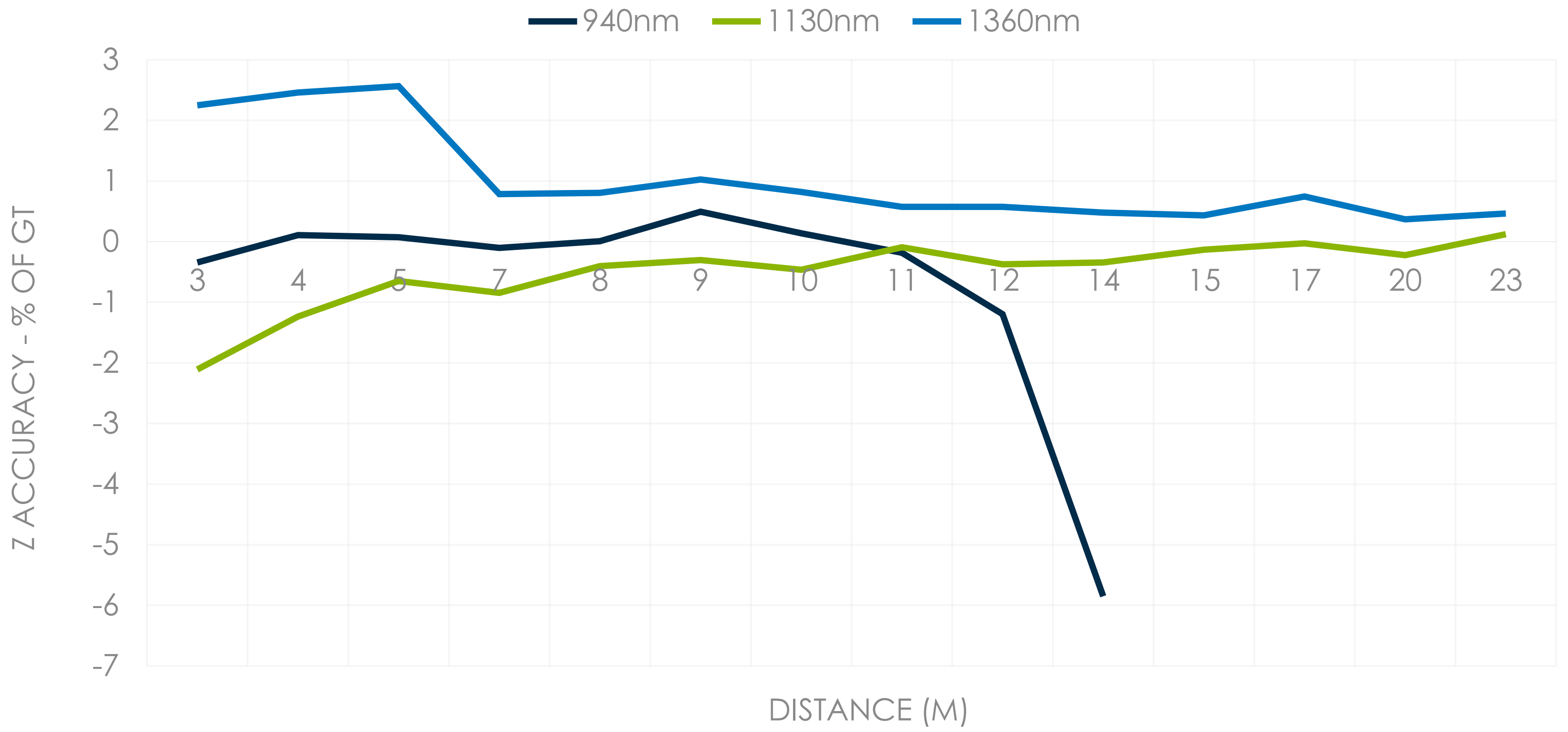
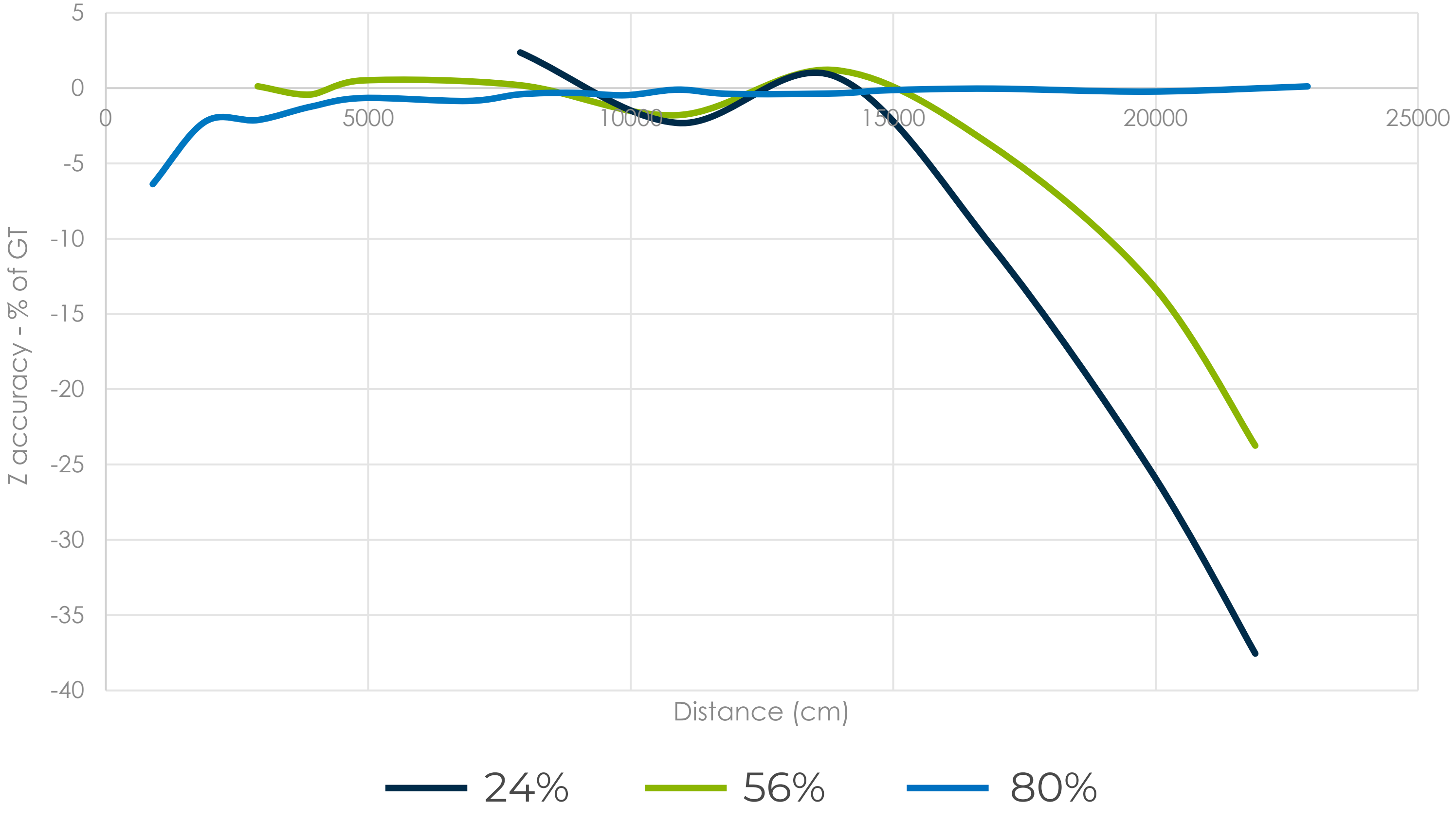


