Solid-state imaging LIDAR for close proximity navigation in the new generation of medium size satellites

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ESTEC, 12/09/2019

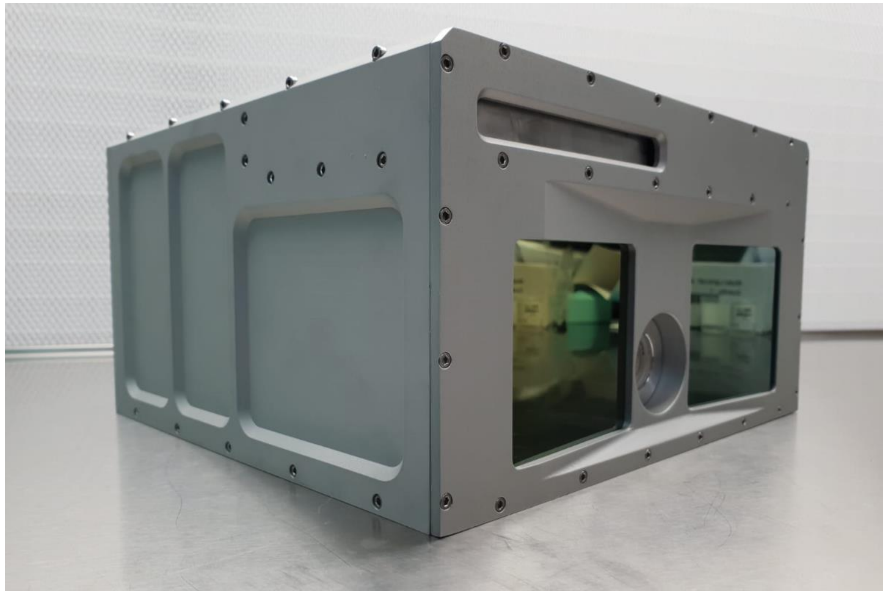
Company overview

- Beamagine was born for commercializing imaging lidar sensors built on proprietary technology awarded by multiple patents granted all over the world.

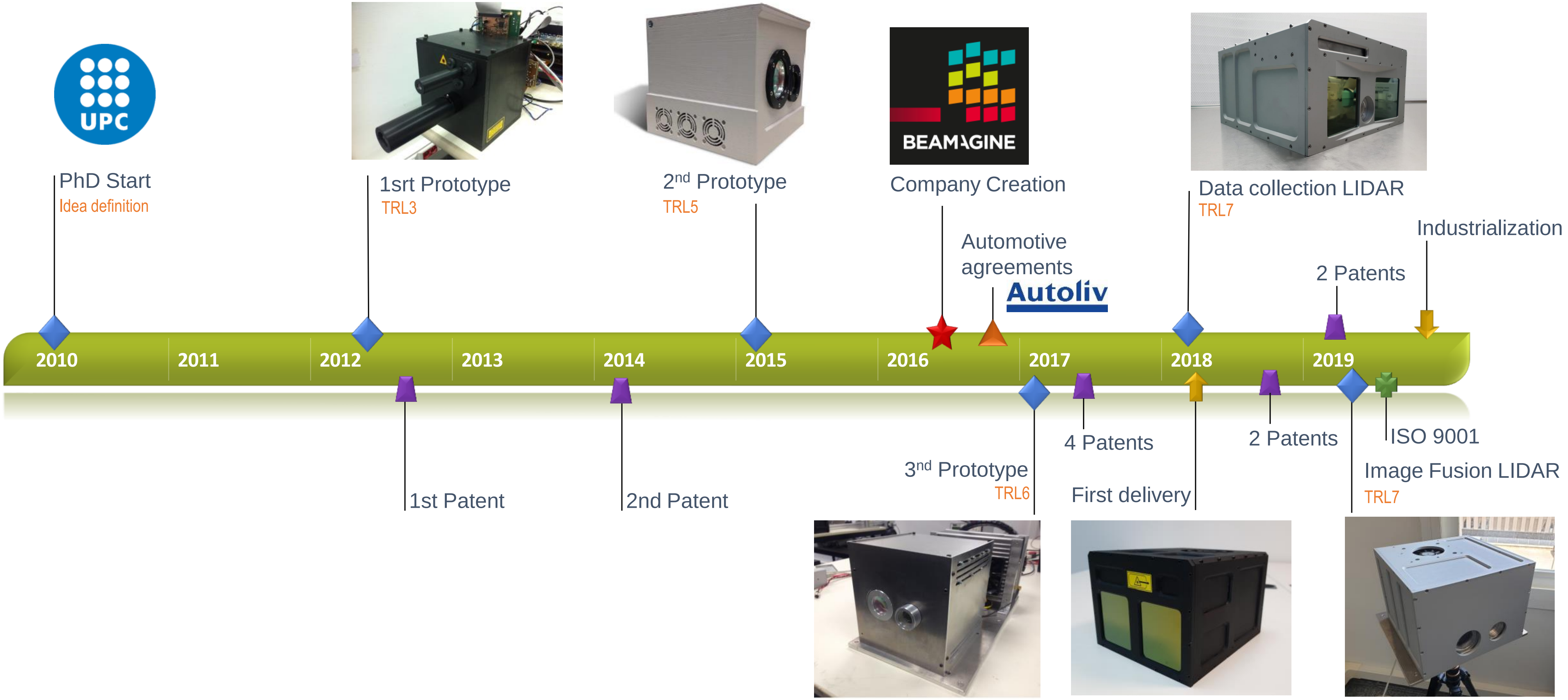
- The company relies in accumulated knowledge in its engineers accumulated in ten years of lidar, optomechanical, electronics and software development.

- Since then we've been developing innovative solutions and imaging lidar sensors to automotive, railway, maritime and space users, always in applications with demanding point cloud density or demand of sensor fusion procedures.

