NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

# NIST Strategic and Emerging Research Initiatives (SERI) – AV Sensor Perception Project

**Prem Rachakonda**

Standards and Performance Metrics for On-Road Automated Vehicles
*September 5-8, 2023 (Virtual Event)*

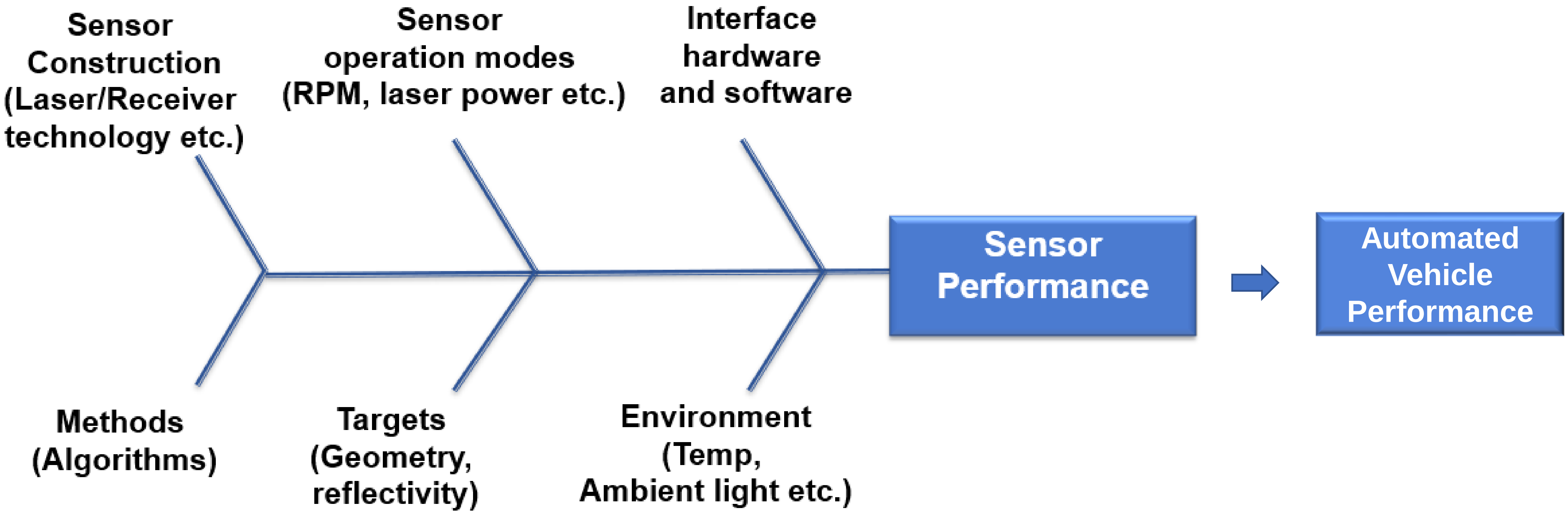
Date: 9/6/2023

# Overview

- Problem statement
- Background and feedback from 2022 workshop.
- Focus on AV Lidars
- Technical approach
  - Testbed development
  - Initial results.
- Future directions

# Problem statement

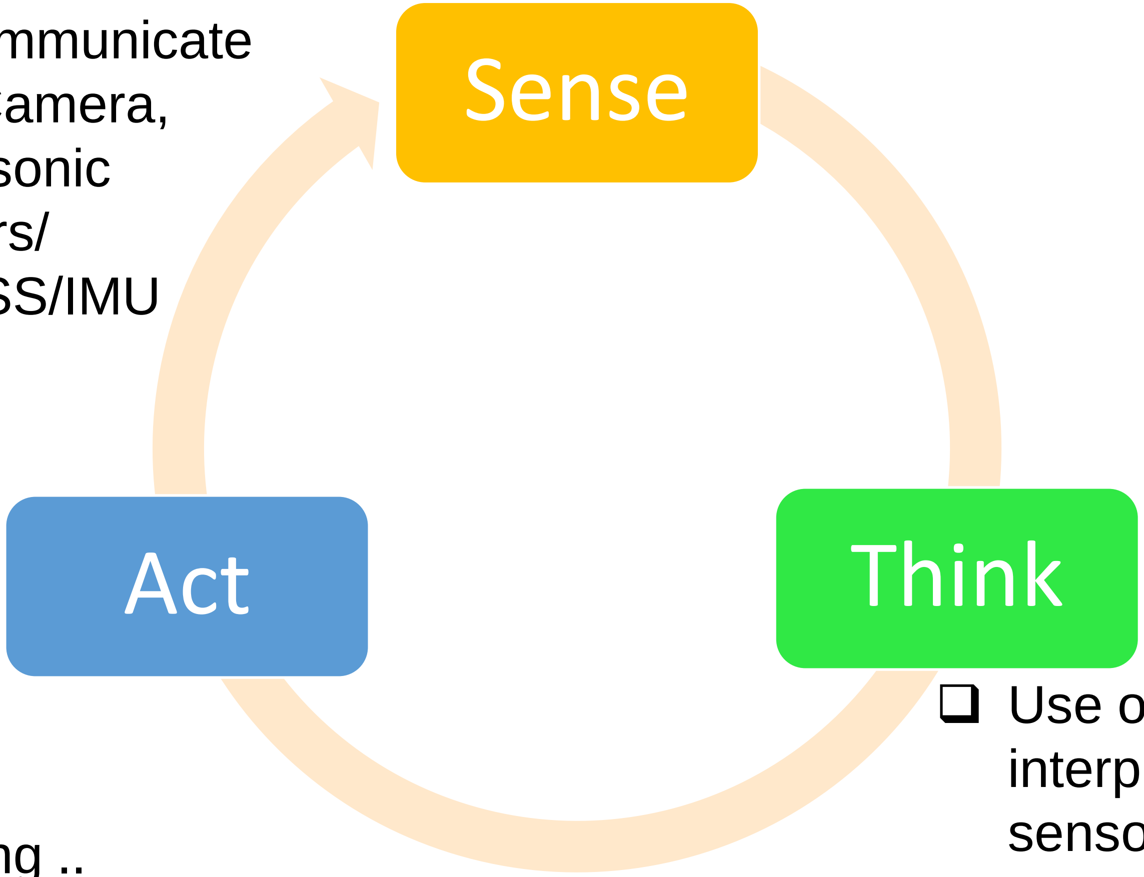
- There are several parameters that affect Automated vehicle (AV) sensor performance, however there are very few standard test procedures to evaluate many of these parameters.



# What makes a vehicle Autonomous

NIST

- For sensing the environment, objects, people, ego localization and communicate
  - Lidar, Radar, Camera, Thermal, Ultrasonic
  - Wheel encoders/ odometry, GNSS/IMU




## Aided by

- in-vehicle and ex-vehicle communication h/w and s/w,
- communication protocols,
- HD maps
- Infrastructure (road signs etc.)
- Computing hardware/software
- Operating systems, middleware, hypervisors

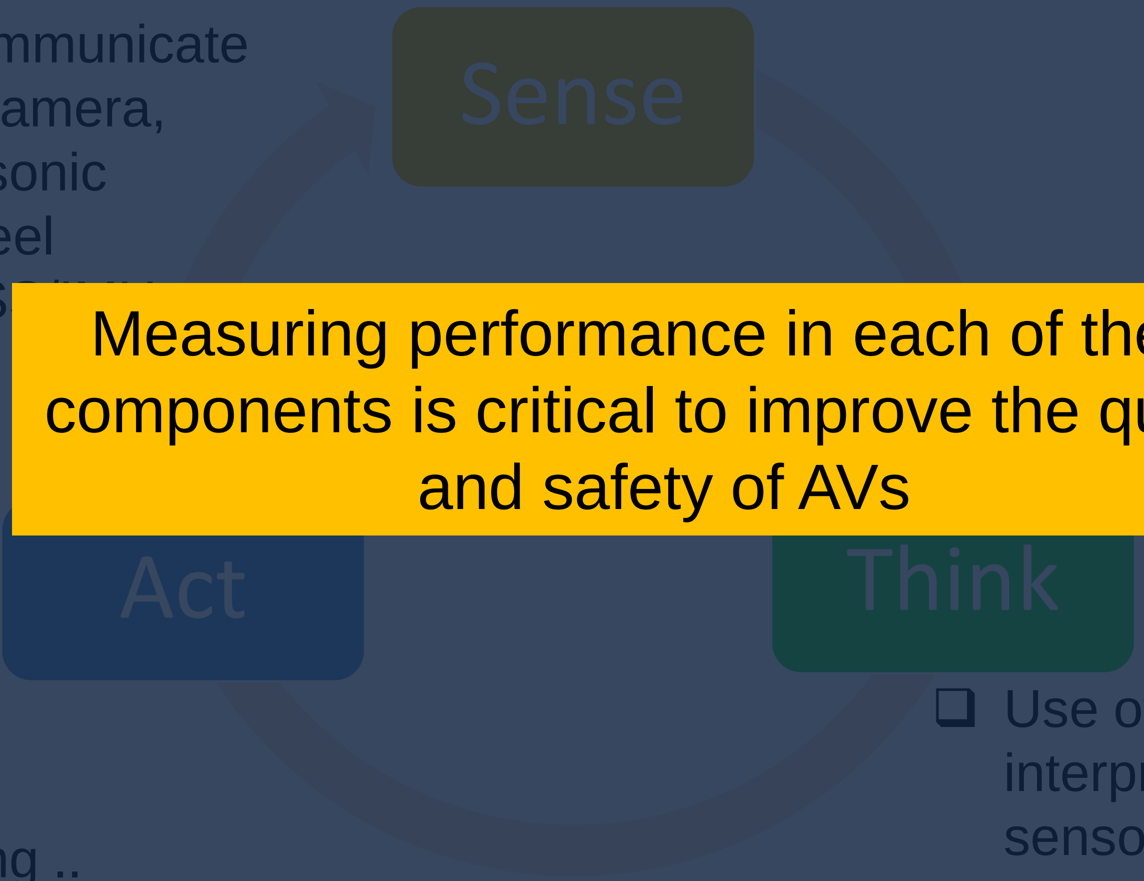
- Use of computing hardware/software to interpret the data communicated by the sensors and plan a strategy
  - Object recognition, localization etc.
  - Path planning ..

- Use of actuation hardware to respond.
  - Acceleration, braking, steering ..

Note: There are several other sensors that are not listed here that ensure the safety of a vehicle regardless of the car's type (autonomous or otherwise). Sensors such as O2 sensors, Torque sensors, TPMS etc. Regulations also play a huge part in enabling AVs.

# What makes a vehicle Autonomous

- For sensing the environment, objects, people, ego localization and communicate
  - Lidar, Radar, Camera, Thermal, Ultrasonic
  - Odometry, Wheel encoders, GNS




**Measuring performance in each of these components is critical to improve the quality and safety of AVs**

Aided by
- in-vehicle and ex-vehicle communication h/w and s/w,
- communication protocols,
- HD maps
- structure (road signs etc.)
- puting hardware/software
- rating systems, middleware, ervisors

- Use of actuation hardware to respond.
  - Acceleration, braking, steering ..

- Use of computing hardware/software to interpret the data communicated by the sensors
  - Object recognition, localization etc.
  - Path planning ..

Note: There are several other sensors that are not listed here that ensure the safety of a vehicle regardless of the car's type (autonomous or otherwise). Sensors such as O2 sensors, Torque sensors, TPMS etc. Regulations also play a huge part in enabling AVs.

# Industry Voices: What did stakeholders request from NIST?

NIST

* Within NIST scope and expertise/infrastructure is available

*Within NIST scope and expertise/infrastructure is lacking (NIST can support agencies)

*Not within NIST scope

| | |
|---|---|
| Develop novel individual and fused sensor *measurement science* solutions for vehicles | *Measure* how different parts of an AV work together |
| Help define *testing* guidance for stakeholders to meet regulatory agency requirements | "Do you know that NIST cybersecurity framework? Just do that for autonomous vehicles." |
| Develop mitigation *standards* for adversarial AI | Define the data that should be *measured* before, during, and after operation of automated vehicles |
| Develop AV simulation-based *measurement science* | Provide *reference materials* for what infrastructure investment state and local governments should invest in |
| Advance *standards* with SAE, 3GPP, and Teleoperation Consortium | Collect *standardized* data from the DoT from accidents to develop representative testing environments |
| Develop *measurement science* for traffic infrastructure that can support AVs | Provide classification and levels for AV components |
| Develop *metrics* to identify what aspects of AVs should be measured to ensure safety | Create and enforce a baseline for AV safety systems testing |
| Create *test models* and *measurement science* for AV communications | Enforce sensor specs that should be used in Avs |
| Foster a community of stakeholders to agree on common *taxonomies and standards* | Create regulation on periodic testing and updating |
| Be a one-stop-shop for pointers to relevant autonomous vehicle *standards* | |

# Industry Voices: What did stakeholders request from NIST?

* Within NIST scope and expertise/infrastructure is available    *Within NIST scope and expertise/infrastructure is lacking (NIST can support agencies)    *Not within NIST scope

- Develop novel individual and fused sensor *measurement science* solutions for vehicles
- Help define *testing* guidance for stakeholders to meet regulatory agency requirements
- Develop m…
- Develop AV s…
- Advance *stand*…
- Develop *meas*… that can support AVs
- Develop *metrics* to identify what aspects of AVs should be measured to ensure safety
- Create *test models* and *measurement science* for AV communications
- Foster a community of stakeholders to agree on common *taxonomies and standards*
- Be a one-stop-shop for pointers to relevant autonomous vehicle *standards*

- *Measure* how different parts of an AV work together
- "Do you know that NIST cybersecurity framework? Just do that for autonomous vehicles."
- … during, and
- …e investment …st in
- …ccidents to develop representative testing environments
- Provide classification and levels for AV components
- Create and enforce a baseline for AV safety systems testing
- Enforce sensor specs that should be used in Avs
- Create regulation on periodic testing and updating

**Develop measurement science to make automated vehicles safer.**

# Industry Voices: What did stakeholders request from NIST?

* Within NIST scope and expertise/infrastructure is available    *Within NIST scope and expertise/infrastructure is lacking (NIST can support agencies)    *Not within NIST scope

- Develop novel individual and fused sensor *measurement science* solutions for vehicles
- Help define *testing* guidance for stakeholders to meet regulatory agency requirements
- Develop m…
- Develop AV s…
- Advance *stand*…
- Develop *meas*… that can support AVs
- Develop *metrics* to identify what aspects of AVs should be measured to ensure safety
- Create *test models* and *measurement science* for AV communications
- Foster a community of stakeholders to agree on common *taxonomies and standards*
- Be a one-stop-shop for pointers to relevant autonomous vehicle *standards*

- *Measure* how different parts of an AV work together
- "Do you know that NIST cybersecurity framework? Just do that for autonomous vehicles."
- … during, and
- …e investment …st in
- …ccidents to …ents
- Provide classification and levels for AV components
- Create and enforce a baseline for AV safety systems testing
- Enforce sensor specs that should be used in Avs
- Create regulation on periodic testing and updating

**NIST Mission:** To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.

# Industry Voices: What did stakeholders request from NIST?

*** Within NIST scope and expertise/infrastructure is available** ***Within NIST scope and expertise/infrastructure is lacking (NIST can support agencies)** ***Not within NIST scope**

- Develop novel individual and fused sensor *measurement science* solutions for vehicles
- Help define *testing* guidance for stakeholders to meet regulatory agency requirements
- Develop mitigation *standards* for adversarial AI
- Develop AV simulation-based *measurement science*
- Advance *standards* with SAE, 3GPP, and Teleoperation Consortium
- Develop *measurement science* for traffic infrastructure that can support AVs
- Develop *metrics* to identify what aspects of AVs should be measured to ensure safety
- Create *test models* and *measurement science* for AV communications
- Foster a community of stakeholders to agree on common *taxonomies and standards*
- Be a one-stop-shop for pointers to relevant autonomous vehicle *standards*

- *Measure* how different parts of an AV work together
- "Do you know that NIST cybersecurity framework? Just do that for autonomous vehicles."
- Define the data that should be *measured* before, during, and after operation of automated vehicles
- Provide *reference materials* for what infrastructure investment state and local governments should invest in
- Collect *standardized* data from the DoT from accidents to develop representative testing environments
- Provide classification and levels for AV components
- Create and enforce a baseline for AV safety systems testing
- Enforce sensor specs that should be used in Avs
- Create regulation on periodic testing and updating

Develop novel individual and fused sensor *measurement science* solutions for vehicles


Potential Impact

- In the first half of 2022*:
  - Total SAE Level 2 car sales in the US' increased to 46.5% and ADAS penetration crosses 70%