The chart on the left shows the z-accuracy of SWIR POCs vs 940nm POC.

The SWIR POCs can achieve <1% depth error for an 80% reflectivity target to a range of 23m.

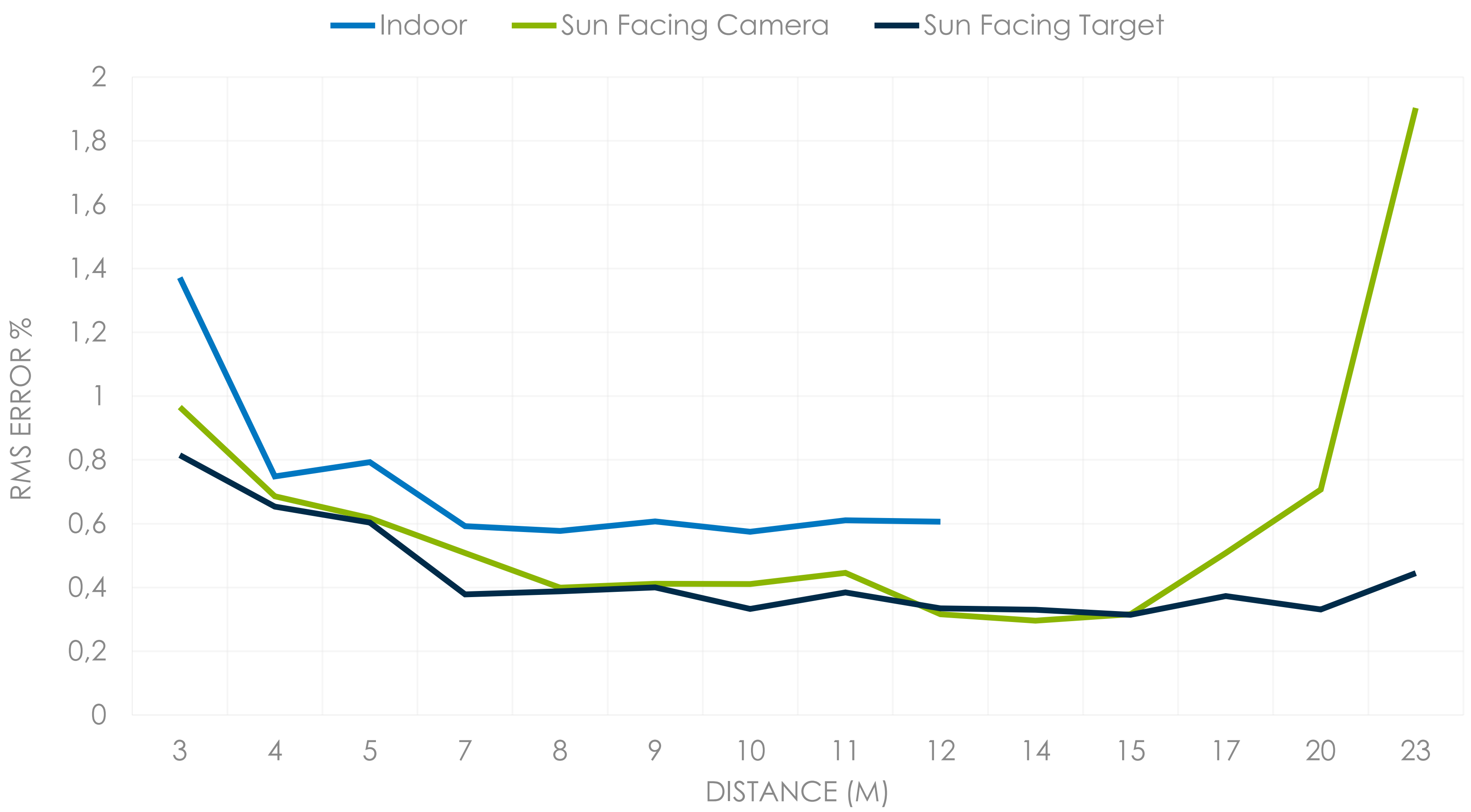
Calibration error is impacting the accuracy of the SWIR POCs at close distances.