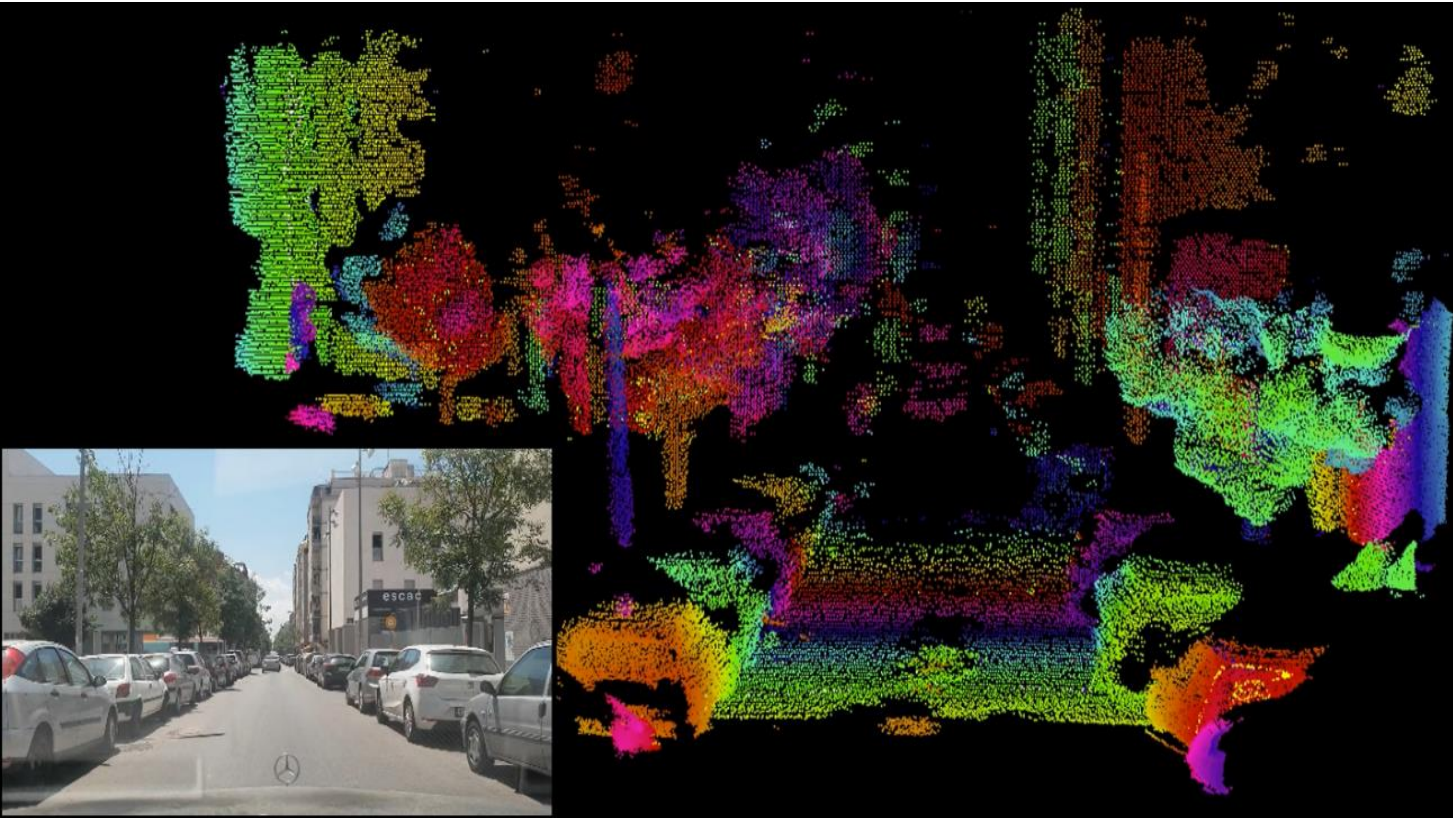
- We develop robust, high performance lidar imaging solutions for sensing applications, in special related to innovative mobility and transport solutions based on autonomous vehicles and robotics.

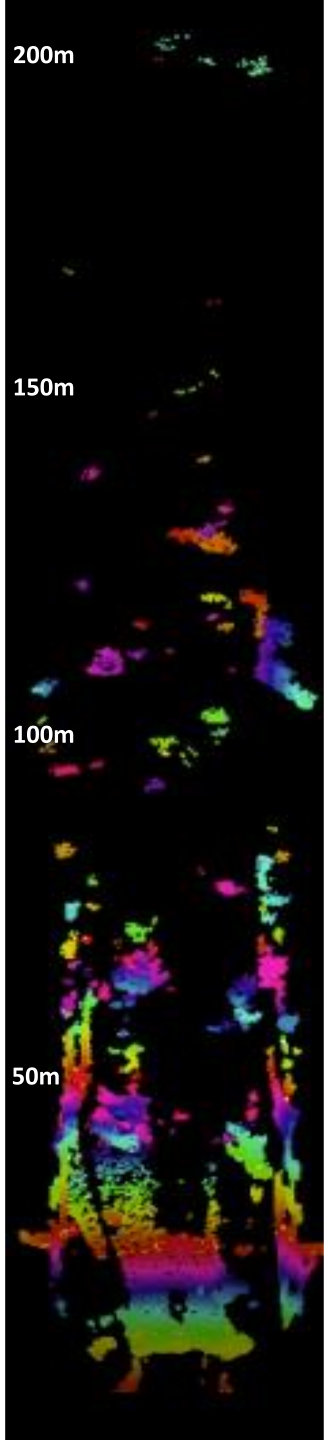


Timeline

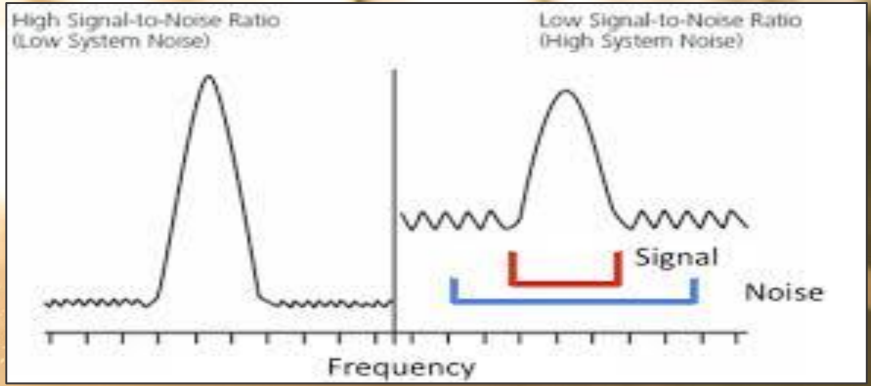

UPC
PhD Start
Idea definition
1srt Prototype
TRL3
2nd Prototype
TRL5
BEAMAGINE
Company Creation
Automotive agreements
Autoliv
Data collection LIDAR
TRL7
Industrialization
2 Patents
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
1st Patent
2nd Patent
3rd Prototype
TRL6
4 Patents
First delivery
2 Patents
ISO 9001
Image Fusion LIDAR
TRL7

High density point clouds and real-time frame rate





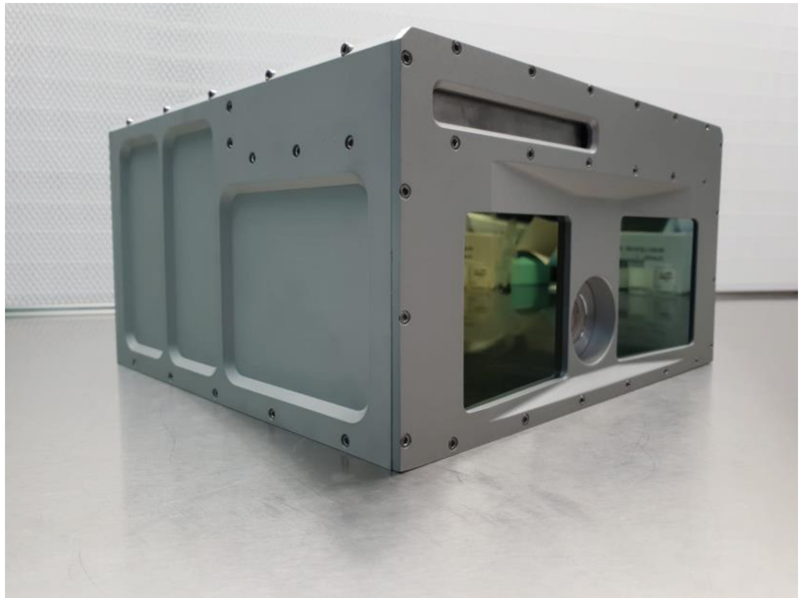
Requirements for a LIDAR sensor in automated vehicles