NIST expertise

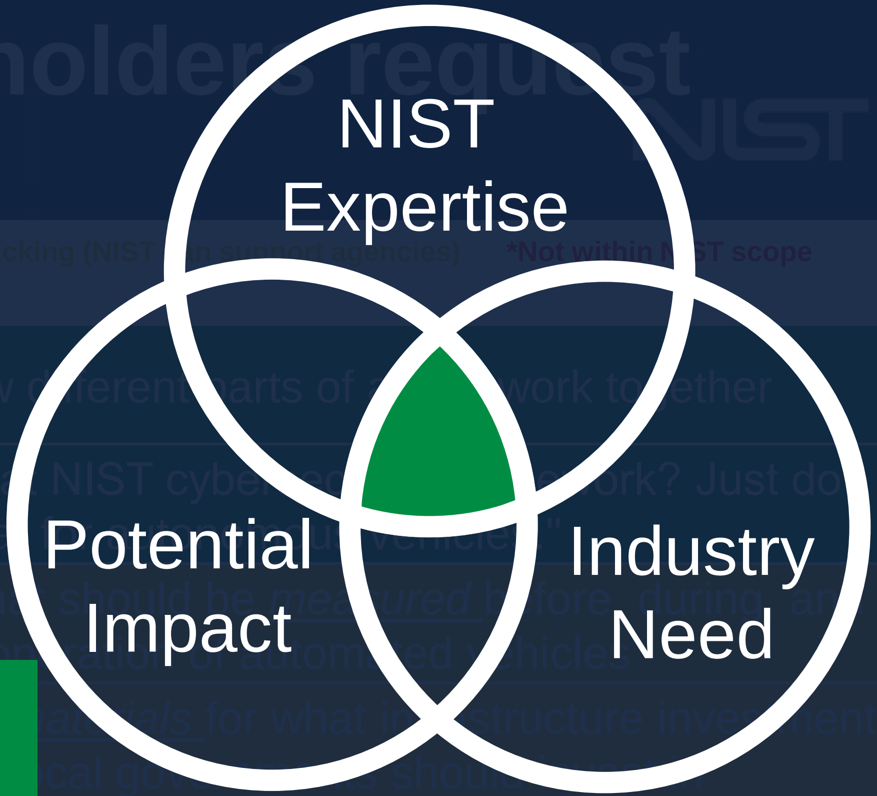
- National Metrology Institute of USA
- Multi-disciplinary experts
- Led the development of several standards related to sensors for manufacturing automation

Source: https://www.counterpointresearch.com/adas-penetration-crosses-70-us-h1-2022-level-2-share-46-5/

Develop novel individual and fused sensor *measurement science* solutions for vehicles

Help define *testing* guidance for stakeholders to meet regulatory agency requirements

Develop mitigation *standards* for adversarial AI




- NIST developed measurement science, test methods and standards can be used:
  - by the manufacturer to spec' their sensors
  - by the end users/integrators to evaluate sensors
  - to perform an apples-to-apples comparison

Create *test models* and *measurement science* for AV communications

Foster a community of stakeholders to agree on common *taxonomies and standards*

Create and enforce a baseline for AV safety systems testing

Enforce sensor specs that should be used in Avs

Create regulation on periodic testing and updating

Source: https://www.counterpointresearch.com/adas-penetration-crosses-70-us-h1-2022-level-2-share-46-5/

# Overview

NIST

- Problem statement
- Background and feedback from 2022 workshop.
- Focus on AV Lidars
- Technical approach
  - Testbed development
  - Initial results.
- Next steps

# Focus on Lidars (NIST expertise)

NIST

- There are several sensor technologies that are used on AVs – our initial focus is on Lidars.
- **Experience in evaluating Terrestrial Lidars for over a decade**.
- **Led the development of multiple standards** related to Terrestrial Lidars and other 3D optical sensors through ASTM E57.
- NIST is the National Metrology Institute of USA with state-of-the art equipment and staff whose expertise can be leveraged for this effort.

| Requirements | Imaging | Radar | Lidar | Ultrasonic |
|---|---|---|---|---|
| Angular Resolution | A | B | A | C |
| Depth Resolution | B | A | A | A |
| Velocity | C | A | B | B |
| Long Range Sensing | B | A | A | A |
| Near Range Sensing | A | C | C | A |
| Traffic Signs Detection | A | C | B | C |
| Object Edge Precision | A | C | A | A |
| Lane Detection | A | C | B | C |
| Color Recognition | A | C | C | C |
| Adverse Weather performance | B | A | B | A |
| Low-Light performance | B | A | A | A |
| Cost | A | A | B | A |

A Meets or exceeds requirements

B Meets requirements in limited conditions

C Minimally meets or doesn't meet requirements in any condition

# AV Lidar technology

- Based on laser wavelength:
  - Near infrared: 850 nm, 905 nm, 940 nm; Shortwave infrared: 1350 nm, 1550 nm
- Based on measurement principle:
  - Time-of-flight (TOF), Frequency Modulated Continuous Wave (FMCW)
- Based on laser diode type (for TOF sensors):
  - Edge-emitting laser (EEL) and Vertical Cavity Surface Emitting Laser (VCSEL)
- Based on beam steering:
  - Mechanical, MEMS, Solid-state and hybrid
- Based on receiver:
  - PIN photodiode, Avalanche photodiode (APD), Single-photon avalanche diode (SPAD), Silicon Photomultiplier (SiPM)

# AV Lidar technology

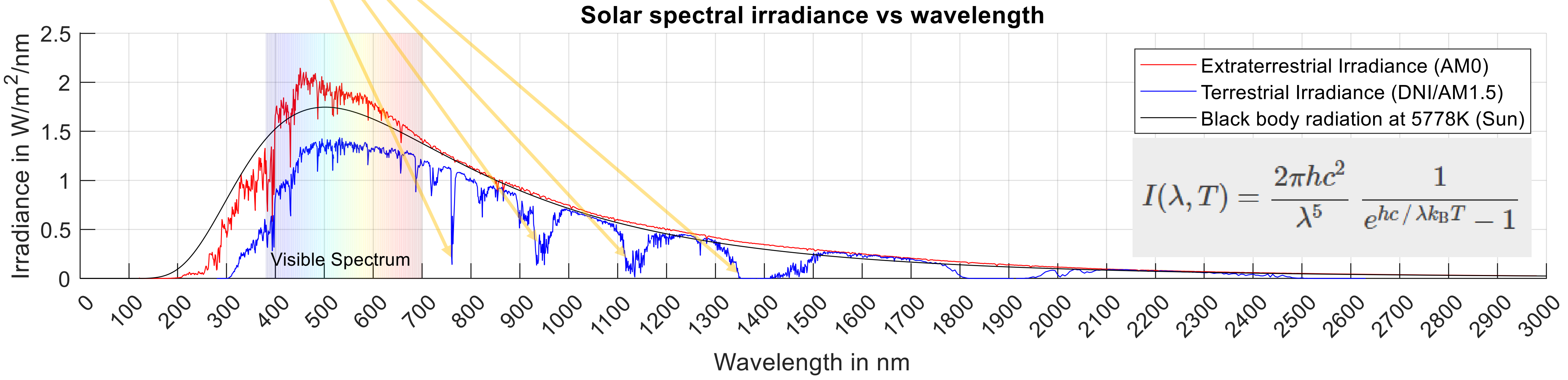
- Choice of the technology depends on:
  - Considerations for eye safety, power consumption, features, component supply chains, manufacturability, packaging complexity, cost (For ex: Silicon for < 1000 nm vs InGaAs for > 1000 nm)
  - Atmospheric absorption
    - Lower photons = higher signal-to noise ratio

# AV Lidar technology

NIST

- Choice of the technology depends on:
  - Considerations for eye safety, power consumption, features, component supply chains, manufacturability, packaging complexity, cost (For ex: Silicon for < 1000 nm vs InGaAs for > 1000 nm)
  - Atmospheric absorption
    - Lower photons = higher signal-to noise ratio
      - enables higher power, long range, eye-safe lasers

**Solar spectral Irradiance****

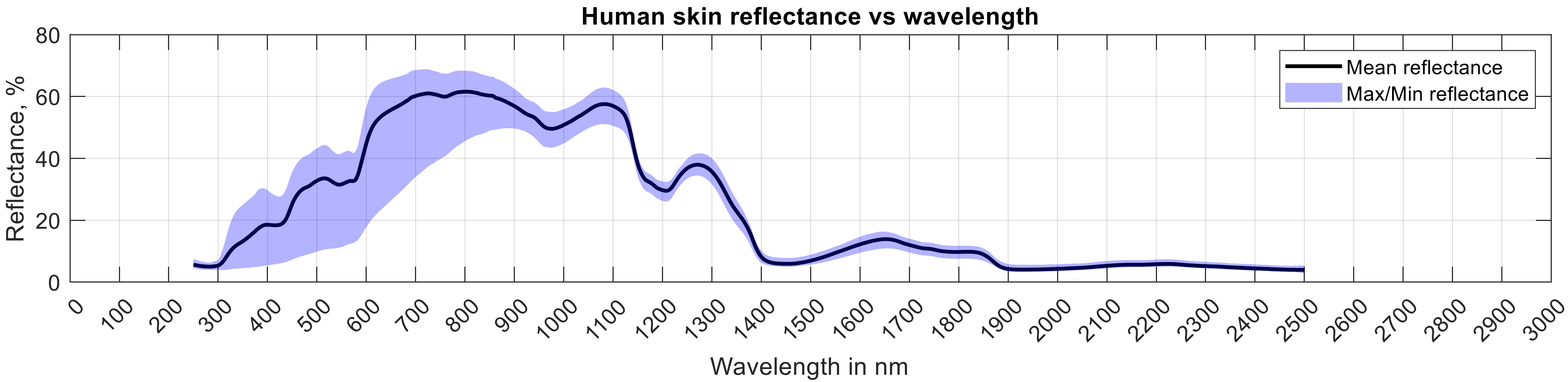



- Direct normal spectral irradiance is within a 5.8° field of view centered on the sun.
- ** Source: ASTM-G173 › Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

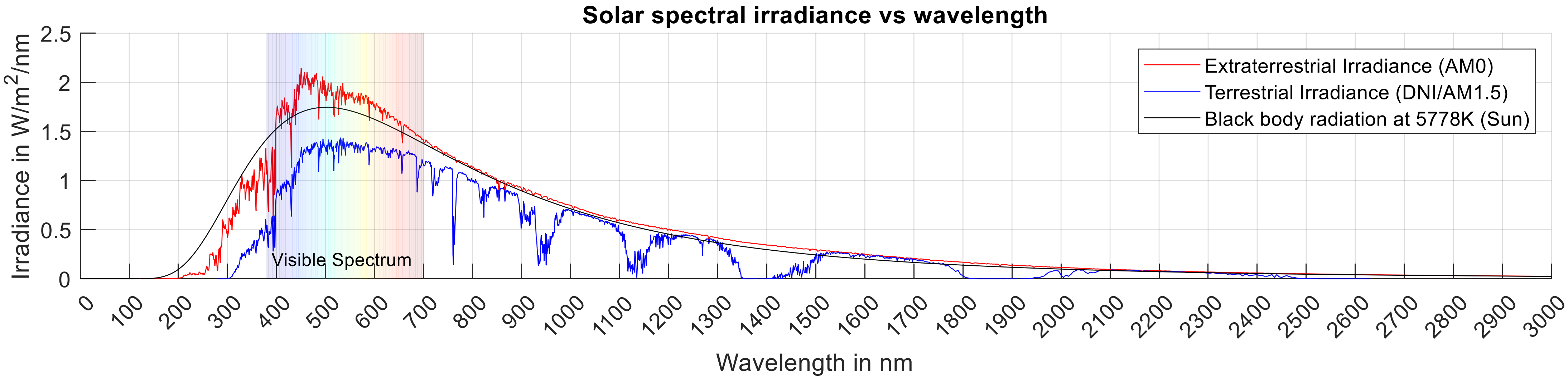
# Solar spectral irradiance and Human skin reflectance

NIST

**Human Skin Reflectance***




**Solar spectral Irradiance****



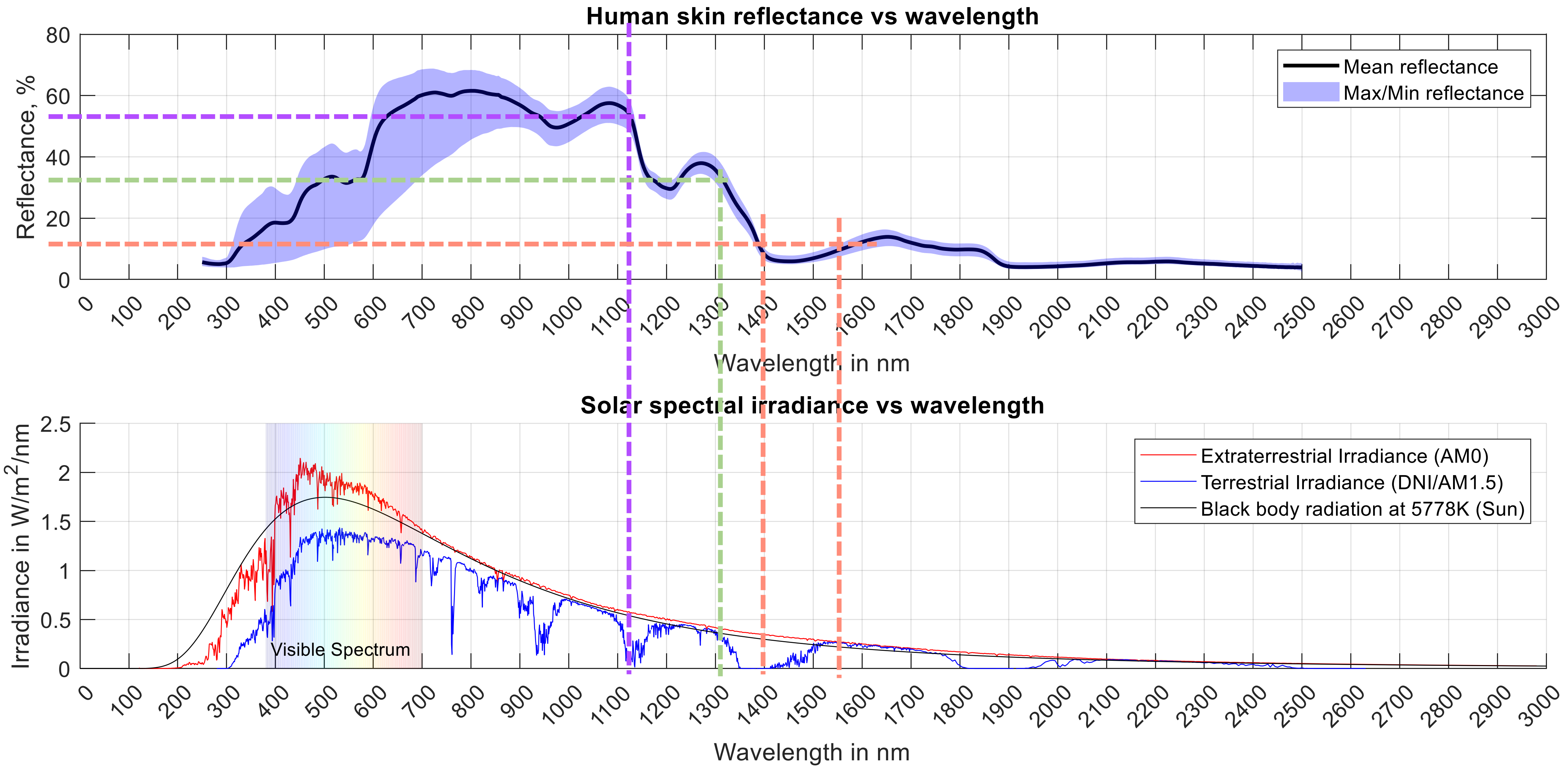

- *Source: NIST data (Cooksey et al): https://files.cie.co.at/x046_2019/x046-PO065.pdf & Ian Blasch (Jabil.com)
- **Source: ASTM-G173 › Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

# Solar spectral irradiance and Human skin reflectance

NIST

**Human Skin Reflectance***

**Solar spectral Irradiance****




- *Source: NIST data (Cooksey et al): https://files.cie.co.at/x046_2019/x046-PO065.pdf & Ian Blasch (Jabil.com)
- **Source: ASTM-G173 › Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