1130NM POC – IMPACT OF TARGET REFLECTIVITY ON Z-ACCURACY



Target reflectivity has a dramatic influence on z-accuracy for 1130nm POC. The result is the effective range of the sensor is shortened.

COMPARISON OF SPATIAL ERROR OF THE 1130NM POC W/ 80% TARGET



The chart on the left highlights the variation in depth across the region of interest or target.

Spatial error of the 1130nm is consistent across the operating range independent of environment.

RMS ERROR AS A FUNCTION OF DISTANCE AND TARGET REFLECTIVITY FOR 1360NM POC

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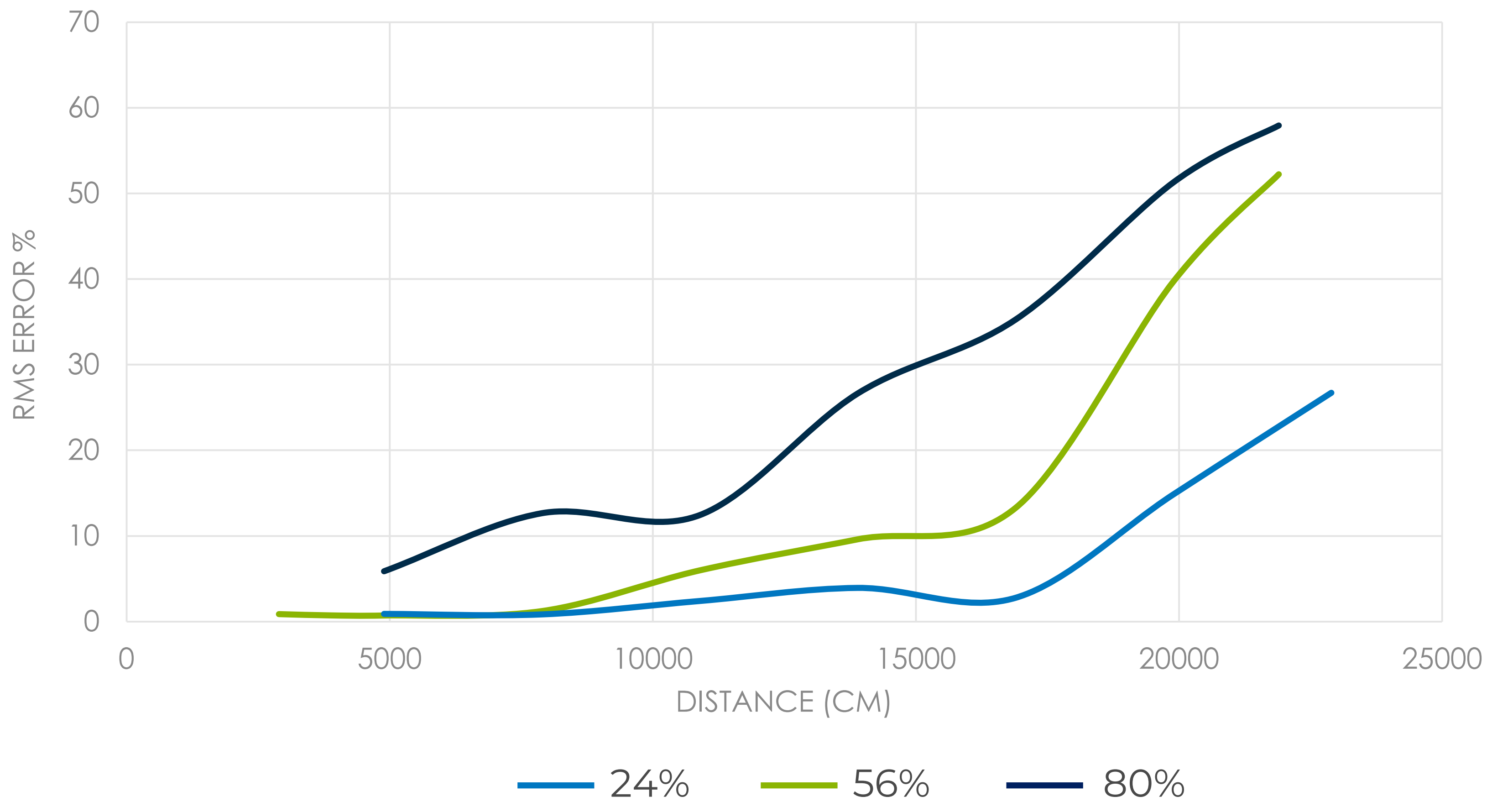

The RMS error (spatial error) highlights the variation in depth over the deviation of the ROI. As shown, the RMS error increases both as a function of distance and as a function of target reflectivity.

The results can be improved with amplitude filtering, phase unwrap error mitigation, and increased illumination.