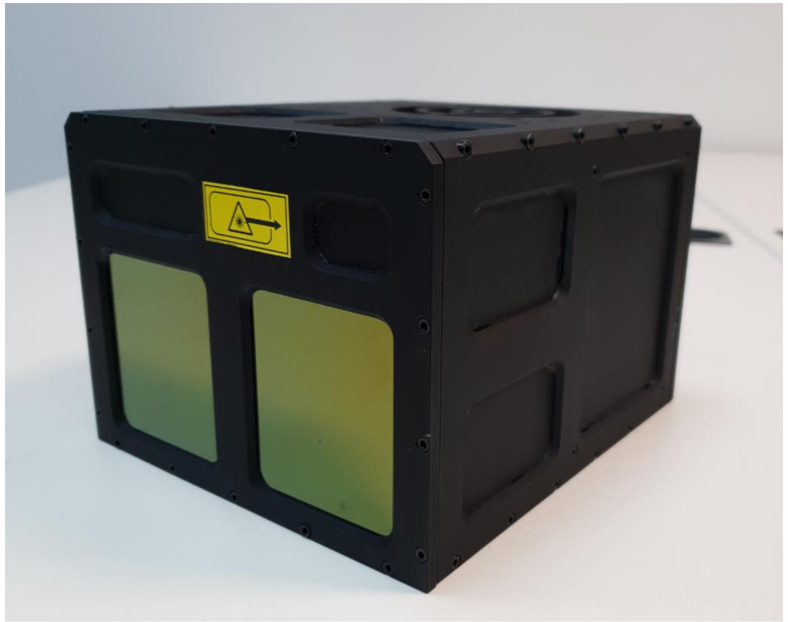


- **Solid-state design with large entrance pupil diameter (long range)**
- **Wide FOV and solar radiation immunity**
- **High resolution real-time vide data**
- **Certifiable according to the application standards**
- **Class 1 eye-safe**

Performance figures

Specifications	VALUES
Electro-optical unit	Full solid state design based in MEMS
Wavelength, Classification	1064nm, Class 1 or 3R selectable by the user
Range	80m @ 10% reflectivity 180m @ 50% reflectivity
Point rate	600 Kpx/s
Image spatial resolution	- 600 x 200px @ 5 frames/s - 500 x 150px @ 10 frames/s
Field-of-view (HxV)	60 x 20º
Angular resolution	- 0,1º in both horizontal and vertical - 0,15º horizontal, 0,13º vertical
Range accuracy	±0,7 cm @ 10m ±1,5 cm @ 25m
Inertial sensor	Included
Mechanical	
Size (WxDxH)	26 x 23 x 13 cm
Weight	3Kg
Electrical	
Power consumption	15W
Supply voltage	12 VDC
Interfaces	UDP Ethernet packets
Software	
Integration	ROS driver for Linux L3CAM library for Windows
Test application	RVIZ and Beamagine Visualizer