# Lidar specifications

NIST

| Lidar | Lidar A1 | Lidar A2 | Lidar A3 | Lidar A4 | Lidar B1 |
|---|---|---|---|---|---|
| **Beam-steering** | Spinning | Spinning | Spinning | Galvo. Mirror | Spinning |
| **Laser emitter** | EEL | EEL | EEL | EEL | VCSEL |
| **Photo detector** | APD | APD | APD | APD | SPAD |
| **Vertical lines** | 16 | 32 | 64 | 32-80* | 32 |
| **Wavelength** | 903 nm | 903 | 905 nm | 905 nm | 850 nm |
| **FOV-Horizontal** | 360 | 360 | 360 | 120 | 360 |
| **FOV-Vertical** | 30 | 40 | 26.8 | 16 | 45 |
| **Rotation rate** | 5 Hz - 20 Hz* | 5 Hz - 20 Hz* | 5 Hz – 15 Hz* | 10-Hz – 25 Hz* | 10 Hz - 20 Hz* |
| **Points/sec** | 300K - 600K | 600K - 1200K | N/A | N/A | 655 K |
| | | | | | |
| **Min. Range** | N/A | N/A | N/A | 0.1 m* | 0.8 m* |
| **Max. Range** | 100 m | 200 m | 120 m* | 170 m* | 120 m* |
| **Range Resolution** | N/A | N/A | N/A | 4 mm | 12 mm |
| **Range Accuracy** | ±30 mm | ±30 mm | < 20 mm | ±50 mm | zero - slight bias |
| **Range Repeatability** | N/A | N/A | N/A | N/A | 15 mm – 100 mm* |
| **False positive rate** | N/A | N/A | N/A | N/A | 1/10000 |
| **Beam Size** | 9.5 mm/12.7 mm* | 9.5 mm/12.7 mm* | N/A | N/A | 10 mm |
| **Beam Divergence** | 0.07/0.18 deg* | 0.09/0.18 deg* | N/A | N/A | 0.13 deg |

*Depends on target, or sensor setting, or sensor type

# Lidar specifications

| Lidar | Lidar A1 | Lidar A2 | Lidar A3 | Lidar A4 | Lidar B1 |
|---|---|---|---|---|---|
| **Beam-steering** | Spinning | Spinning | Spinning | Galvo. Mirror | Spinning |
| **Laser emitter** | EEL | EEL | EEL | EEL | VCSEL |
| **Photo detector** | APD | APD | APD | APD | SPAD |
| **Vertical lines** | 16 | 32 | 64 | 32-80* | 32 |
| **Wavelength** | 903 nm | 903 | 905 nm | 905 nm | 850 nm |
| **FOV-Horizonta[illegible]** | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| **FOV-Vertical** | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| **Rotation rate** | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] - 20 Hz* |
| **Points/sec** | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| **Min. Range** | N/A | N/A | N/A | 0.1 m* | 0.8 m* |
| **Max. Range** | 100 m | 200 m | 120 m* | 170 m* | 120 m* |
| **Range Resolution** | N/A | N/A | N/A | 4 mm | 12 mm |
| **Range Accuracy** | ±30 mm | ±30 mm | < 20 mm | ±50 mm | zero - slight bias |
| **Range Repeatability** | N/A | N/A | N/A | N/A | 15 mm – 100 mm* |
| **False positive rate** | N/A | N/A | N/A | N/A | 1/10000 |
| **Beam Size** | 9.5 mm/12.7 mm* | 9.5 mm/12.7 mm* | N/A | N/A | 10 mm |
| **Beam Divergence** | 0.07/0.18 deg* | 0.09/0.18 deg* | N/A | N/A | 0.13 deg |

*Depends on target, or sensor setting, or sensor type

Many common specifications are missing from the specification sheets and limited information on how these parameters are being measured.

# Lidar specifications

| Lidar | Lidar A1 | Lidar A2 | Lidar A3 | Lidar A4 | Lidar B1 |
|---|---|---|---|---|---|
| **Beam-steering** | Spinning | Spinning | Spinning | Galvo. Mirror | Spinning |
| **Laser emitter** | EEL | EEL | EEL | EEL | VCSEL |
| **Photo detector** | APD | APD | APD | APD | SPAD |
| **Vertical lines** | 16 | 32 | 64 | 32-80* | 32 |
| **Wavelength** | 903 nm | 903 | 905 nm | 905 nm | 850 nm |
| **FOV-Horizontal** | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| **FOV-Vertical** | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| **Rotation rate** | [illegible] | [illegible] | [illegible] | [illegible] | - 20 Hz* |
| **Points/sec** | 300K - 600K | 600K - 1200K | N/A | N/A | 655 K |
| | | | | | |
| **Min. Range** | N/A | N/A | N/A | 0.1 m* | 0.8 m* |
| **Max. Range** | 100 m | 200 m | 120 m* | 170 m* | 120 m* |
| **Range Resolution** | N/A | N/A | N/A | 4 mm | 12 mm |
| **Range Accuracy** | ±30 mm | ±30 mm | < 20 mm | ±50 mm | zero - slight bias |
| **Range Repeatability** | N/A | N/A | N/A | N/A | 15 mm – 100 mm* |
| **False positive rate** | N/A | N/A | N/A | N/A | 1/10000 |
| **Beam Size** | 9.5 mm/12.7 mm* | 9.5 mm/12.7 mm* | N/A | N/A | 10 mm |
| **Beam Divergence** | 0.07/0.18 deg* | 0.09/0.18 deg* | N/A | N/A | 0.13 deg |

*Depends on target, or sensor setting, or sensor type

**Motivation for this work: Develop a testbed and test methods to evaluate AV Perception sensors**

# Overview

- Problem statement
- Background and feedback from 2022 workshop.
- Focus on AV Lidars
- Technical approach
  - Testbed development
  - Initial results.
- Next steps

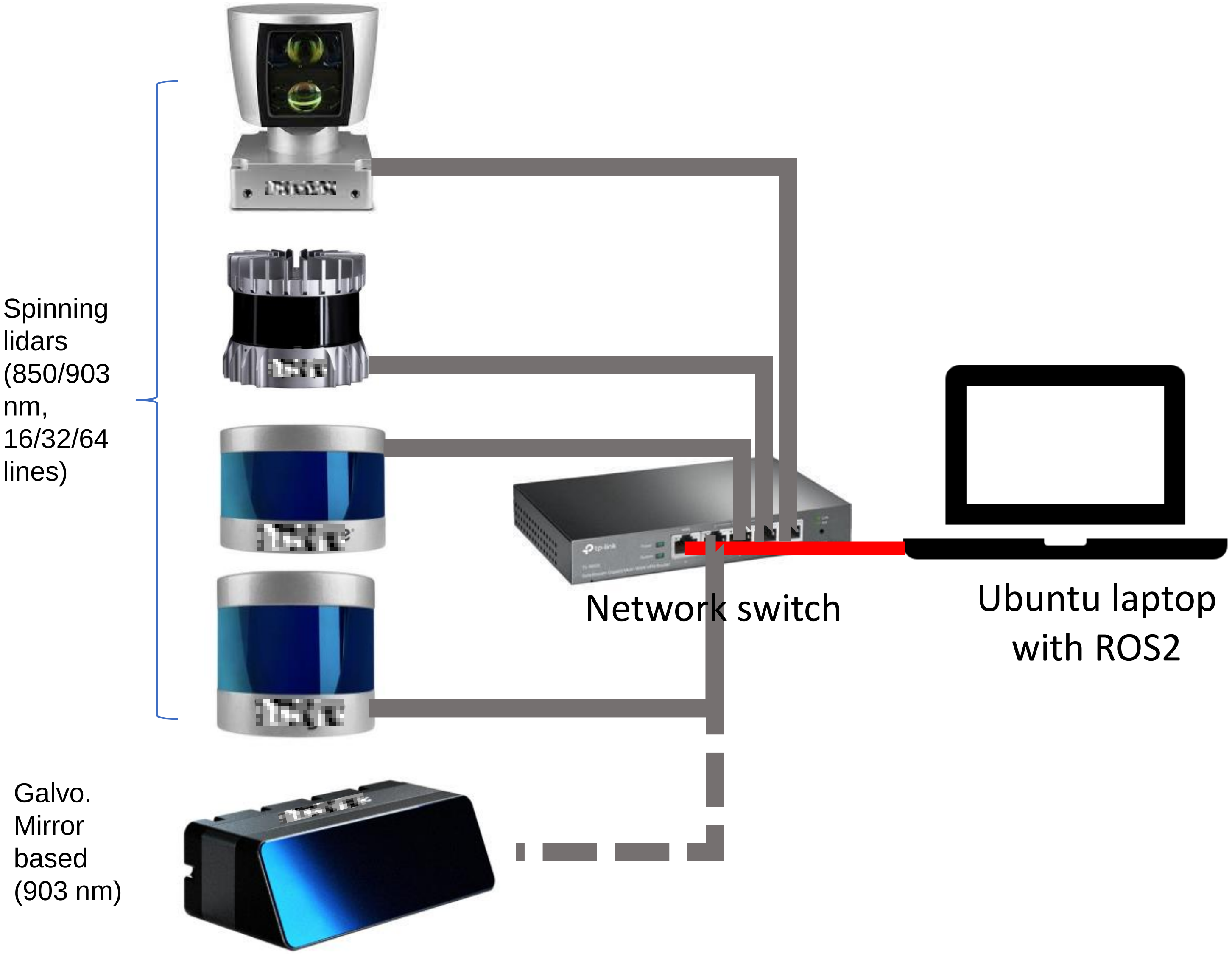
# Technical approach for testbed development

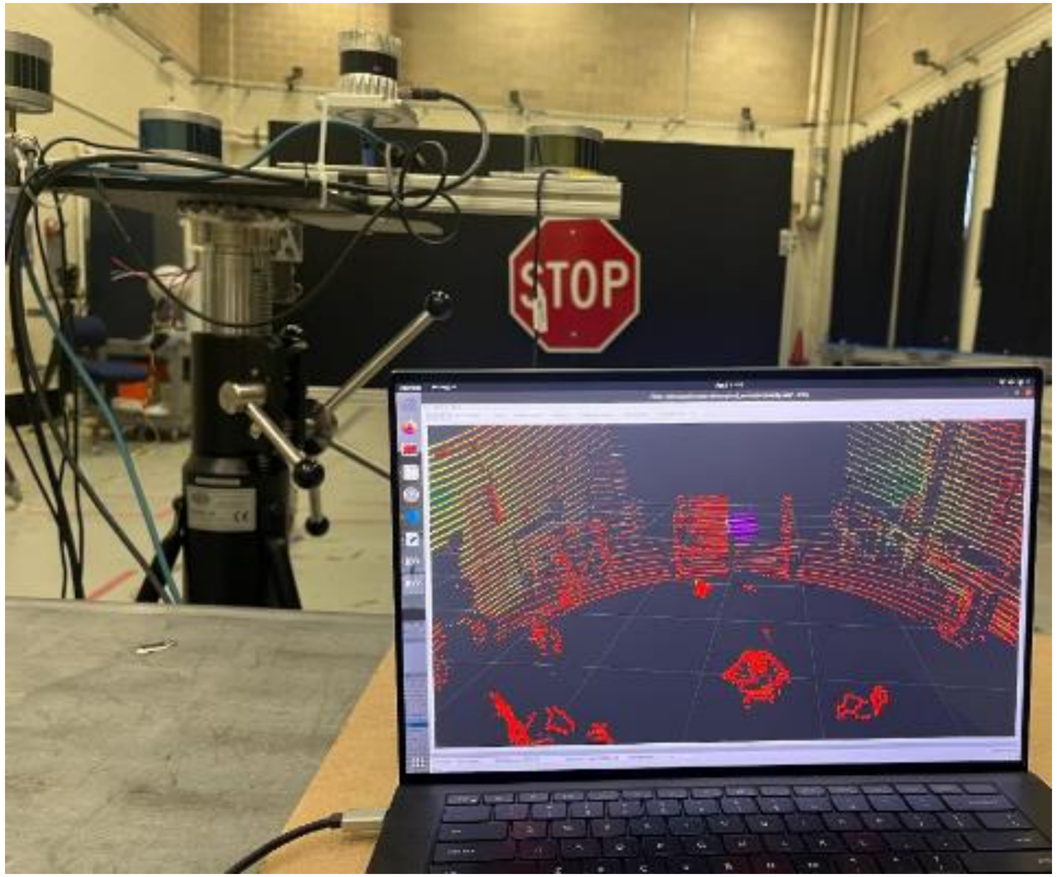
- Develop a testbed  and develop methods to evaluate sensors using SI traceable artifacts and instrumentation*.
  - Sensor integration with ROS2
  - Preliminary tests to understand data quality.
  - Internal/external length error tests using calibrated artifacts.
  - Lidar-Lidar calibration, registration, evaluation.
  - SLAM testing using ICP algorithms



*ROS2: Robot Operating System 2; SLAM: Simultaneous localization and mapping; ICP: Iterative closest point

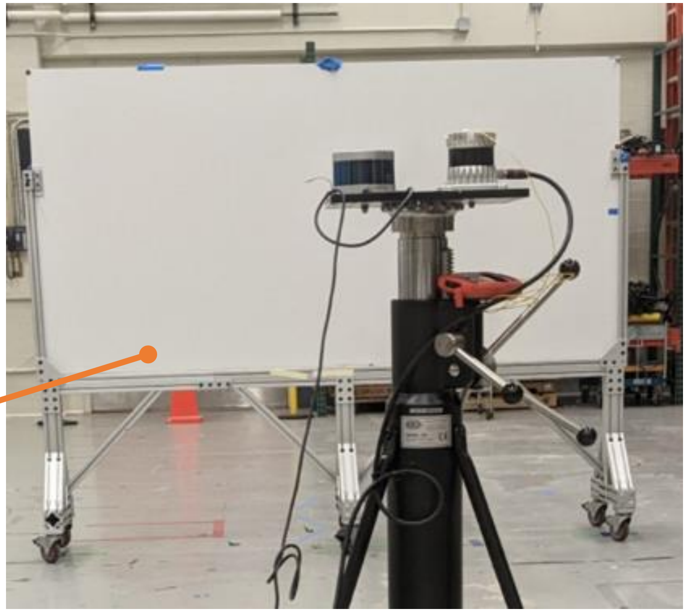
# Testbed and apparatus: Sensors

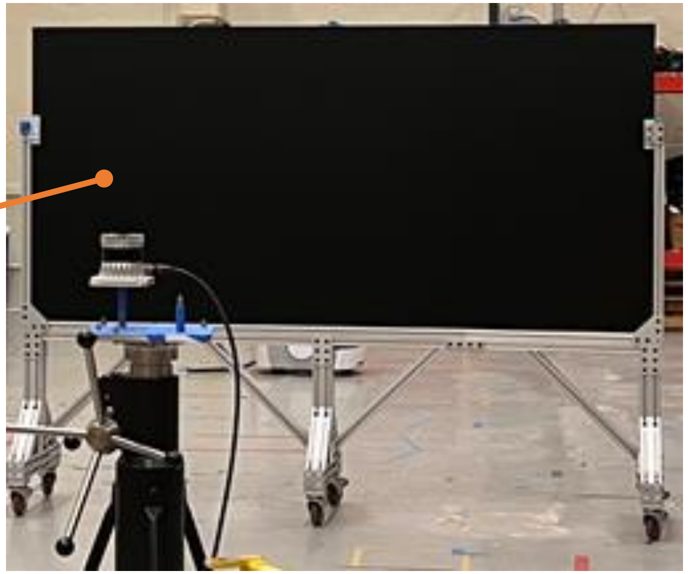



**Disclaimer:** Commercial equipment and materials may be identified to specify certain procedures. In no case does such identification imply recommendation or endorsement by the NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

# Testbed and apparatus: Planar targets



Target size: 1.2 m x 2.4 m and dimensional flatness: < 0.2 mm

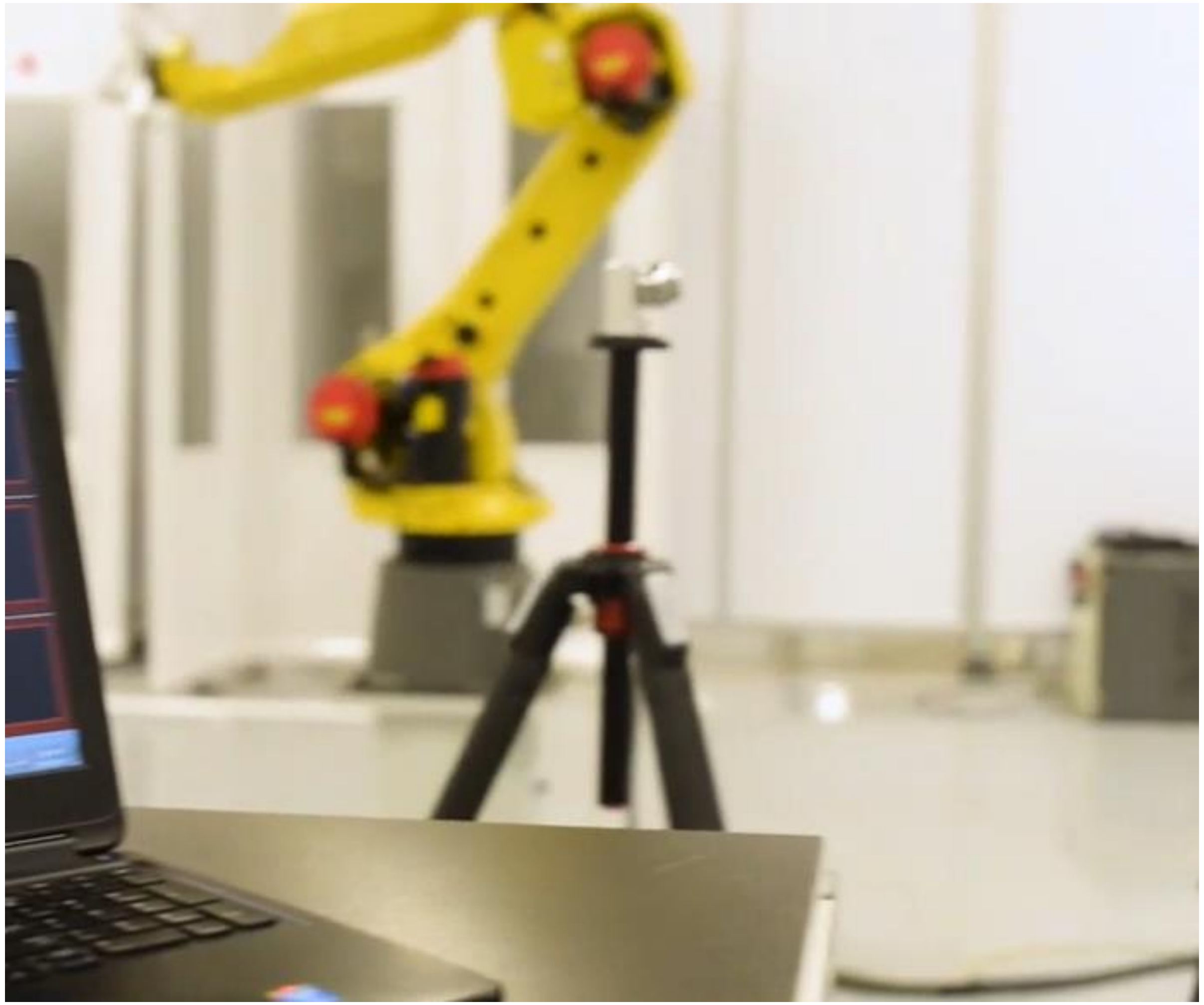
# Testbed and apparatus: Spherical Targets