COMPARISON OF TEMPORAL NOISE @7M W/ SUN FACING THE TARGET

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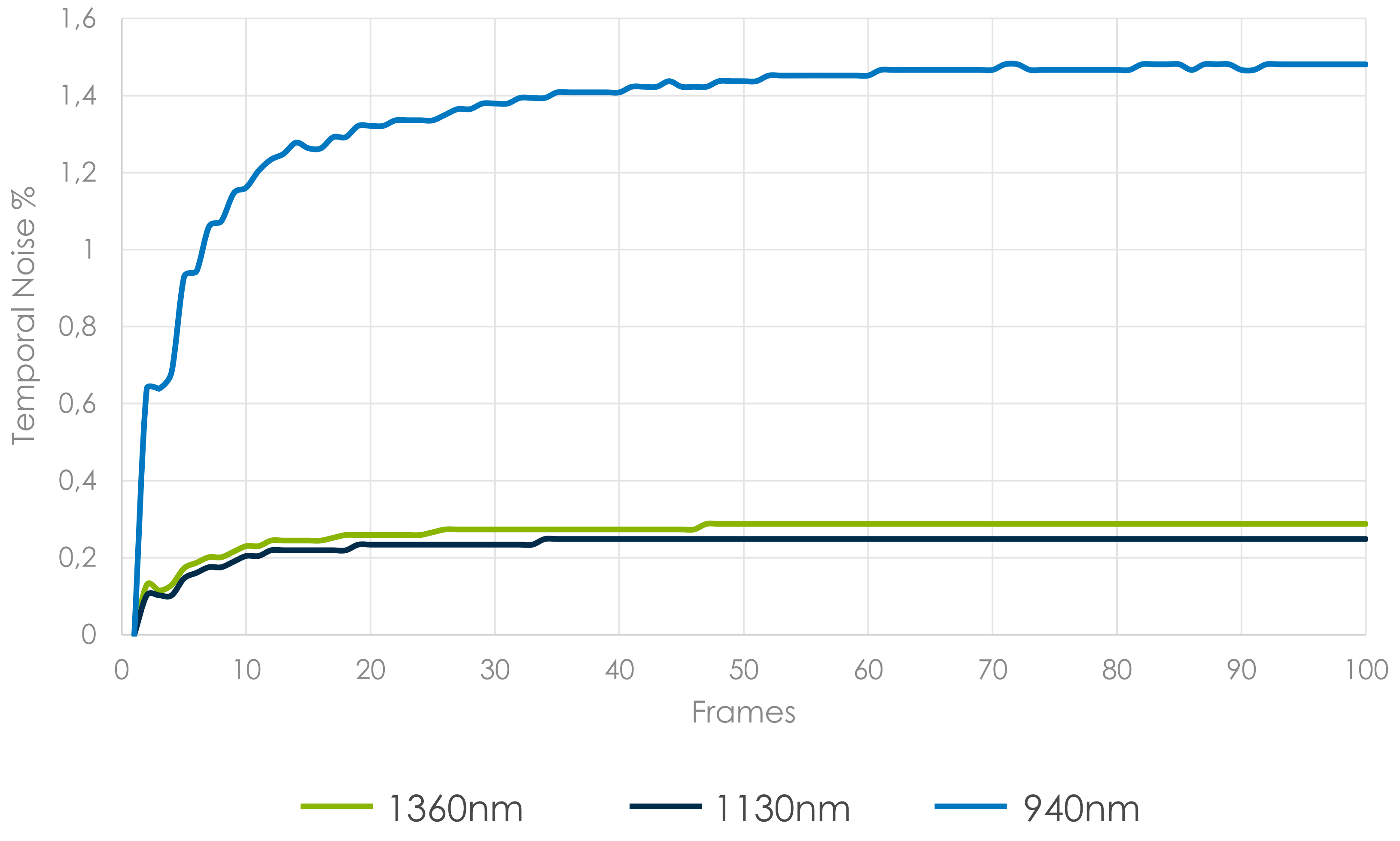
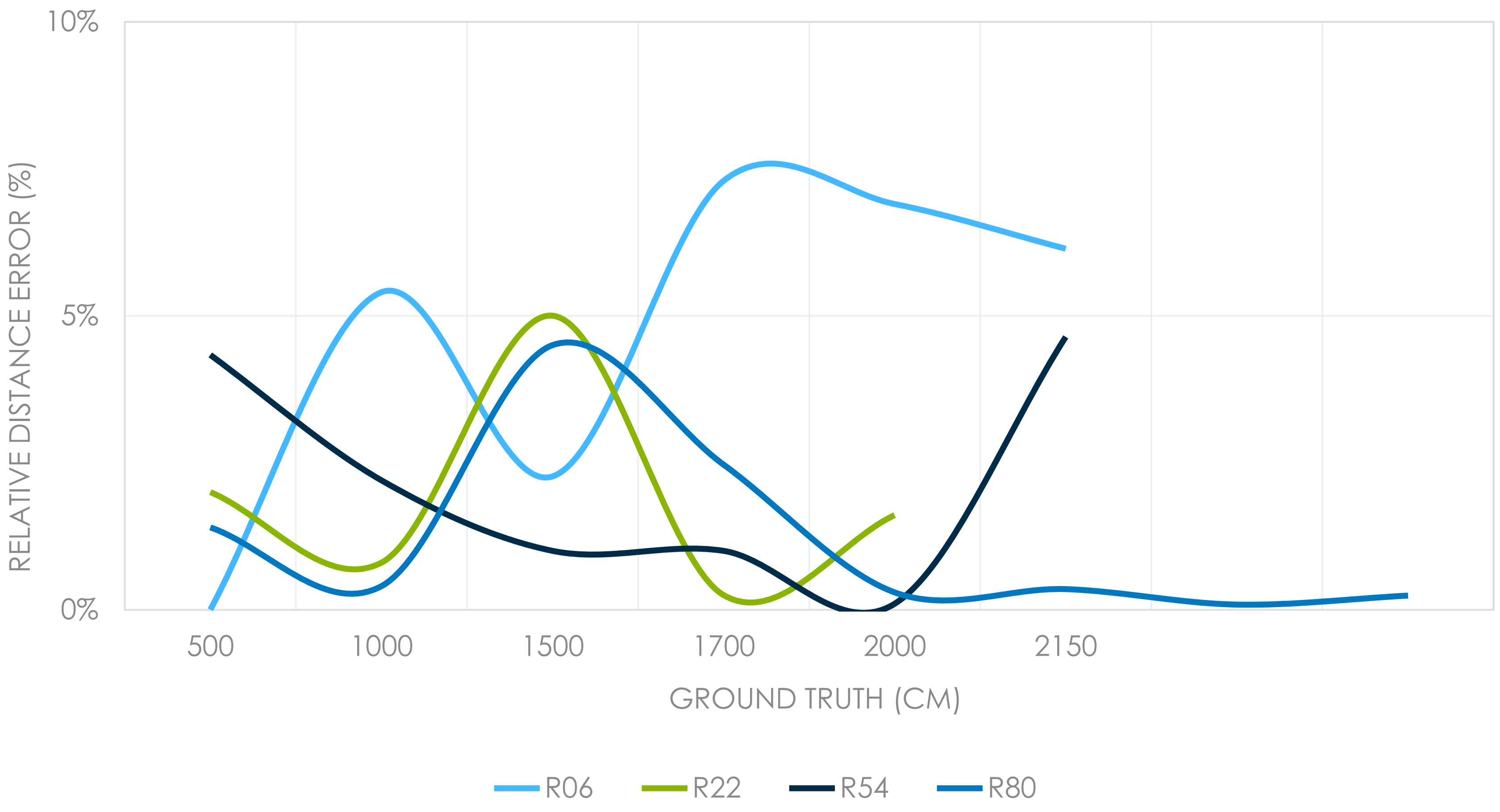