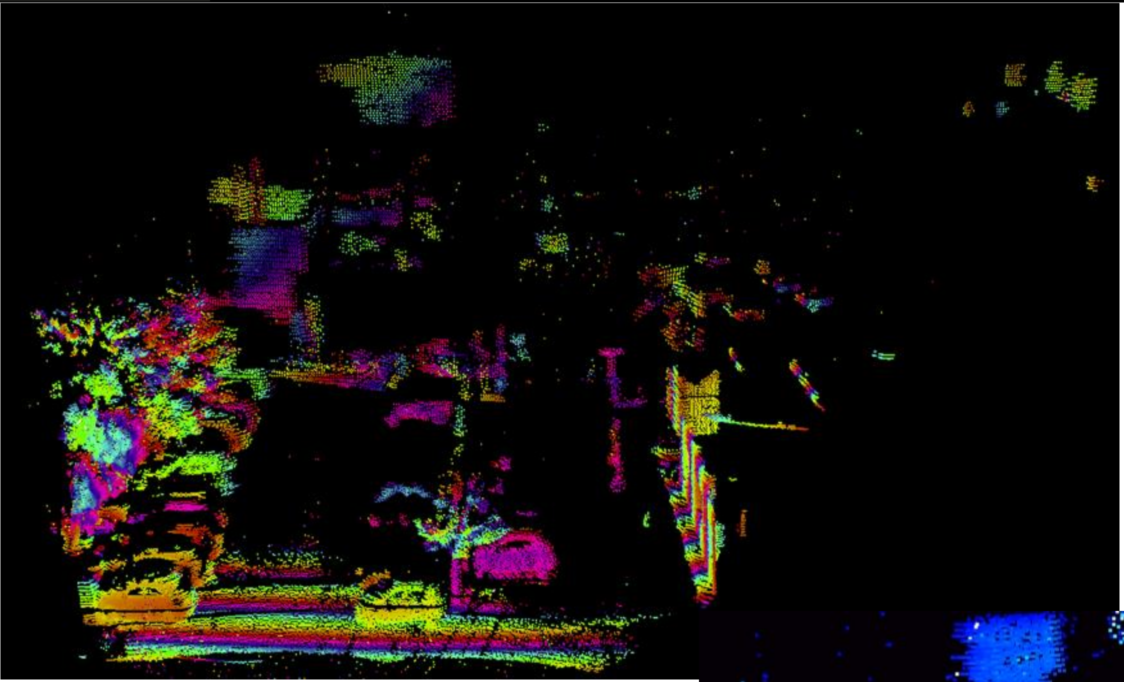




Performance test

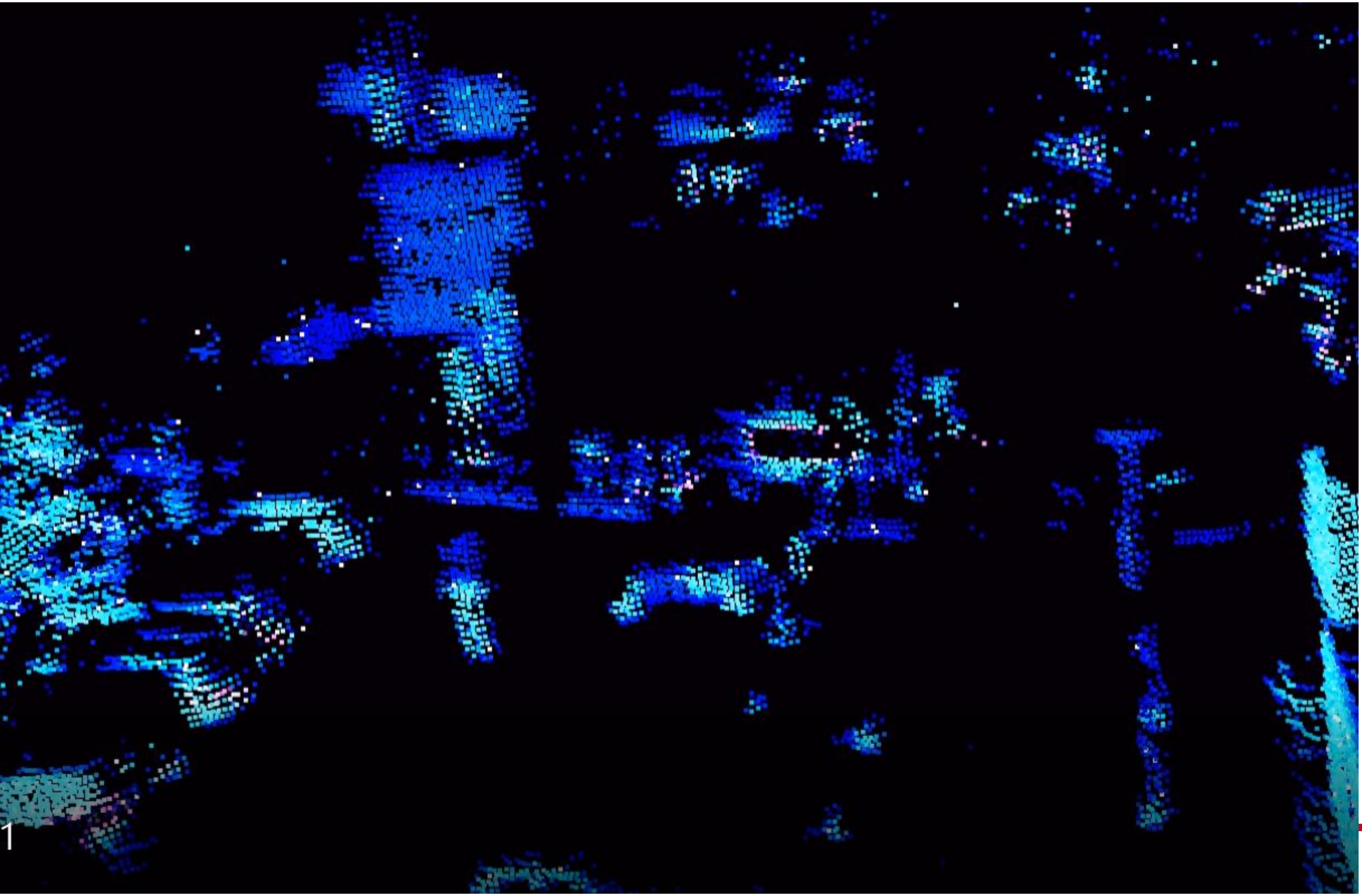
- Double reflectivity target (10%-75%)
- Tests up to 80m (Google Maps) 10% reflectivity
- Range and Intensity images obtained
- Some objects (buildings) visible at 200m