NIST

- Sphere targets:
  - Vapor blasted aluminum, with a matte finish for near Lambertian reflectance.
  - ~15” or 381 mm nominal diameter
    - Diameter uncertainty of ~0.1 mm
    - Worst case roundness of 1.13 mm

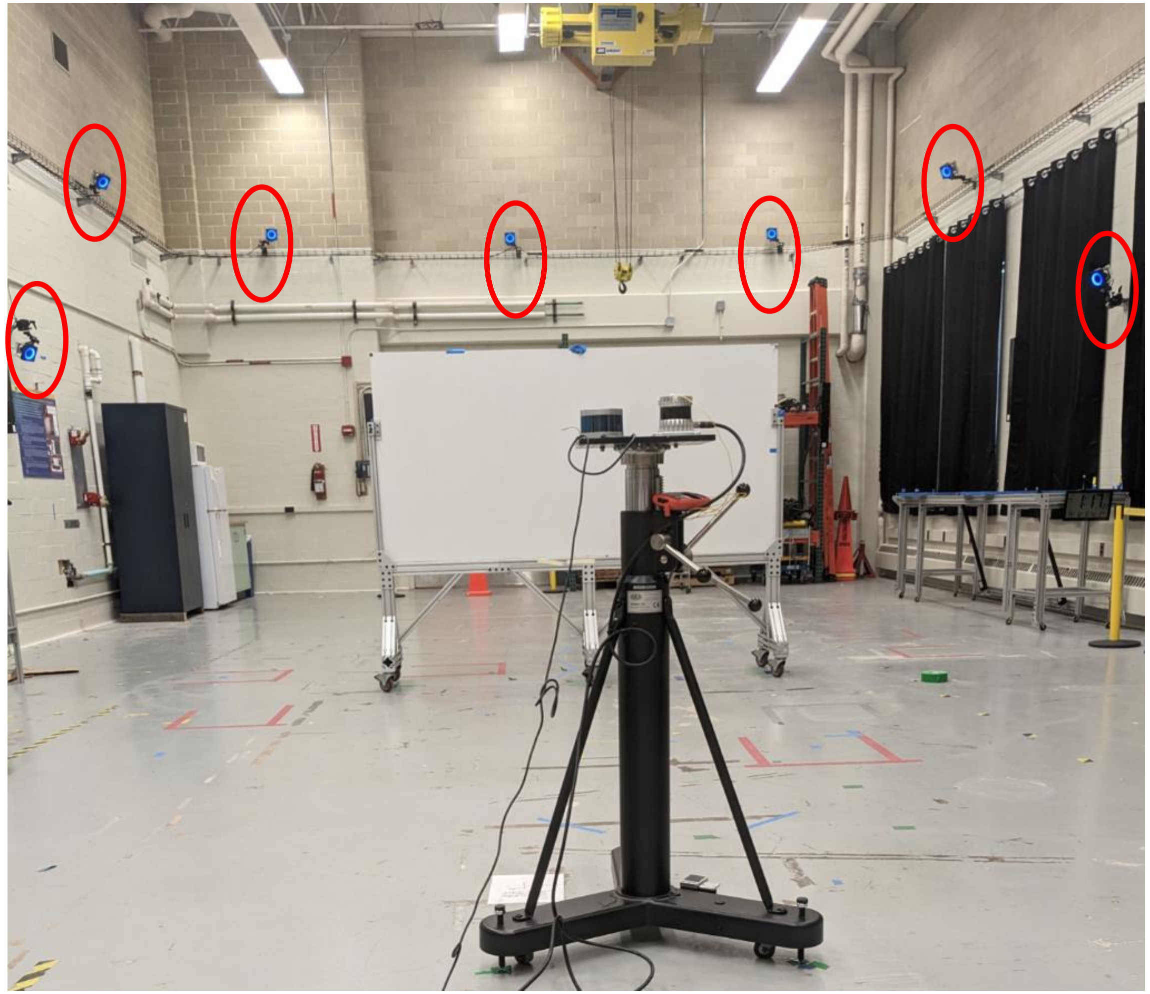
# Testbed and apparatus: Reference systems

**API T3 Laser tracker**



Source: https://www.youtube.com/watch?v=FEjXfUrkueg

**OptiTrak Motion capture cameras**



**Disclaimer:** Commercial equipment and materials may be identified to specify certain procedures. In no case does such identification imply recommendation or endorsement by the NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

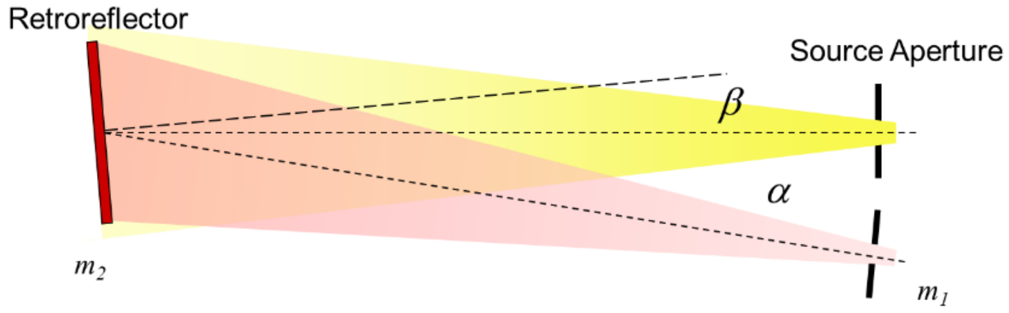
# Overview

- Problem statement
- Background and feedback from 2022 workshop.
- Focus on AV Lidars
- Technical approach
    - Testbed development (Retroreflection facility)
    - Initial results.
- Next steps

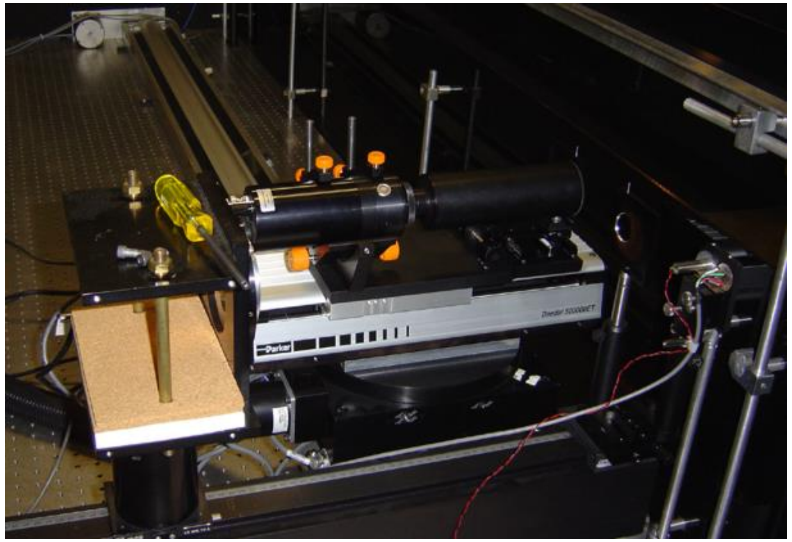
# Retroreflection Facility

- NIST established retroreflection - calibration and characterization facility in the early 2000s.
    - It was limited to visible wavelengths supporting ASTM activities in E12 – Color & Appearance and SAE activities.
- In support of automated vehicles, the retroreflection facility has been upgraded to work with infrared wavelengths (800 nm – 1650 nm).
- Infrared wavelengths support infrastructure assisting LIDAR and infrared imaging systems.
- Calibrated samples will allow in-situ measurements and calibrations of mounted devices

**Ratio Method**




Ratio = Radiance/Irradiance



# Extending an Automated Vehicles Vision

- The retroreflection facility can be extended to characterizing and calibrating device through imaging capabilities. Demonstration in the visible range are shown in the panel to the right.

- Some companies sell materials that are retroreflective only in the infrared.
    - Visible to the infrared imaging systems while not adding to the confusing human signaling environment.

- Coupling infrared QR codes shown to the right can digitally communicate information quickly and with high confidence.

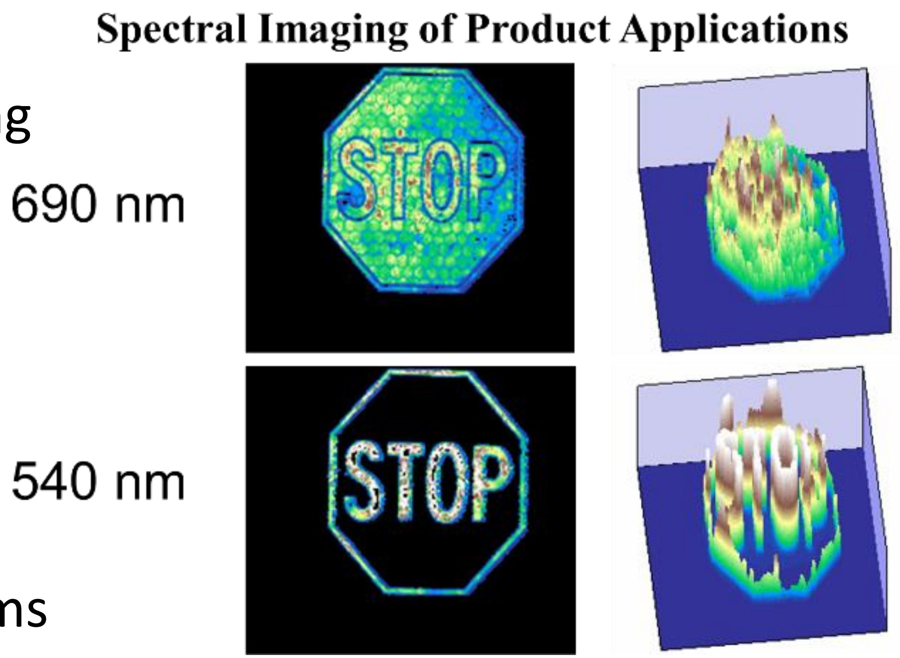




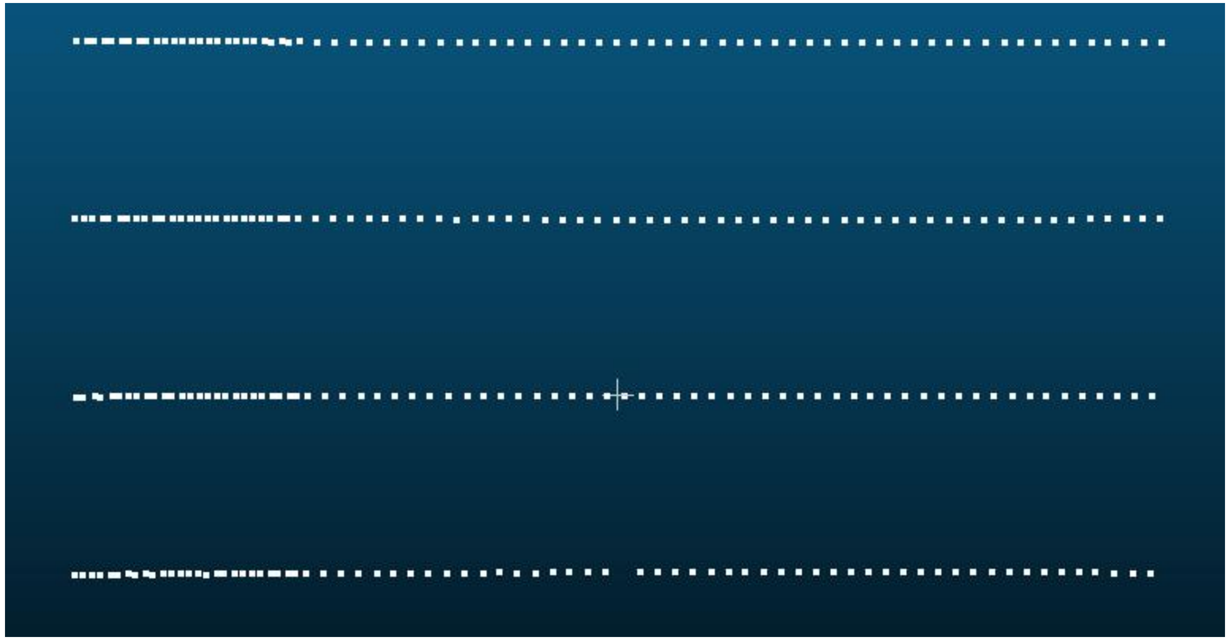
Image credit: Cyalume Technologies

# Overview

- Problem statement
- Background and feedback from 2022 workshop.
- Focus on AV Lidars
- Technical approach
    - Testbed development
    - Initial results.
- Next steps

# Data inconsistencies due to software version/platform

Frame 1



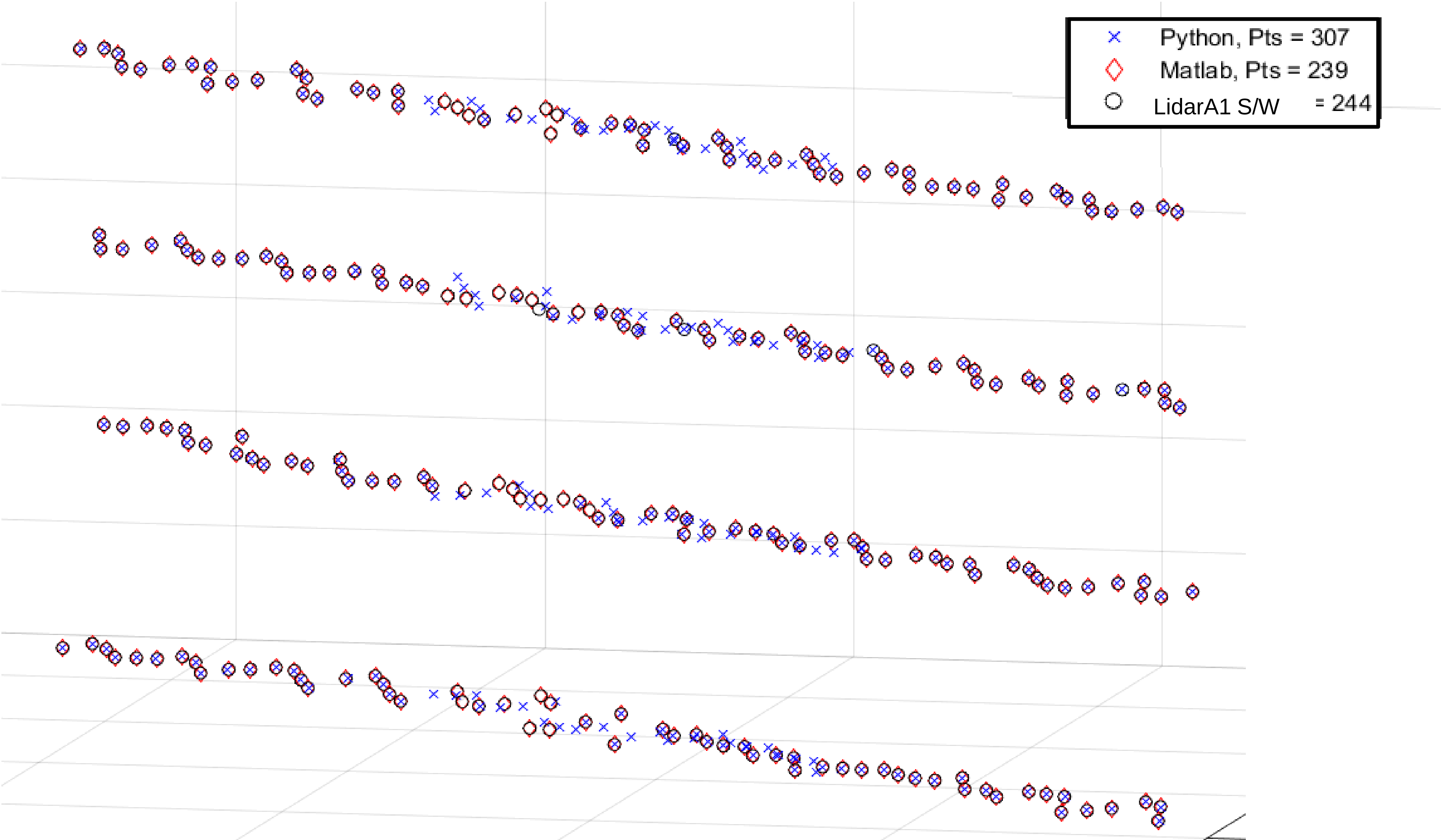
Frame 2

**Data from LidarA1**

- Change in point density along the azimuth direction – an artifact of the 3rd party ROS2 driver
- (X and Y axes were also swapped – code modification was needed to fix the issue)