The chart on the left highlights the variation in depth per pixel over time (frame-to-frame).

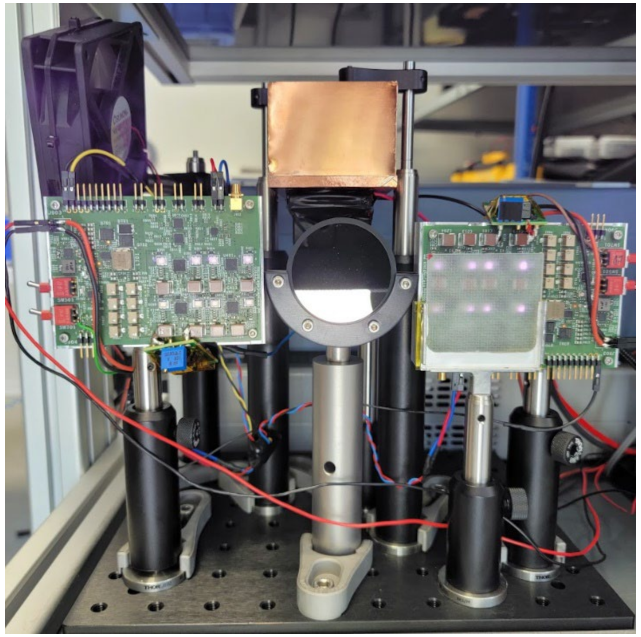
The SWIR POCs stabilize at a near constant error rate significantly faster than the 940nm POC.

TRIEYE: PERFORMANCE WITH DIFFERENT REFLECTIVITY TARGETS



Ground Truth [cm]	R80-distance error
500	1.40%
1000	0.40%
1400	4.50%
1500	2.47%
1700	0.29%
2000	0.35%
2300	0.09%
2500	0.24%

SOURCES OF ERROR – SWIR COMPONENTS



1. Off-the-shelf bandpass filters were wider than intended. FOI didn't match FOV. Lens didn't have optimized AR coating.

2. Lasers were early engineering samples. Additionally, Jabil designed custom illumination boards powering 16 lasers.

3. Sensors provided engineering samples subject to calibration errors, temperature drift, cooling and other sources of system errors.

4. Limited use of software filtering.

SOURCES OF ERROR – TEST SETUP

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1. Flatness of large targets. Ripples in 2m x 2m fabric.
2. Maintaining alignment of sensors on cart. Rolling cart over ground surfaces, accidental bumping, etc.
3. Changing environmental conditions with time:
   - Maintaining a constant lux
   - Other: wind, dust, ground flatness, shadows, reflections
4. Tools to measure ground truth at longer distances – precision of the tools decreases with distance.

NOT SO FAST....