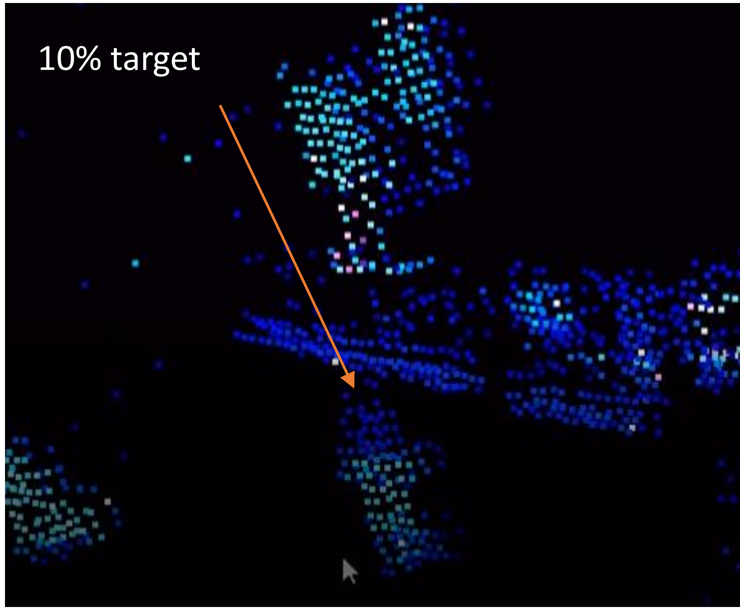
Range and intensity mode point-cloud

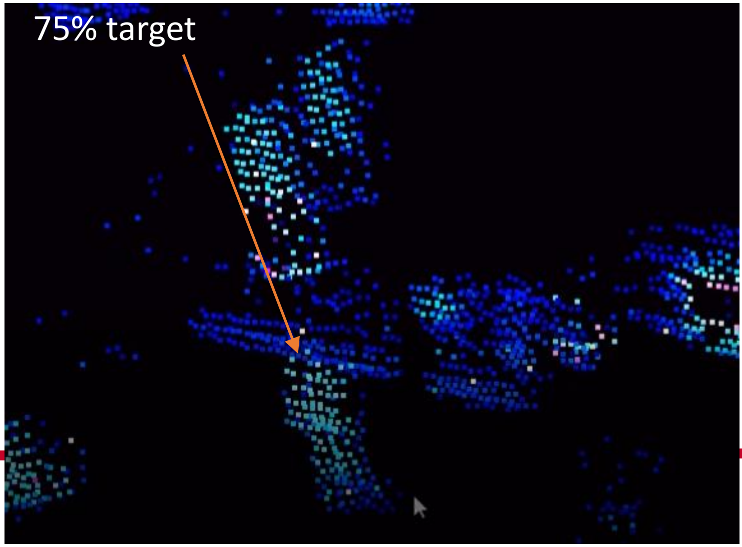


Raw data, no filtering applied

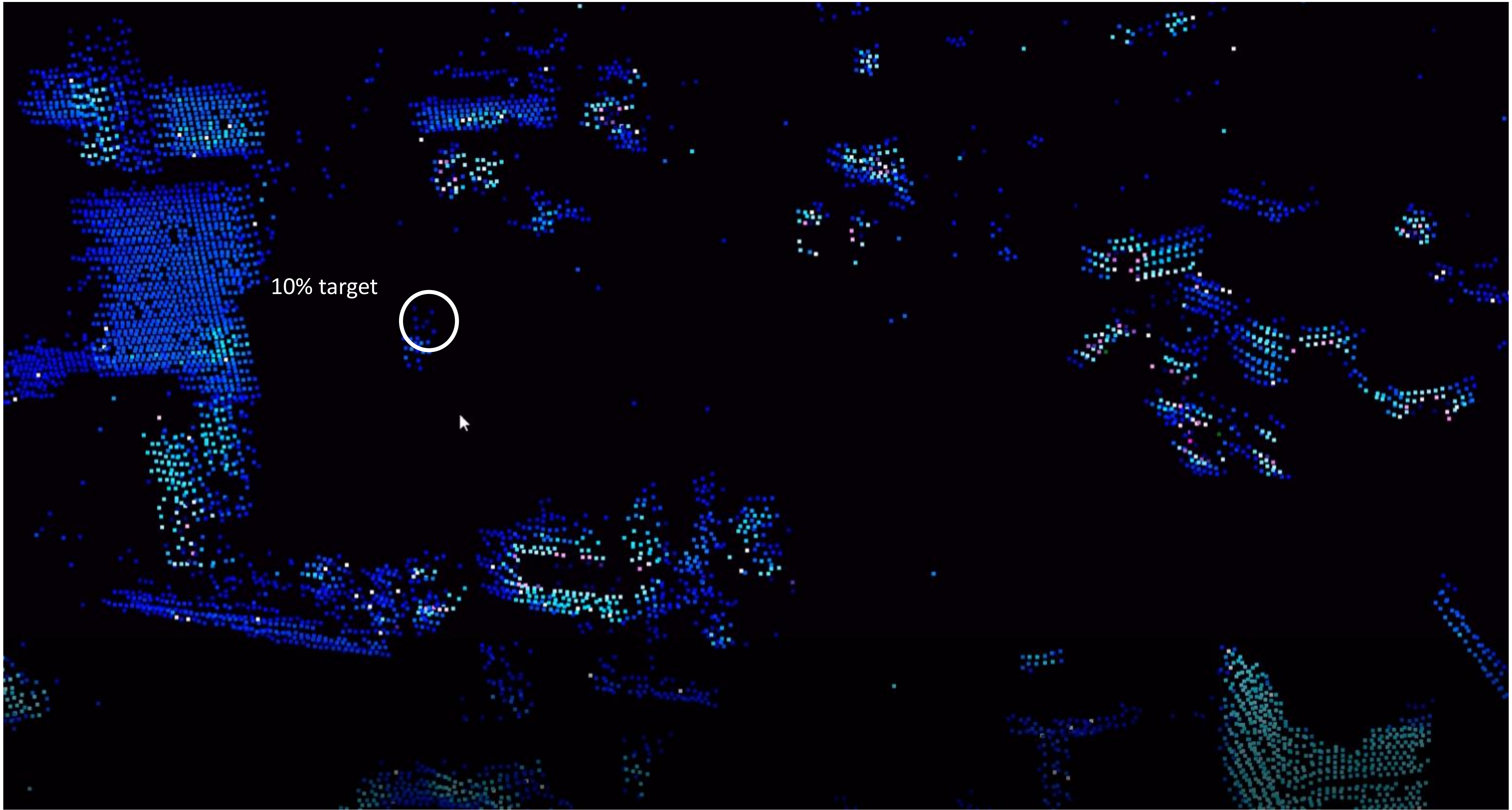
Performance test: 50m @ 10% reflectance



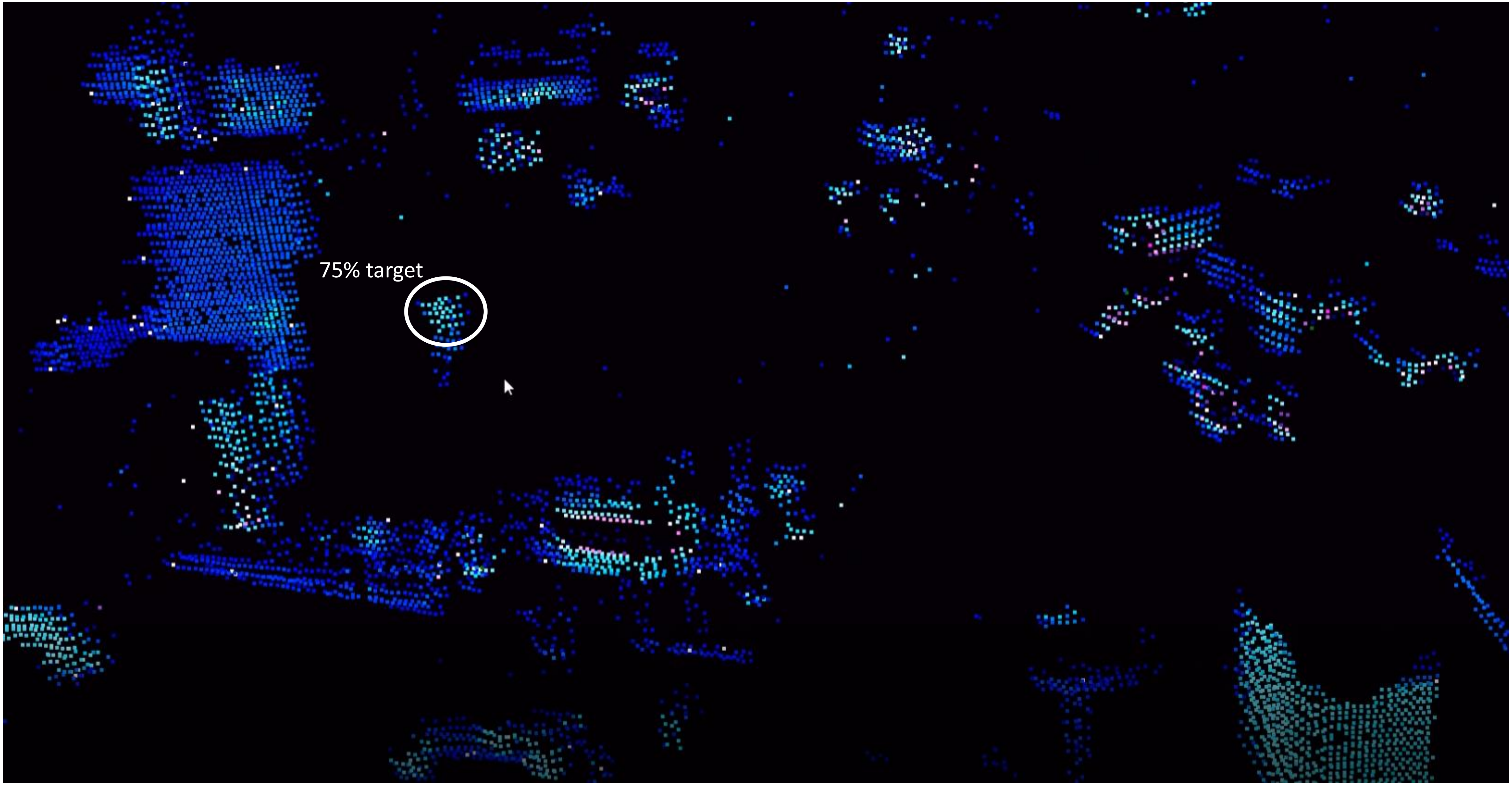




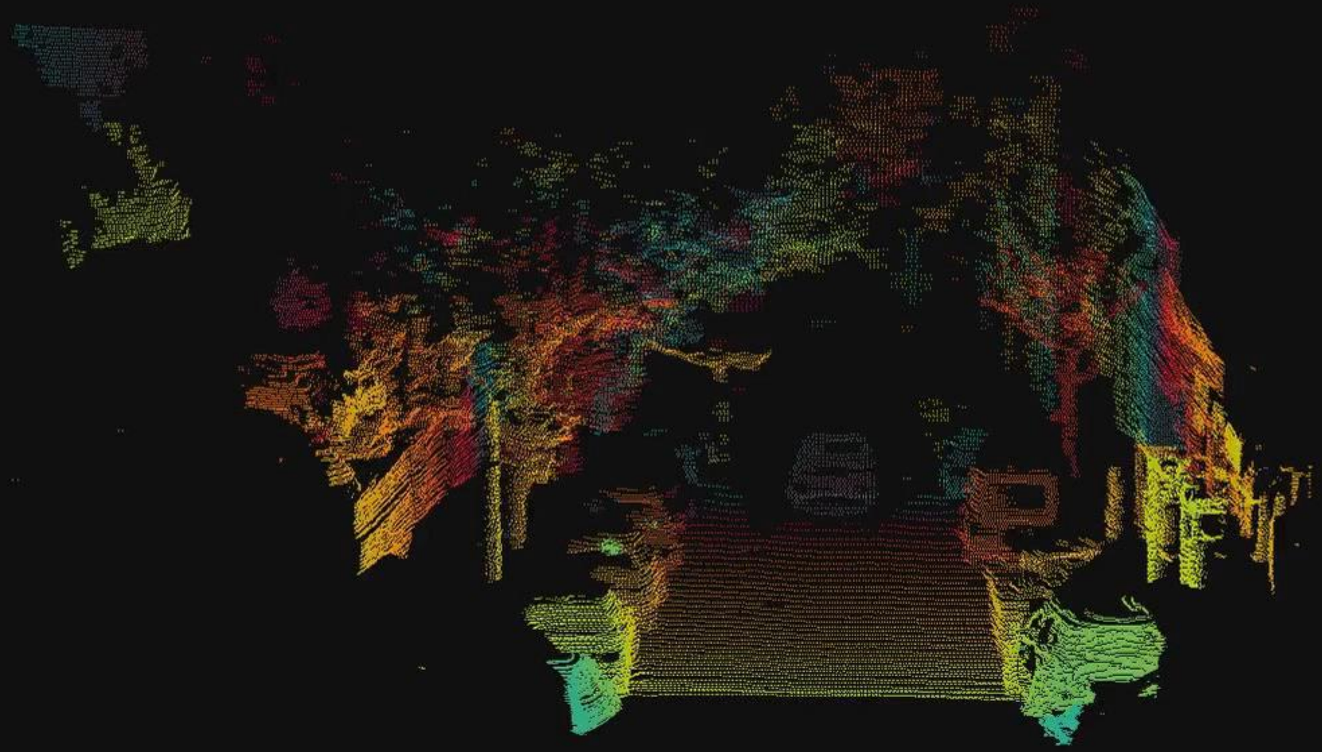
Performance test: 80m @ 10% reflectance



Performance test: 80m @ 10% reflectance

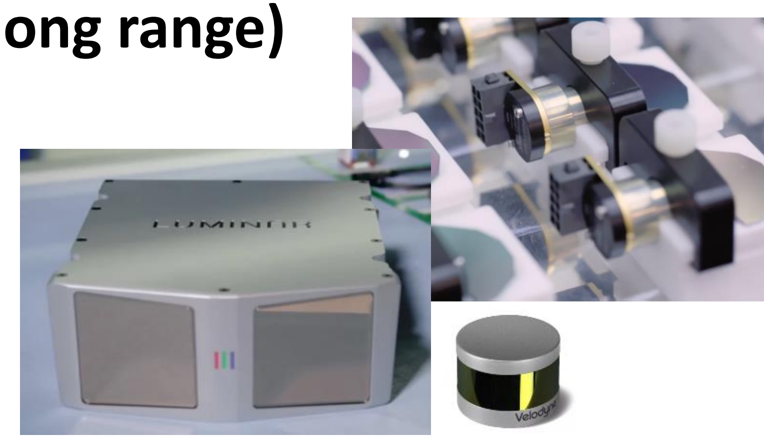


Sample video

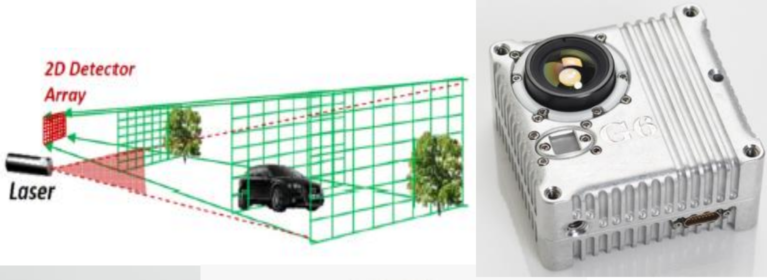


Most distinctive features of the Beamagine LIDAR

1) SOLID-STATE DESIGN WITH LARGE ENTRANCE PUPIL DIAMETER (long range)

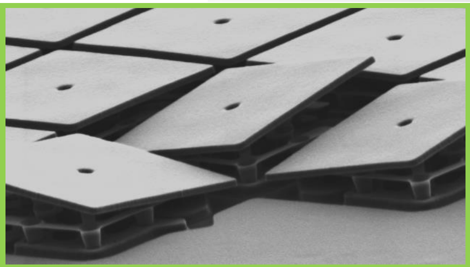


- **Mechanical Scanning**
  - Most of the current imaging LIDAR devices contains macro moving elements like spinning mirrors, galvanometric scanners or rotating heads. Moving parts usually are not a problem in a car, but the ones contained in an imaging LIDAR are **high precision optical elements** that can be sensitive to shock, temperature and vibration. The LIDAR functioning depends directly of the robustness/stability of such elements. High precision optomechanical elements may not be reliable at mid/long term installed on a vehicle.