[Link: velodyne-decoder · PyPI]

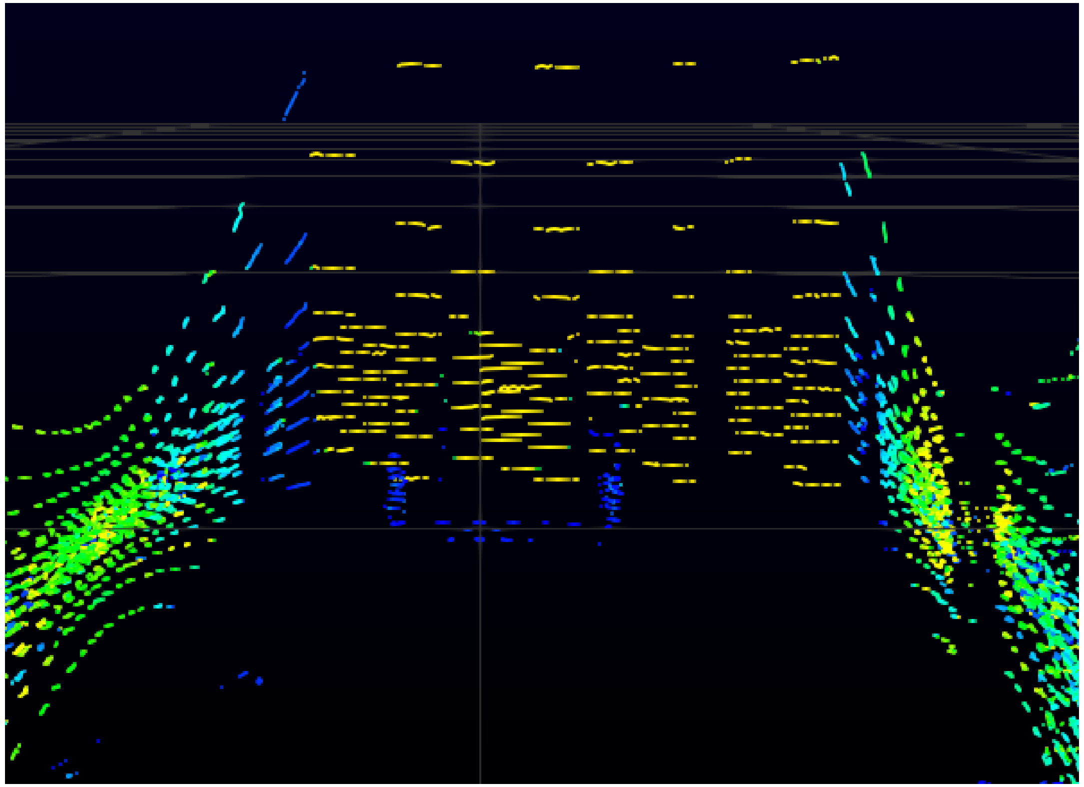
# Data on the target using different software



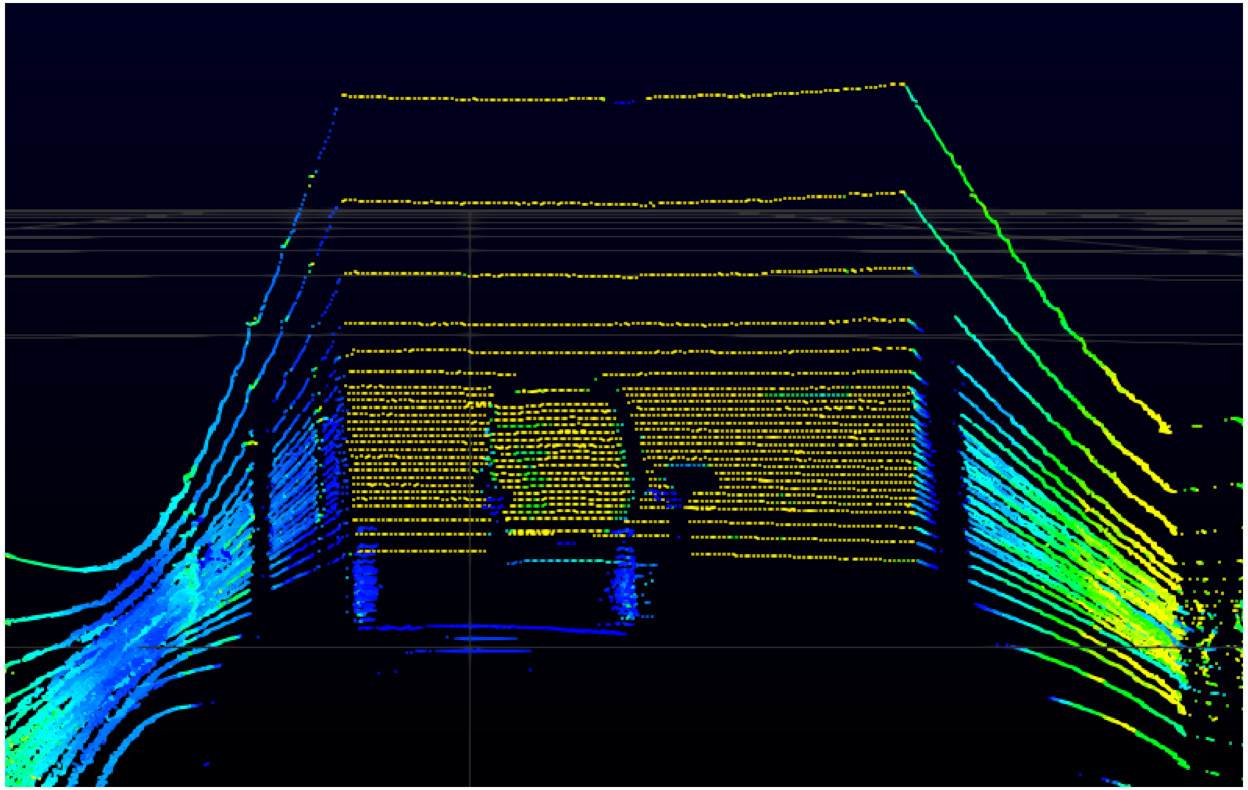
# Degradation in data quality due to communication issues

- Some sensor/hardware combination can degrade data quality.
- In this instance, adding a network switch between the 2 improves the quality of signal/point cloud.

**Lidar ➔ Laptop➔ROS2**



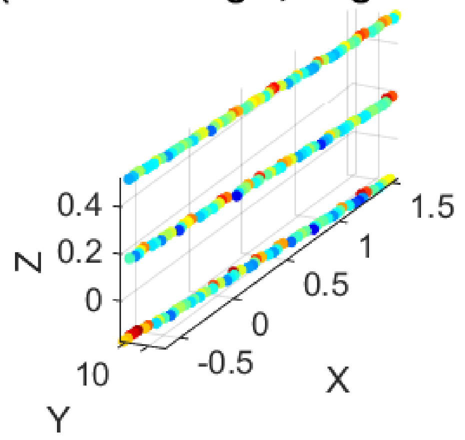
**Lidar ➔ Network Switch ➔ Laptop➔ROS2**

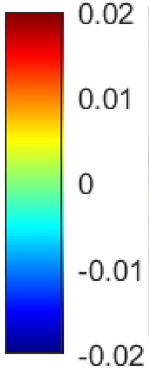


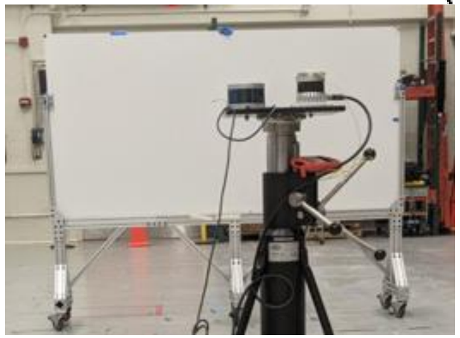
# Noise and intensity profiles

## LidarA1

**LidarA1 : Deviations from a flat plane, in m**
**(On whole target, single frame)**

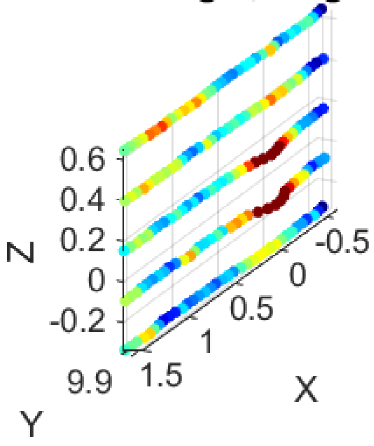


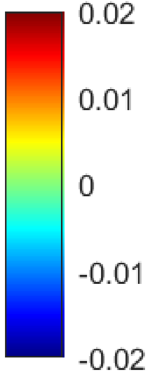



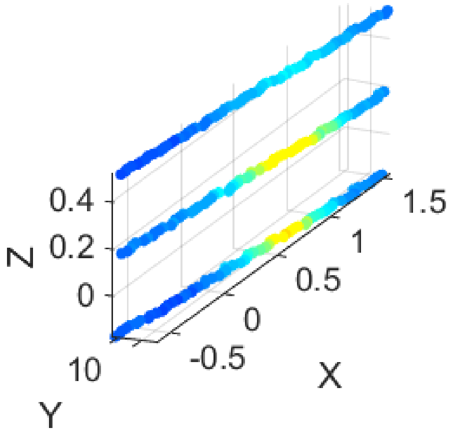
## LidarB1

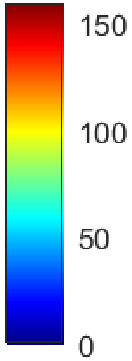
**Lidar B1 : Deviations from a flat plane, in m**
**(On whole target, single frame)**