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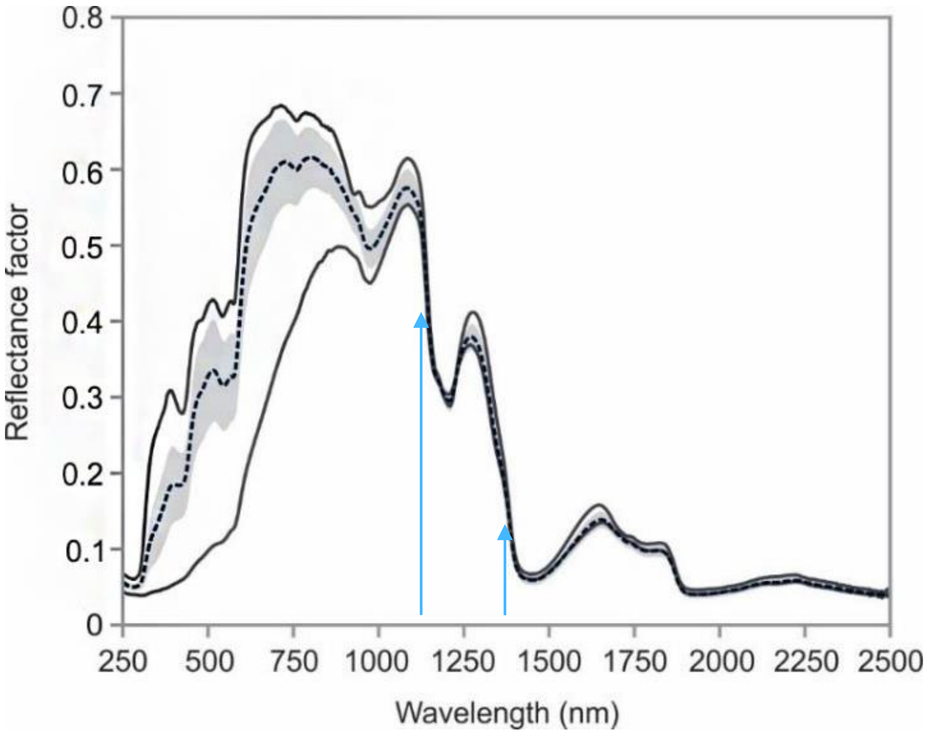
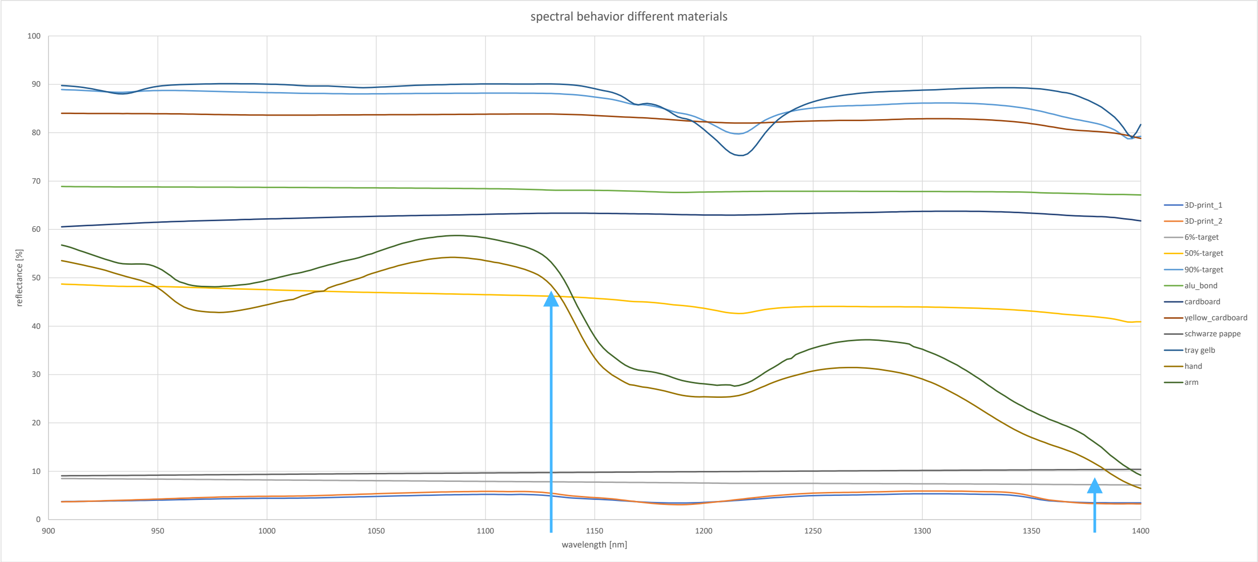
HUMAN SKIN DETECTION



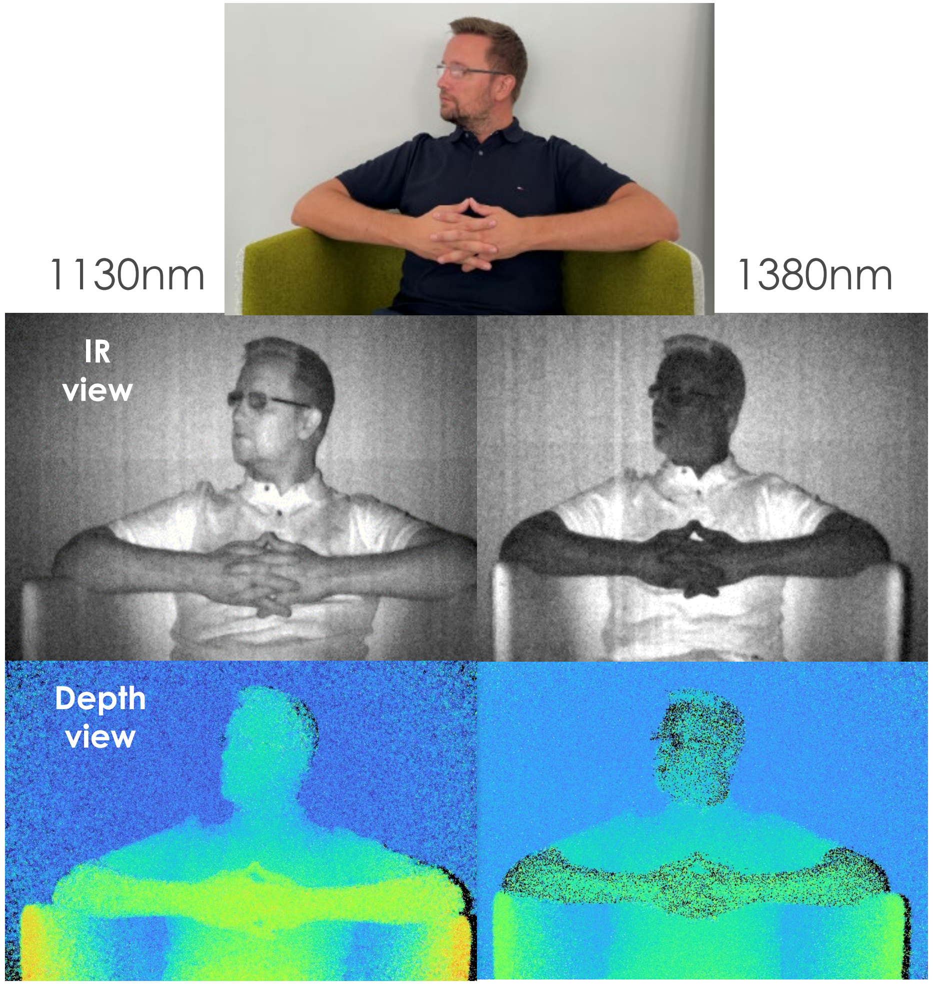
REFERENCE DATA SET AND VARIABILITY STUDY FOR HUMAN SKIN REFLECTANCE
Cooksey, C.C., Allen, D.W., Tsai, B.K.
National Institute of Standards and Technology, Gaithersburg, MD, USA
Collected with spectrophotometer equipped with a 150 mm integrating sphere.