- **Flash**
  - Elegant solution (solid-state also) but impractical for mid/long range detection because the laser energy is spread over a large area. Low image spatial resolution.

- **MEMS based scanning**
  - Good balance between laser energy efficiency and solid-state solution. Limitations related to the mirror aperture (~2mm) that limits the achievable range



- **Beamagine solid-state scanning**
  - Combines the advantages of a solid-state scanning based on MEMS with a large entrance pupil diameter thanks to a patented double MEMS approach (slide 6). A large entrance pupil enables long range detection within eye-safe power levels.

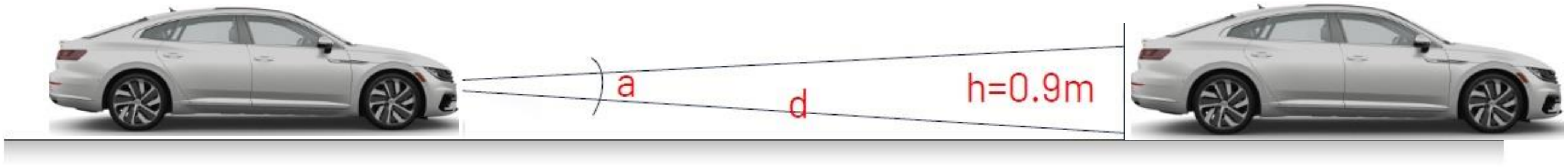
2) DRIVABLE SPACE DETECTION

Range and resolution requirements are connected:

- Range determine how fast you can drive
- Resolution determine how small objects can be classified.
- Range without resolution is not enough.