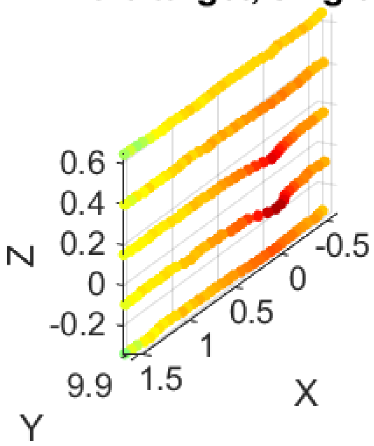



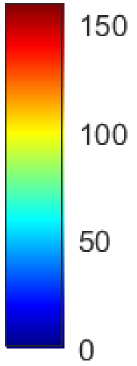

**LidarA1 : Intensity on a flat plane**
**(On whole target, single frame)**



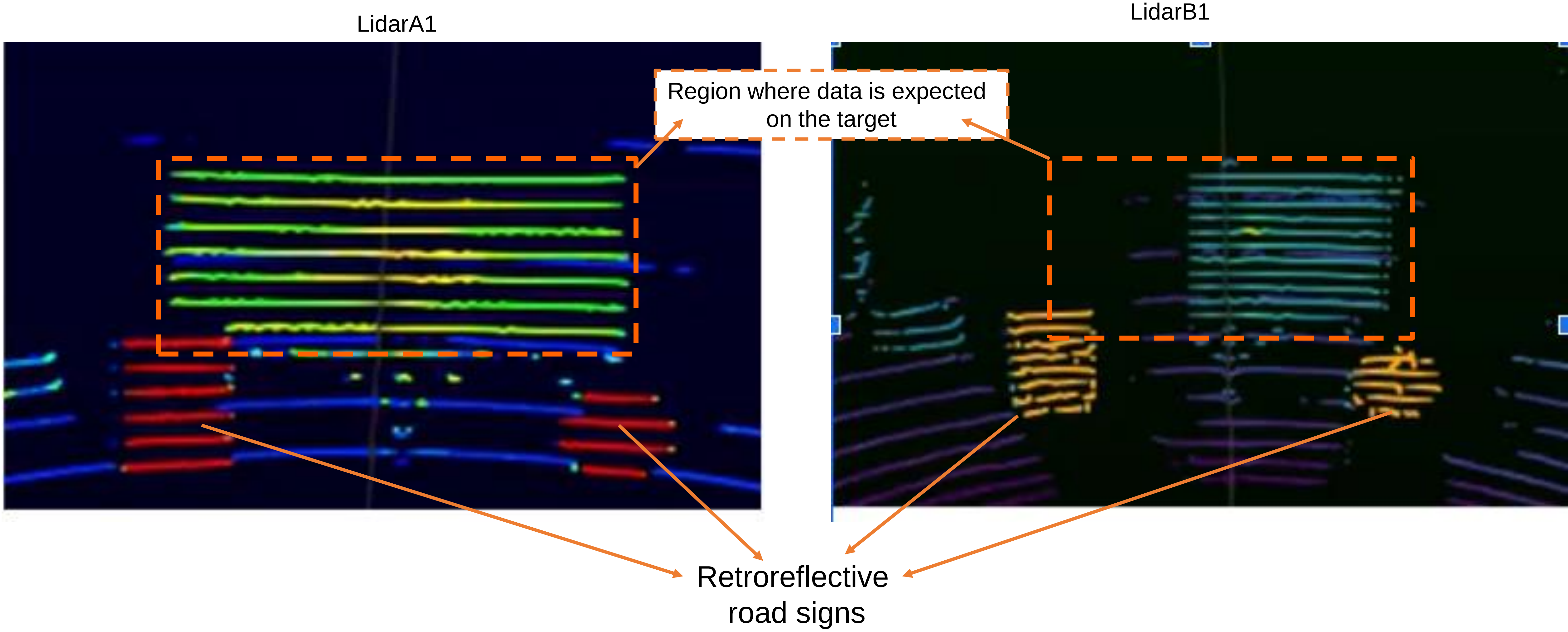




**Lidar B1 : Intensity on a flat plane**
**(On whole target, single frame)**

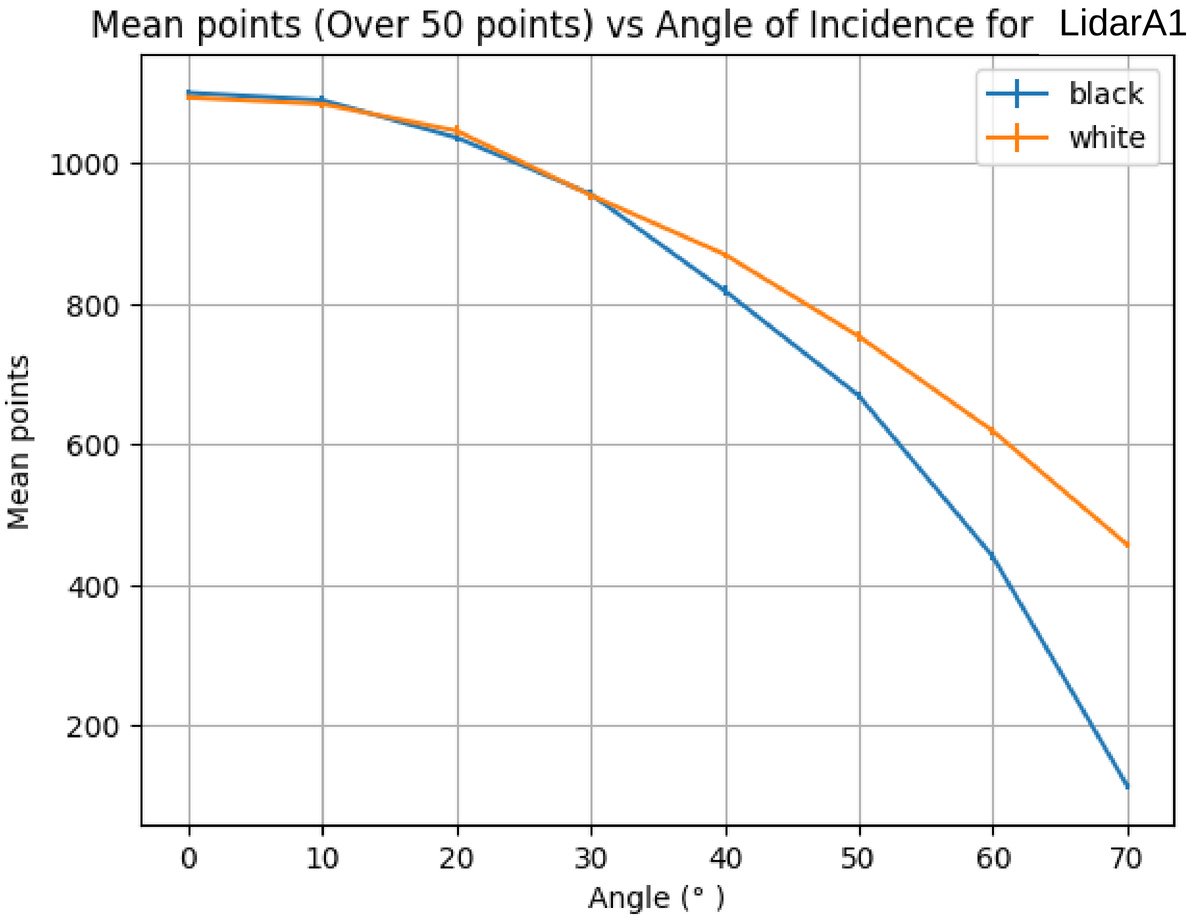


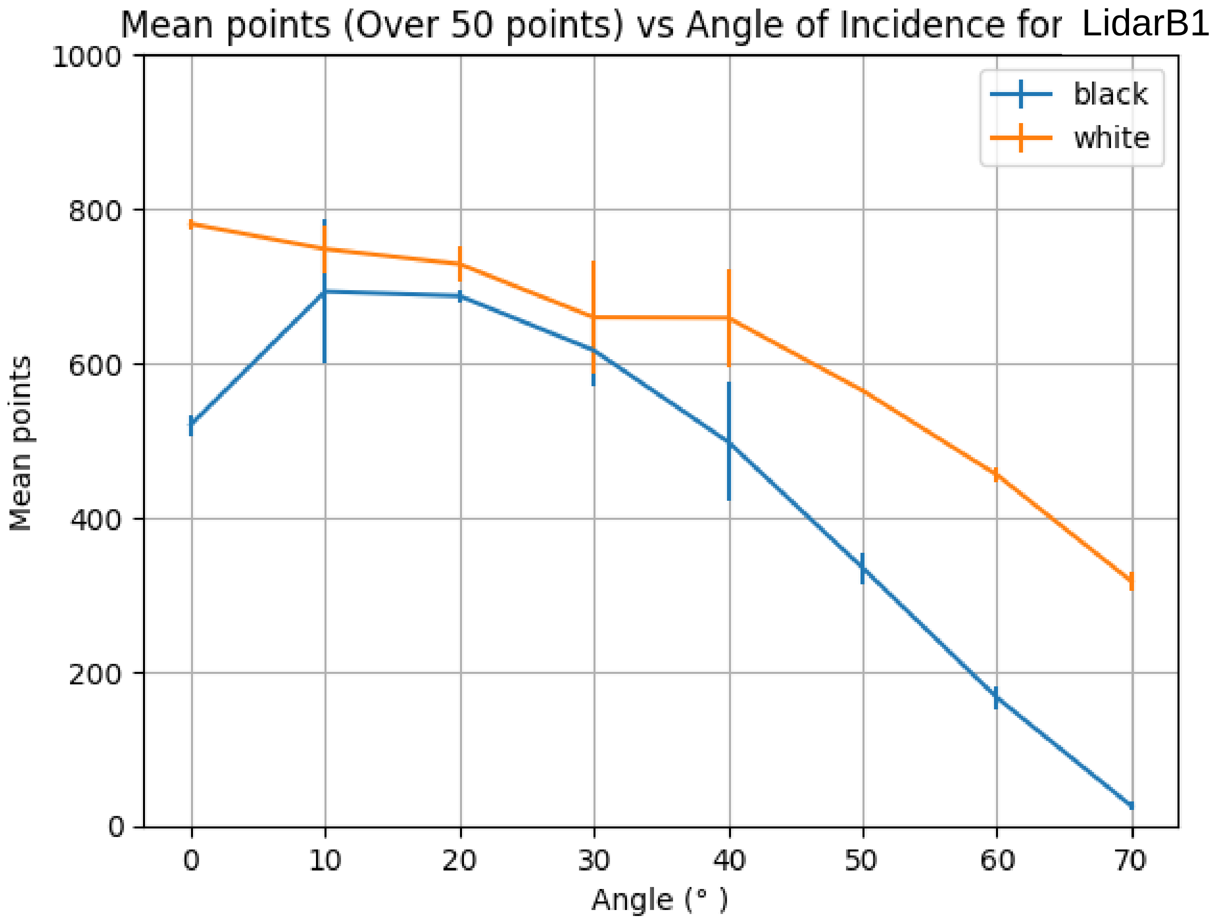



# Effect of retroreflective surfaces on lidar data

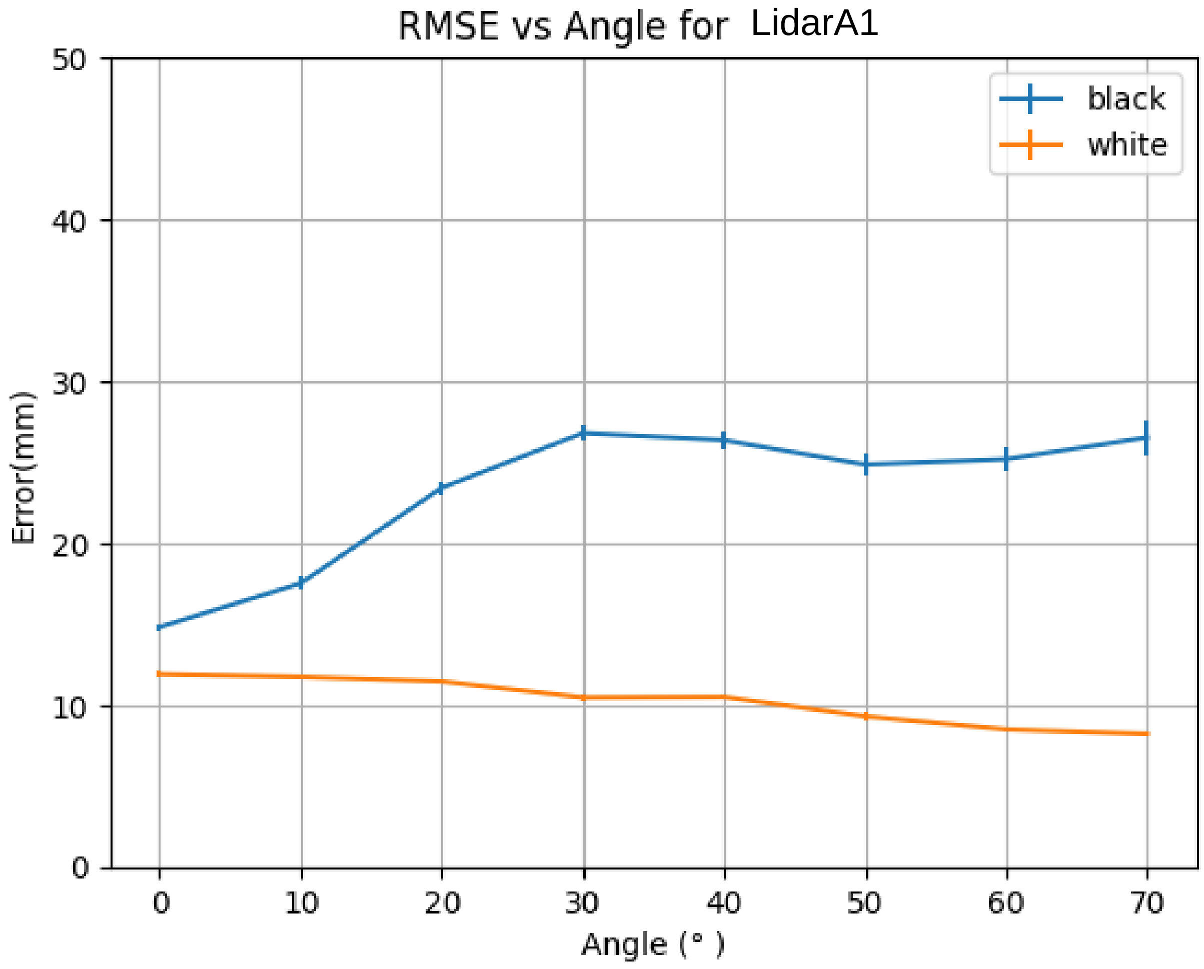


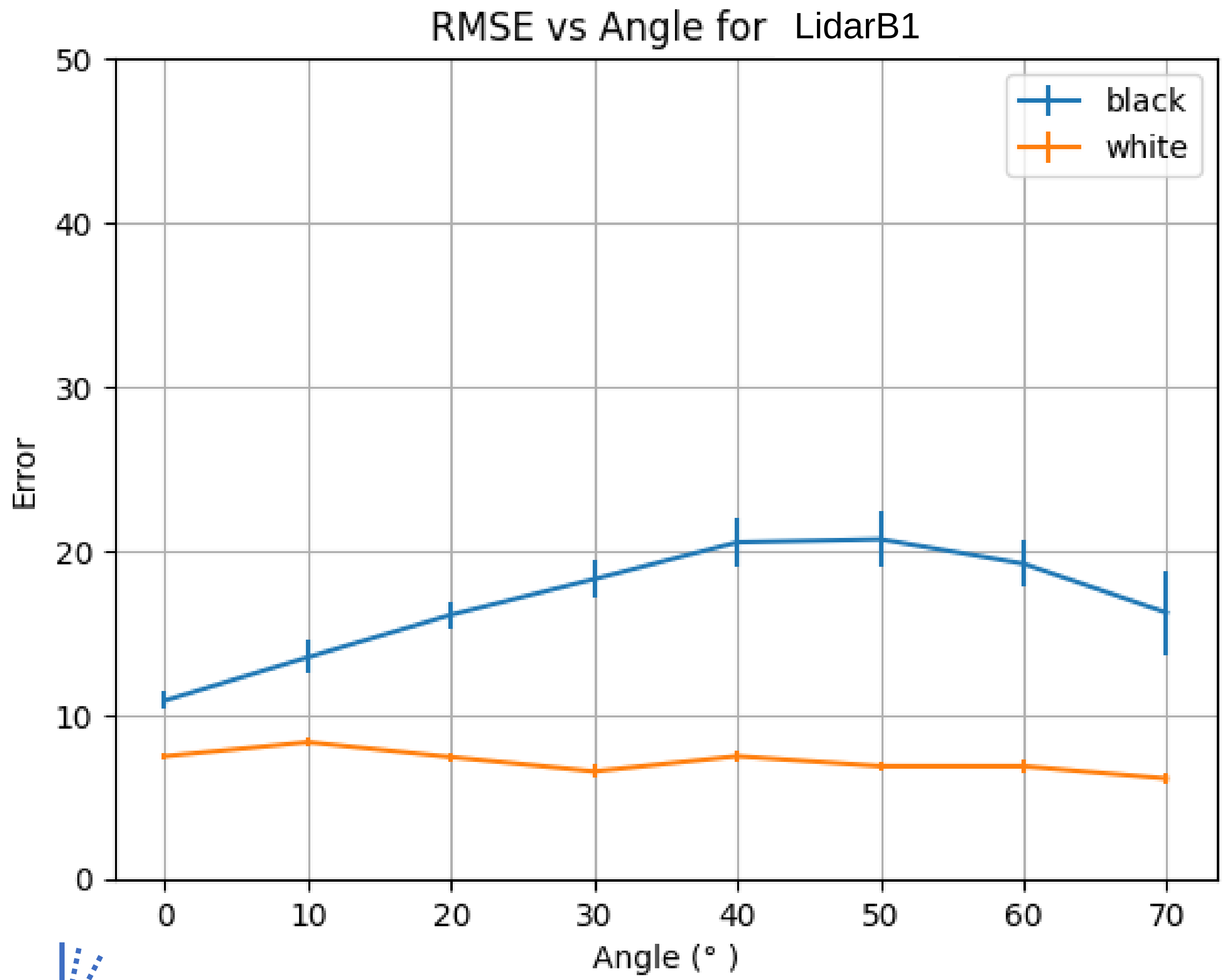
# Target Angle vs # of Points



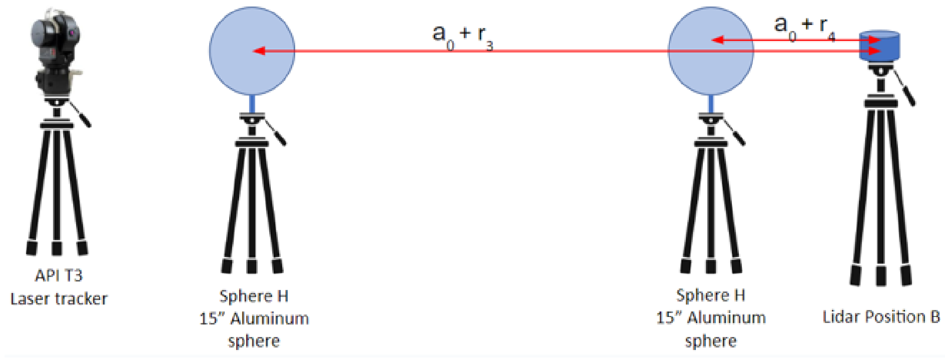




# Target Angle vs Plane fit RMSE

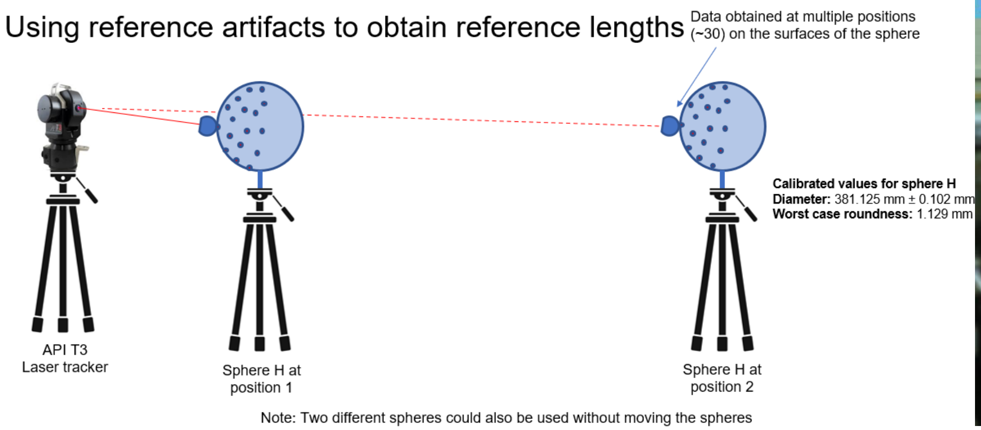


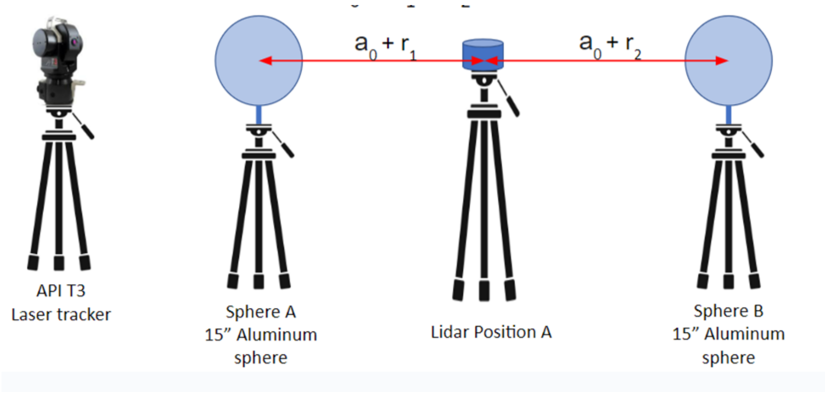

# Test procedures: Length error tests




Exterior length error test







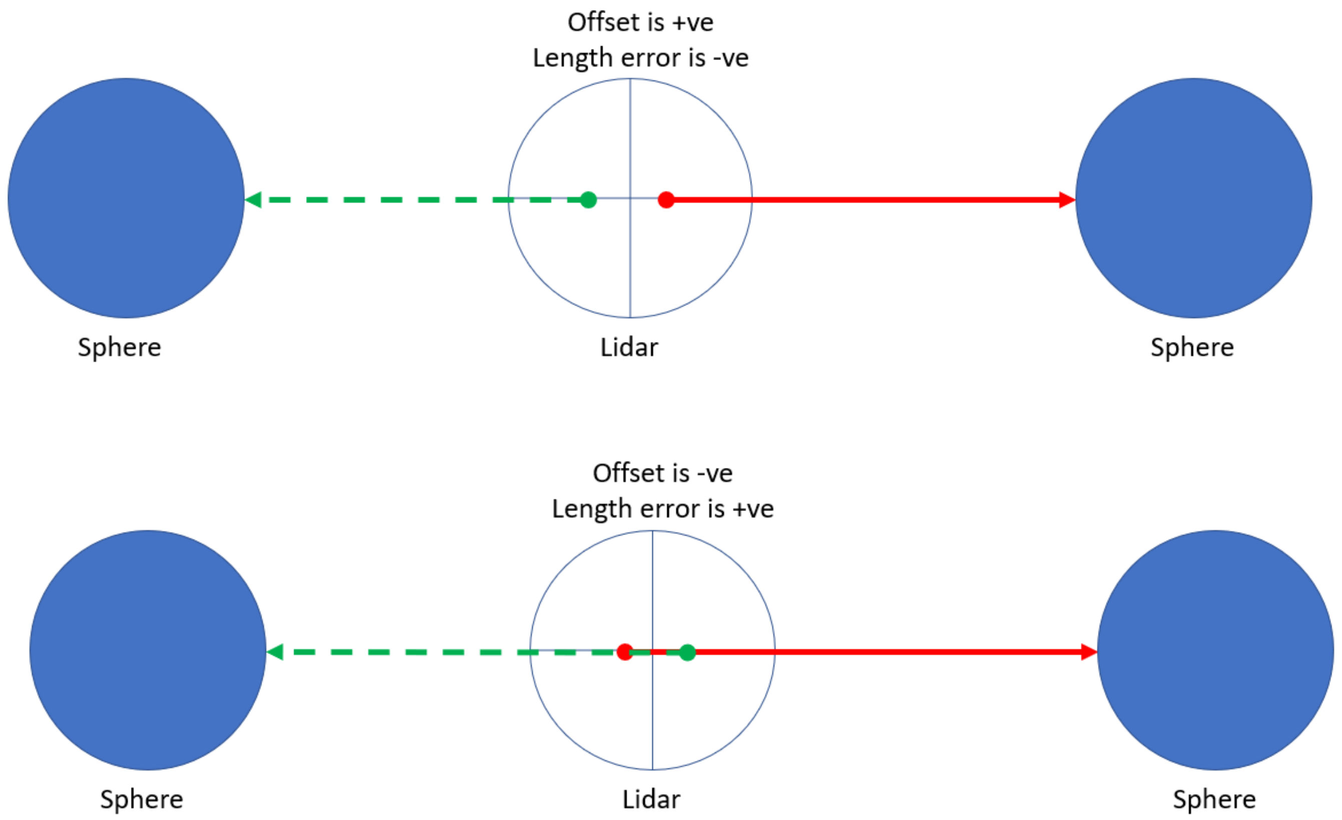

Interior length error test

| Error in mm (Reference length between spheres = 2.3 m) | | | | |
|---|---|---|---|---|
| | Exterior length error (mm) | | Interior length error | |
| | Mean (mm) | Std. (mm) | Mean (mm) | Std. (mm) |