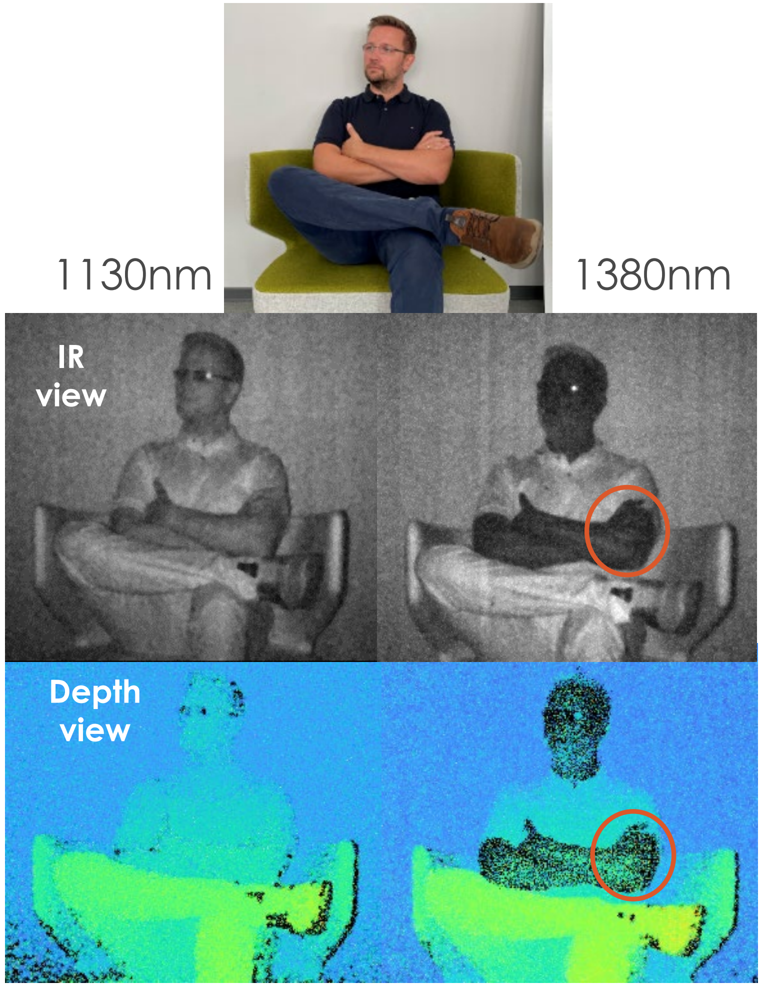
Jabil Material Reflectance Measurements



Wavelength (nm)	Hand	Arm
1130nm	48.5%	53.3%
1380nm	11.4%	15.6%

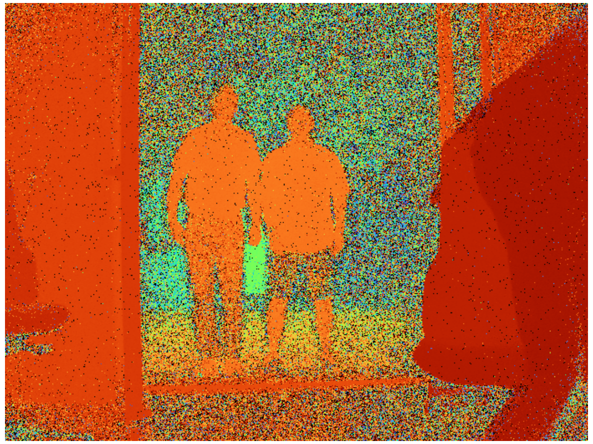
COMPARISON OF HUMAN SKIN DETECTION



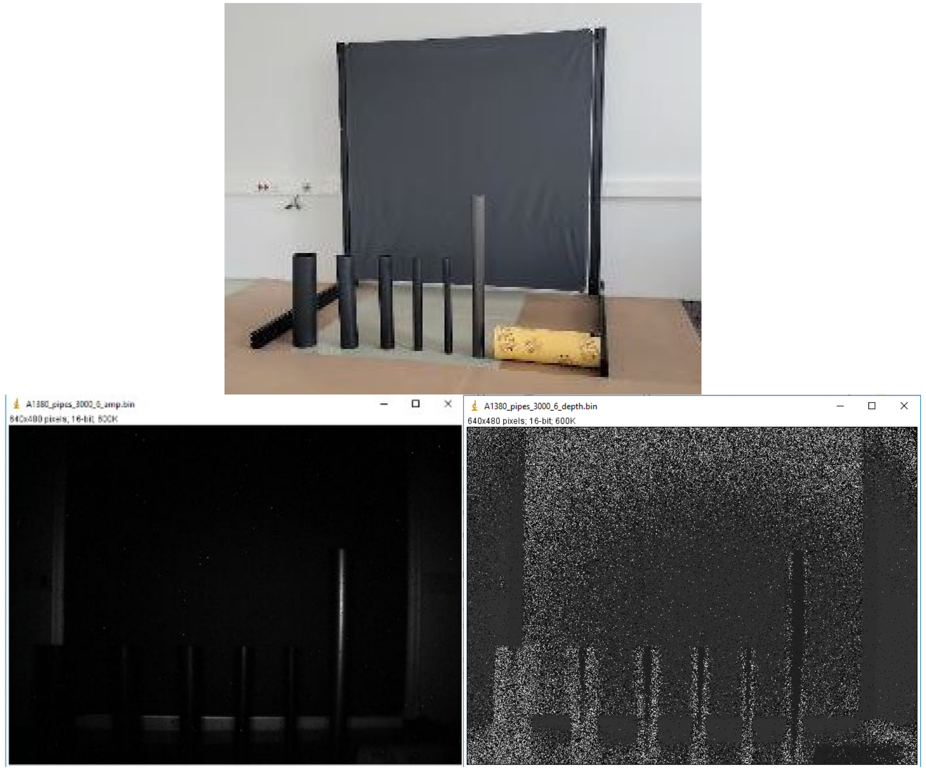


In contrast to the skin's reflection of 1130nm wavelength, skin absorbs 1380nm leading to unusable data for depth calculations

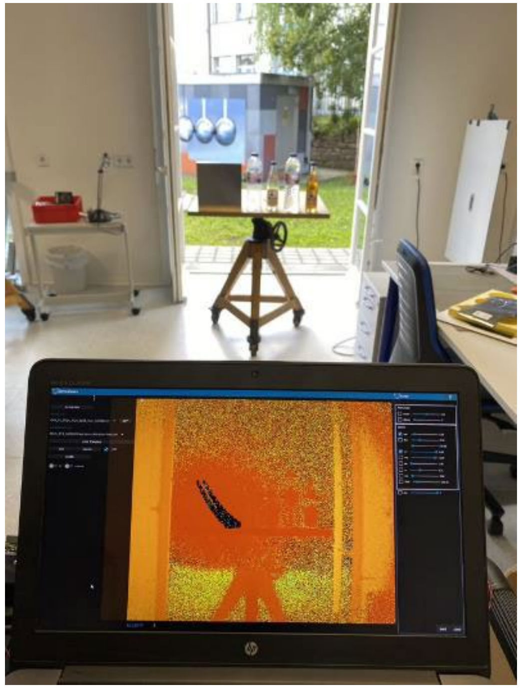
MATERIAL DETECTION TESTING AT SWIR WAVELENGTHS



Polyester shorts @ 8m



Low reflectance objects @ 3m



Highly reflective objects

CONCLUSIONS & NEXT STEPS

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SNAPSHOT OF CURRENT TECHNOLOGIES

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- **Success with SWIR**
  - An 1130nm proof-of-concept and a 1360nm proof-of-concept were able to demonstrate ~1% depth error for 80% reflectivity targets in ambient light
  - The SWIR POCs achieved a similar performance level for both indoor and outdoor conditions
  - The SWIR POCs surpassed the 20m benchmark – opening new market opportunities
  - 1130nm POC was able to detect human skin, a clear advantage over higher SWIR wavelengths for applications that interact with humans.

- **Supply Chain**
  - Component suppliers will introduce new technologies to the market over the next 3 years
  - Innovation is occurring at many SWIR wavelengths

CONCLUSIONS
WAVELENGTH COMPARISON

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	Perform in Ambient Light	Laser Power	Laser Eye Safety[1]	Cost	QE[2]	Human Skin Detection