  - Example: Velodyne HDL-64 S3 (64 channels):
    - Measurement range: up to 120m
    - Vertical FOV (Y-axis): 26.9º -> Vertical angular resolution: 0.42º
    - It gives h=120*rad(0.4) = 0.9m

  - Then: Max 2 spots on the height of a tall vehicle (SUV). Probably not enough for classification of a vehicle at measurement range. Not enough for smaller objects.

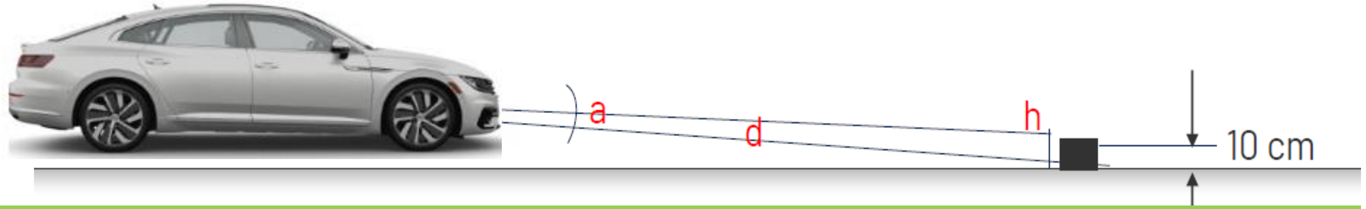


Most distinctive features of the Beamagine LIDAR

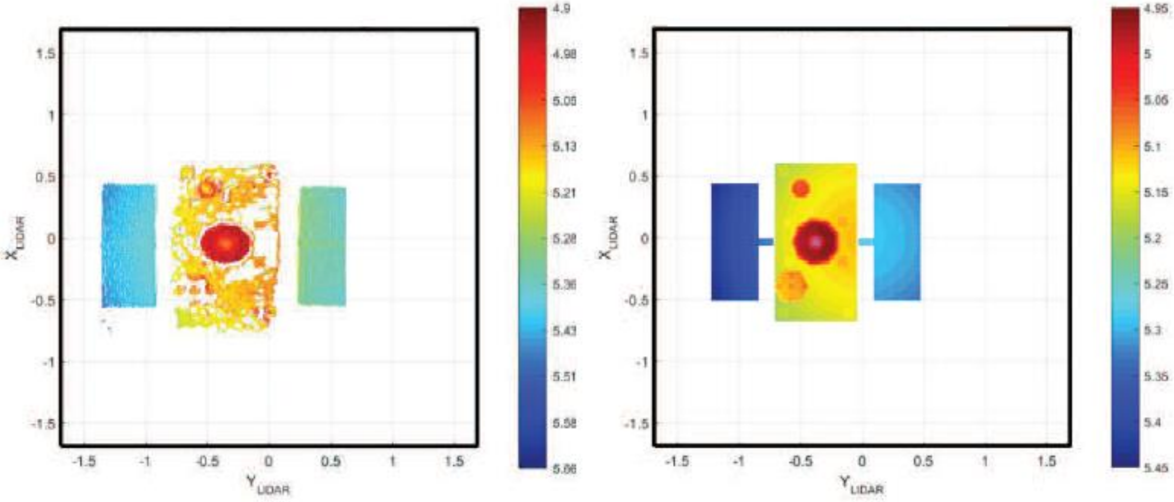
2) DRIVABLE SPACE DETECTION

ROAD DEBRIS USE CASE:
Systems mounted in fast-driving cars need to “see” a minimum of 150 meters forward, and detect small objects down to 10cm in height. Translated to resolution requirements:

- Range: 150m
- Vertical **minimum** resolution given by road obstacle: 0.1m
- Then Minimum vertical angular resolution: 0.038º
- Vertical FOV assuming 128 vertical points:
    - vFOV = 128 * 0.038 = 4.9º
    - Vertical FOV < 5º is not enough for various amount of cargo in vehicle or driving in hilly streets



The Beamagine LIDAR provides good resolution not only in horizontal axis, but also in vertical axis. Depending on the OEM specs, it can be customized to achieve an angular resolution down to 0.05º. This ensures the capability to detect low height object that the vehicle can’t override.



BEAMAGINE

Most distinctive features of the Beamagine LIDAR

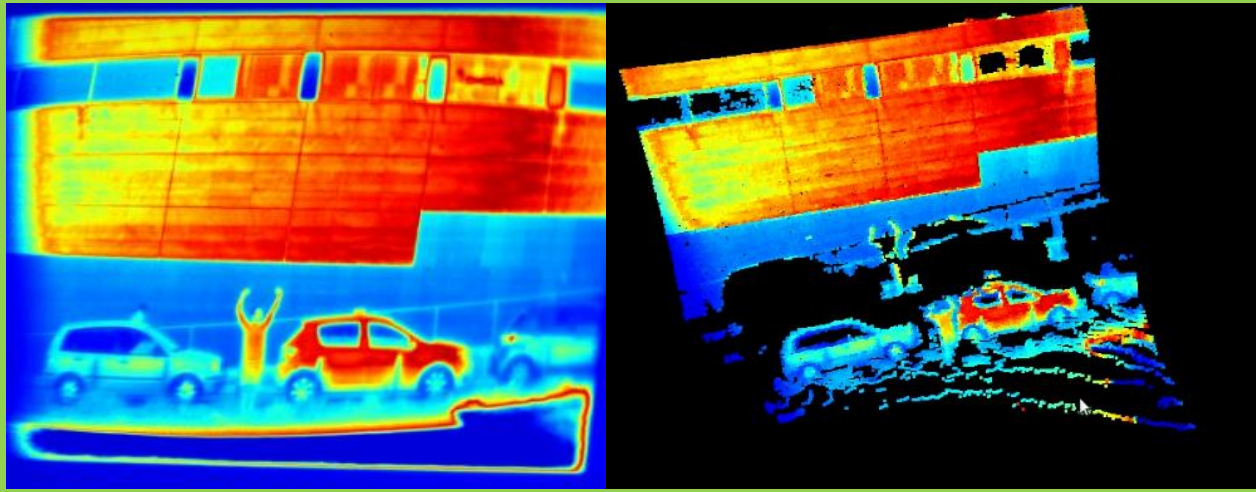
3) AUTOMATIC DATA FUSION: 2D + 3D

PROBLEM: When different sensors (LIDARs and cameras) are placed on a vehicle in a detached basis, parallax errors in the image fusion appears due to:

- Sensors are placed in different locations on the vehicle
- Different FOVs
- Different frame-rates
- Relative misalignments between sensors occurred after the calibration process