| LidarA1 | 10.23 | 1.16 | 52.1 | 0.42 |
| LidarA2 | 5.27 | 0.58 | 13.5 | 0.38 |
| LidarA3 | 0.42 | 0.89 | 26.9 | 0.87 |
| LidarB1 | 21.9 | 1.78 | -96.2 | 1.27 |

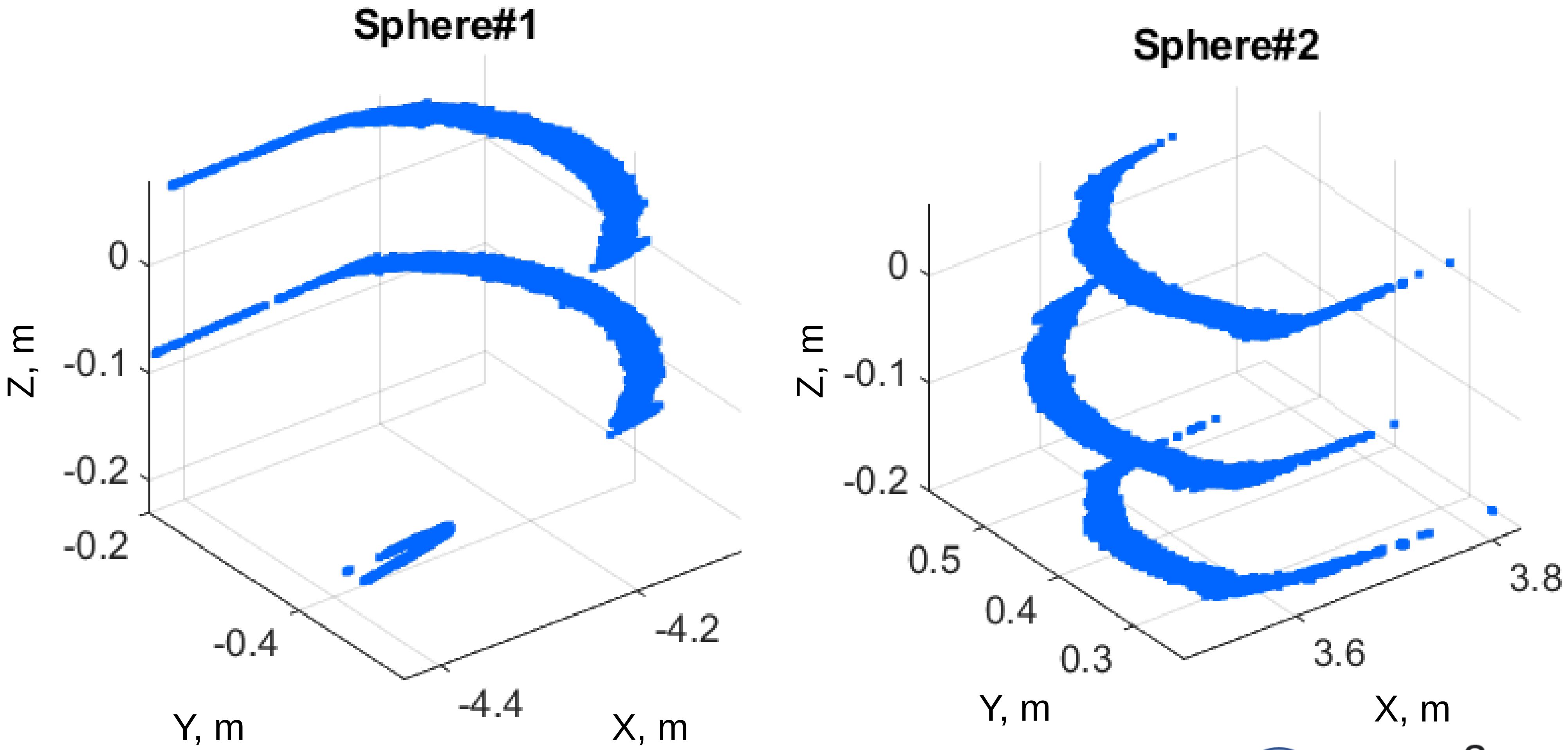
# Possible explanation of the length error in interior tests

- LidarA* exhibited +ve length error.
  - It could be attributed to the –ve offset of the laser origin with respect to lidar’s rotation axis.

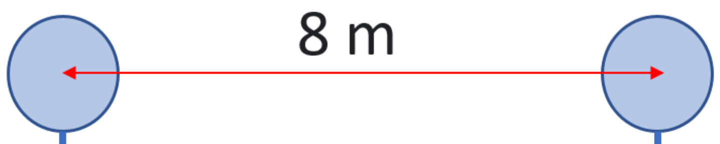
- Similarly, LidarB exhibited -ve length error
  - It could be attributed to the +ve offset of the laser origin with respect to lidar’s rotation axis



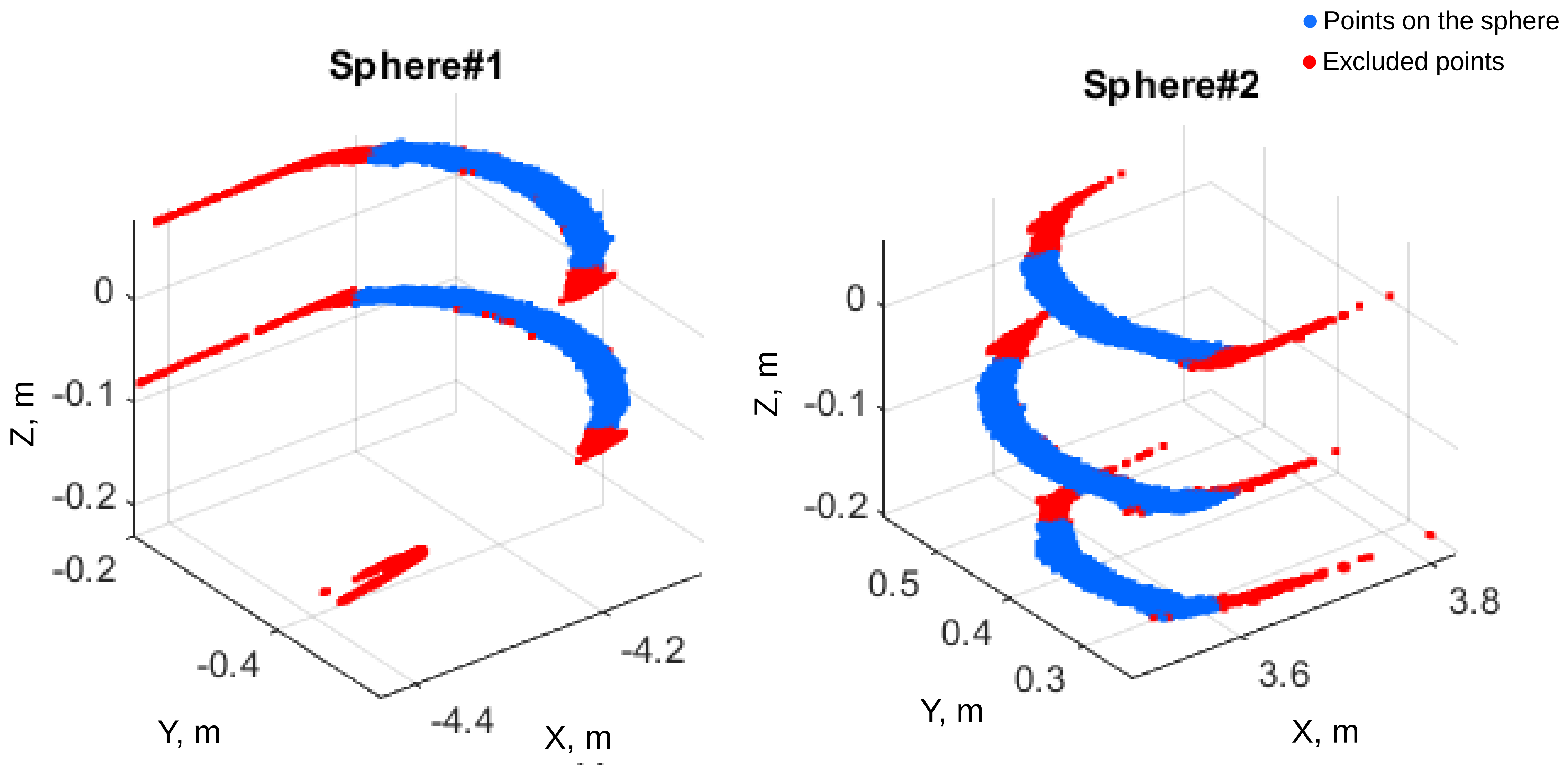
# Sphere segmentation:




Scans from Lidar A1 with spheres at 8m away from the lidar (1182 frames combined)



# Sphere segmentation: NIST/ASTM E57 Algorithm



# Minimum distance test

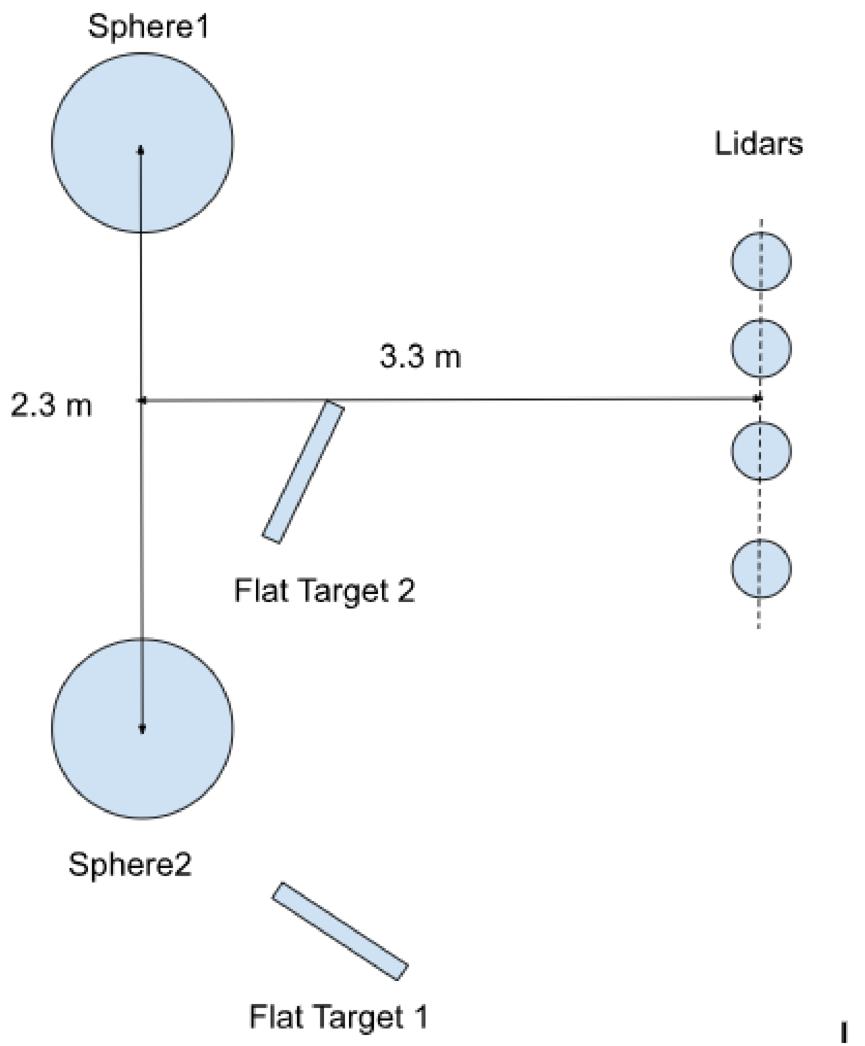
- Minimum distance: Minimum distance at which Lidar scans the target surface.
- Distances are approximate and as reported by lidar.
- Targets were positioned manually away from the lidars until the points appear.