1130nm	Yes	Higher than 940nm	1.5x-2x	Close to 940nm	Close to 940nm	Yes
1360nm	Yes	Highest	100x	Highest	Lowest	No
940nm	No	Lowest	1x	Lowest Cost	Highest	Yes

(1) Estimate of eye safety level. Not to be used for specific implementations.
(2) Specific to Artilux SR5 image sensor

NEXT STEPS
CURRENT POCS

- **Whitepaper release in November**
  - Comparison of SWIR technologies with current off-the-shelf solutions
- **Further testing**
  - 940nm performance comparison
- **Software filtering**
  - Removing pixels with low amplitude values
  - Filtering phase unwrap errors

NEXT STEPS
DERIVATIVE POCS

- **Test new SWIR components (true 1380nm) as they are released**
  - Lasers with higher power output and increased efficiency
    - Take advantage of laser eye safety limits, improve SnR with low reflectivity objects
  - Image sensors (higher resolution, less noise, reliability)
    - Improved SnR, higher quality, lower cost
  - Support components (diffusers, OTS lens solutions, laser drivers, ASICs)
    - Lower system costs and higher performance

- **Perform testing specific to the intended applications**
  - Structured vs. unstructured environments
  - Platform, motion artifacts, price, objects, power, etc.

GET IN TOUCH WITH US

Please feel free to contact us for further information and a deeper discussion.

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THANK YOU

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