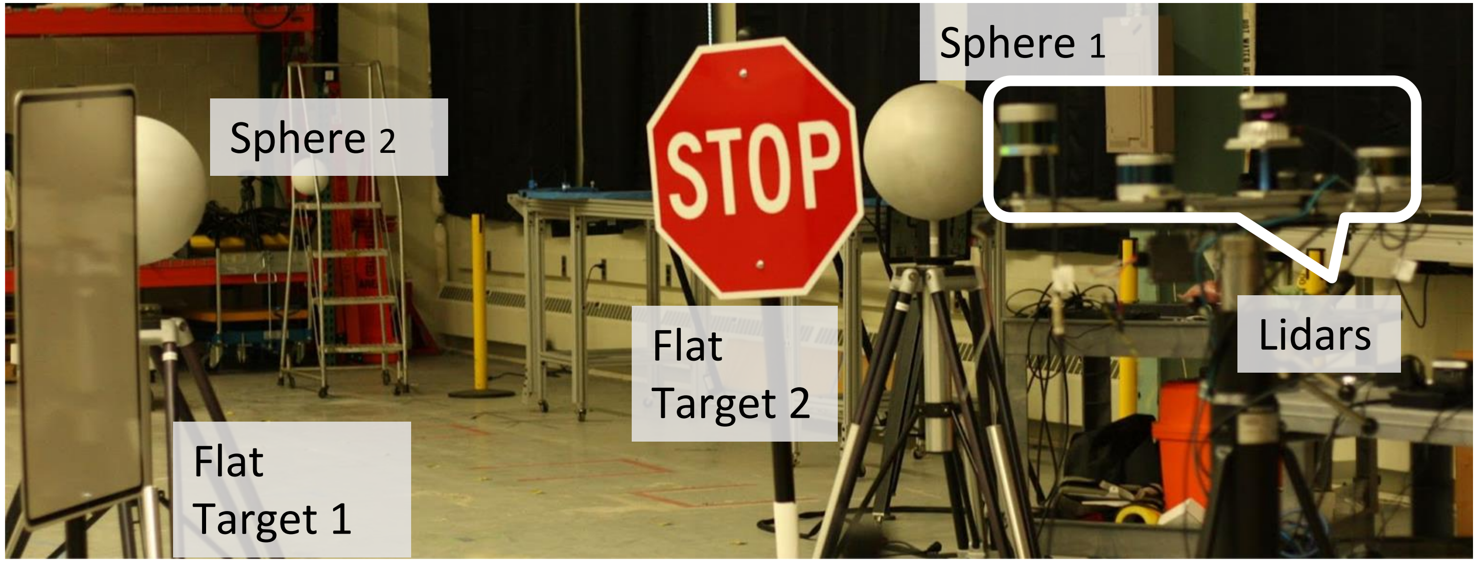
Minimum Distance (m)

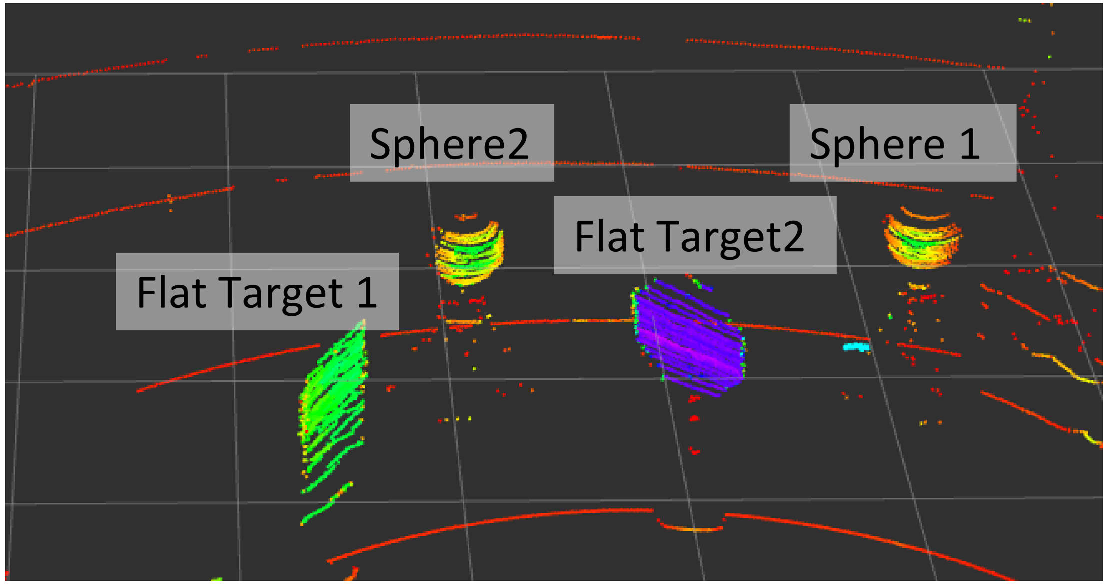
| Sensor/ Target *** | White Kynar Board | Black Kynar Board | 15" Aluminum Sphere |
|---|---|---|---|
| LidarA1 | 0.92 | 0.94 | 0.99 |
| LidarA2 | 0.91 | 0.98 | 0.80 |
| LidarA3 | 0.80 | 0.91 | 0.87 |
| LidarB1 | 0.50 | 0.40** | 0.45 |

* To the outer surface, not lidar-center distance
** Excluding anomaly in black (Missing points on the target surface at certain locations)
*** Kynar Black has a reflectance of 5.9%, Kynar white is at 66.7% and Aluminum sphere is approximately at 55%

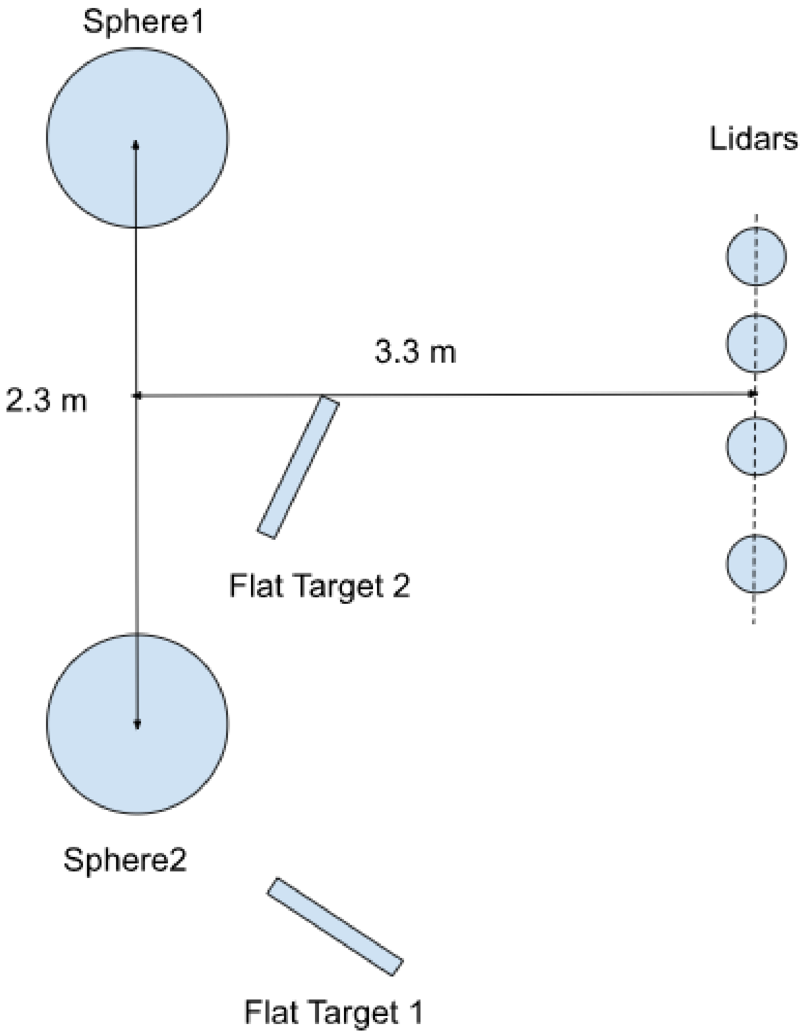
# Multi-lidar calibration

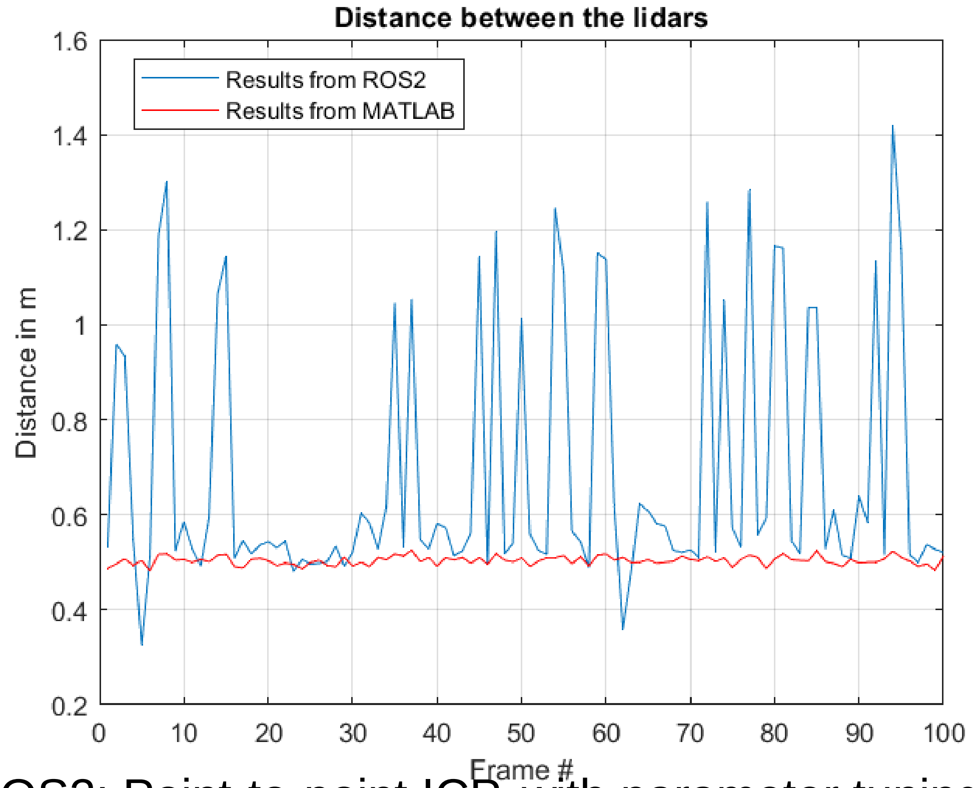


# Multi-lidar calibration



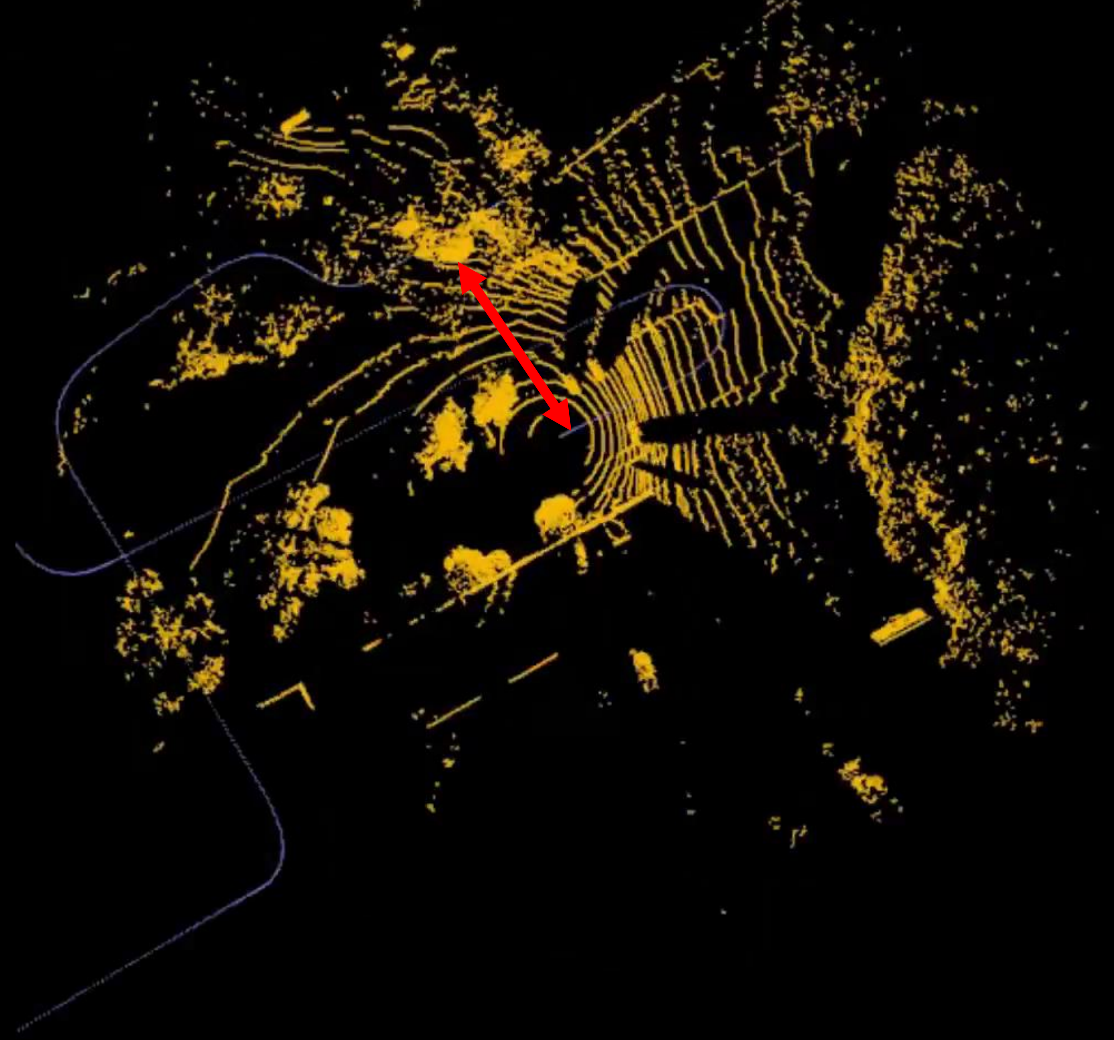

ROS2: Point-to-point ICP, with parameter tuning
MATLAB: Plane-to-plane ICP.

| Length error between the spheres in the merged data | | |
|---|---|---|
| **Sensors** | **Mean Error (mm)** | **Std (mm)** |
| **LidarA1-LidarB1** | **32.48** | **2.94** |
| **LidarA1-LidarA2** | **32.96** | **3.23** |
| **LidarA1-LidarA3** | **46.84** | **6.65** |
| **LidarA1 only*** | **23.59** | **1.74** |

# SLAM using Lidar (KISS-ICP)


# SLAM using Lidar (KISS-ICP)

- ~52 m/170ft offset between the starting and ending location
- Highlights the need for sensor fusion and improved SLAM algorithms

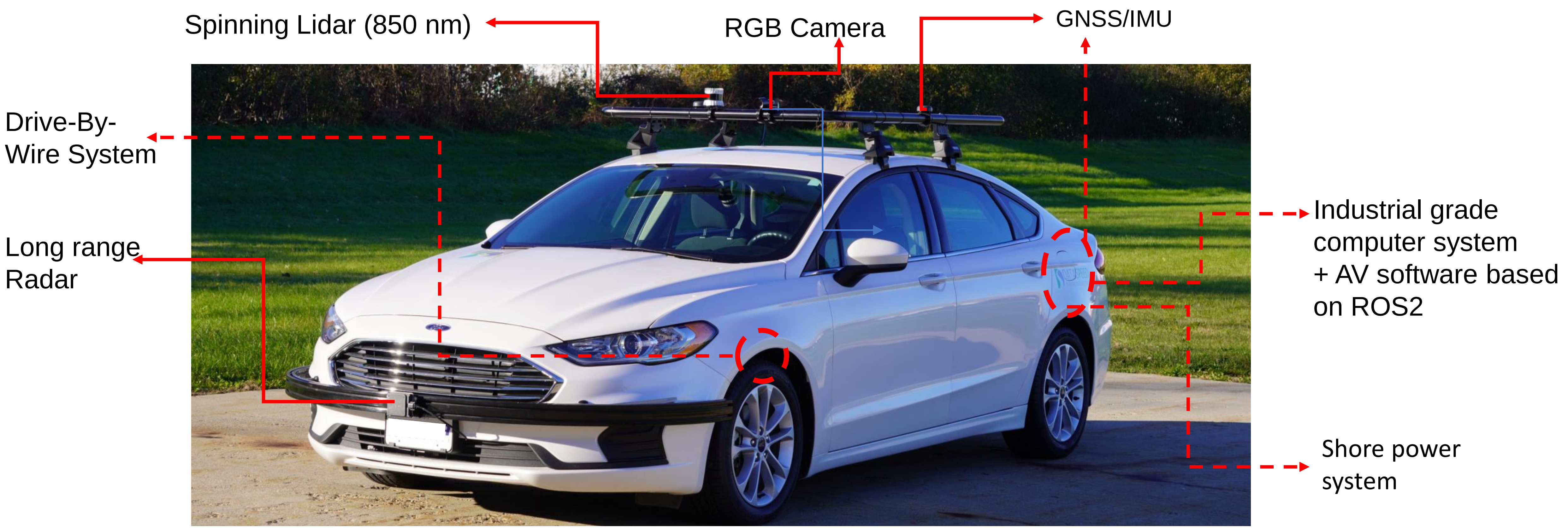


# Overview

NIST

- Problem statement
- Background and feedback from 2022 workshop.
- Focus on AV Lidars
- Technical approach
  - Testbed development
  - Initial results.
- Next steps

# Next steps: AV Development mule (9/15/2023)




Ford Fusion 2020 Hybrid (Image Source: DataspeedInc.com)

**Disclaimer:** Commercial equipment and materials may be identified to specify certain procedures. In no case does such identification imply recommendation or endorsement by the NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

# Future Directions

- Static testing:
  - Expand sensor suite (solid state sensors, cameras) and perform sensor fusion
  - Evaluate range performance of sensors to understand the effect of sensor degradation, distance, color, reflectance
- Dynamic testing*:
  - Evaluate the localization performance of the development mule in cases of
    - Sensor degradation
    - GPS denial
    - GPS without RTK adjustments
    - Alternative SLAM algorithms
- Understanding the sensor and software integration challenges (Kinematic Autonomy Software vs Autoware vs CARMA)
- Initiate and/or participate in benchmarking and standards development

* Contingent upon vehicle delivery timeline and funding

# Acknowledgements

- Abhilash Mane (University of Maryland; NIST/EL Associate)
- Cameron Miller (NIST/PML) – Retroreflection Facility
- Heather Patrick, David Allen & Susana Deustua (NIST/PML)
- Kamel Saidi, Marek Franaszek, Omar Aboul-Enein (NIST/EL)
- Adam Pintar (NIST/ITL)

# Questions?

- Prem.Rachakonda@nist.gov