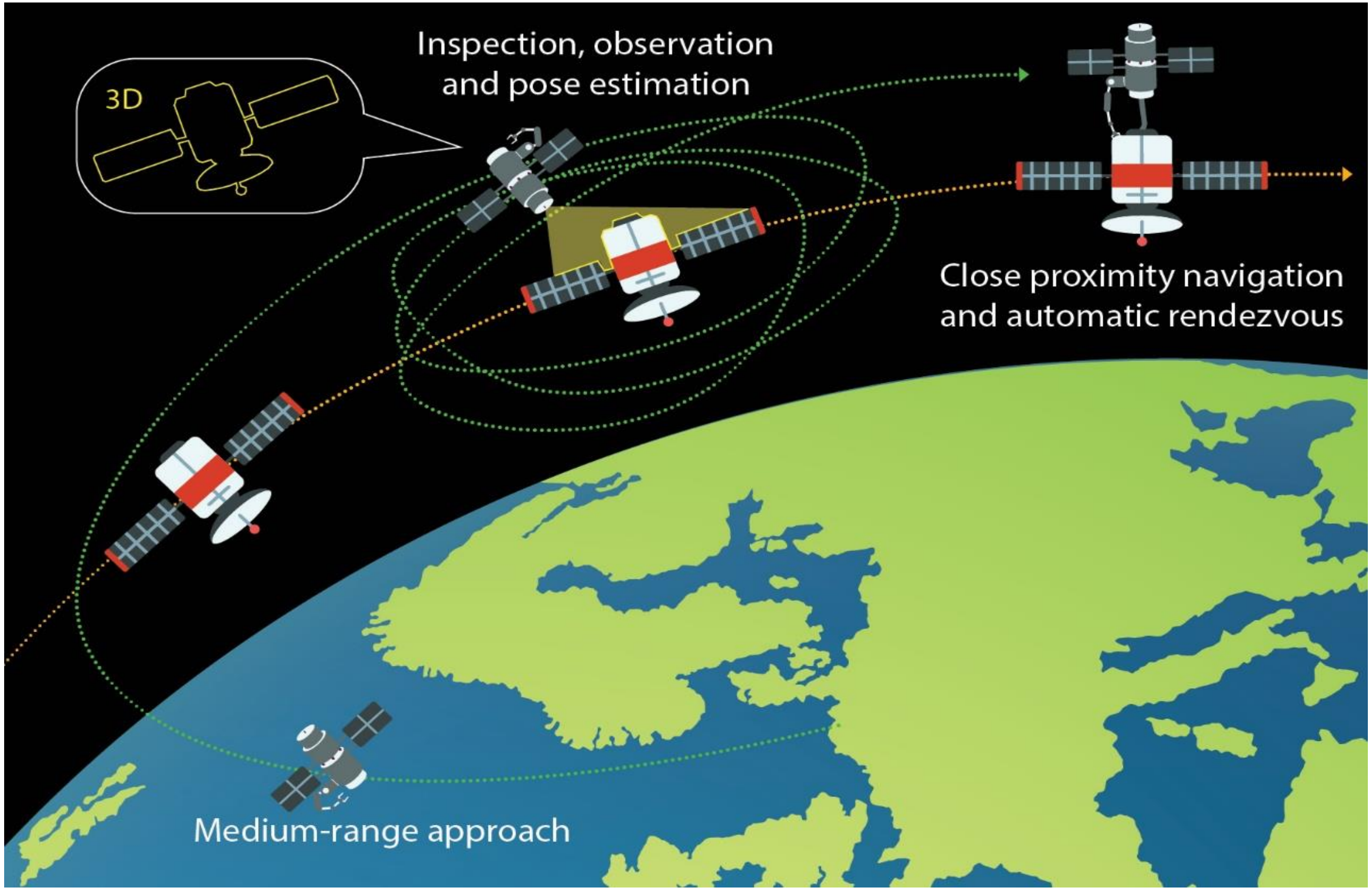
Traditional solutions like transforming the lidar points into camera images don't avoid the parallax misalignments.

Beamagine technology enables a unique feature: a self-registered 3D lidar image with another 2D imaging mode (**RGB, NIR, SWIR, polarimetric, hyperspectral and even thermal**). This is enabled by a patented technique that collects both imaging modes through the same optical system which enables a hardware based automatic registration that **avoids complex data fusion algorithms and parallax error at all distances, even in the smallest cross-section objects at far distances**. In addition, as long as both lidar and camera share position and optical system, it makes the the system immune to misalignments generated by chassis deformation along the time.



Sample video

Use cases in New Space



- <u>Orbital robotics</u>
  - *Satellite docking and rendezvous*
  - *Spaceborn close proximity navigation*
  - *Satellite pose estimation*
  - *Space debris removal*
  - Refueling missions

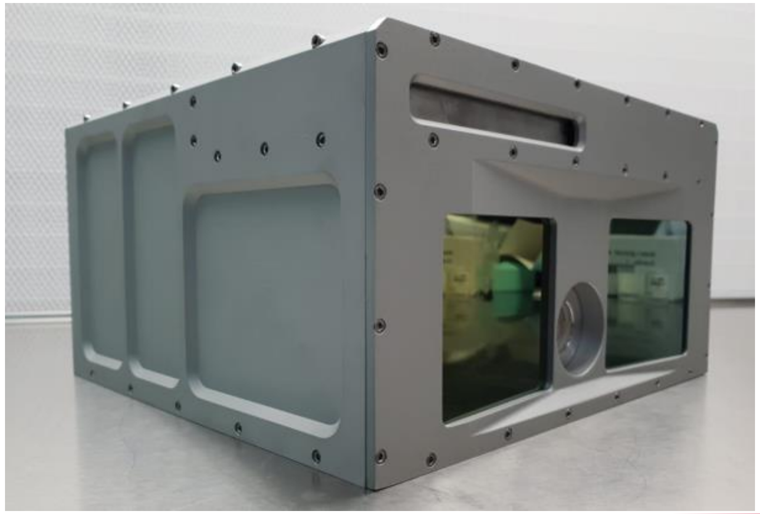
- <u>Planetary exploration</u>
  - *Rover navigation*
    - *Path planning*
    - *Terrain assessment*
    - *Obstacle detection & avoidance*
    - *Self-guiding*
  - *Terrain mapping landing aid*

Performance at the orbital environment

OPTICAL AND IMAGING PERFORMANCE

Field-of-view	50x50º
Image resolution	350x350 px
Frame rate	5 Hz
Point rate	612,5 Kpx/s
Angular resolution (x-y)	0.14 - 0.14º
Angular sampling accuracy	<0.01º
Range resolution	±1 cm
# of returns	4

- Sun Simulator: Arrimax 18/12 kW, 1400 W/m^2, 5778 ºK
- Halogen lamp 5 kW: 580 W/m^2, 3000 ºK



Class 1 – Full eye-safe

Irradiance (W/m^2)	Range @ 80% refl. (m)	Range @ 50% refl. (m)	Range @ 10% refl. (m)
No sun simulator	112	89	40
580 – Indirect	85	68	30
1400 – Indirect	78	61	27
580 – Direct	18	15	7
1400 – Direct	16	13	6

Class 3R

Irradiance (W/m^2)	Range @ 80% refl. (m)	Range @ 50% refl. (m)	Range @ 10% refl. (m)
No sun simulator	327	258	115
580 – Indirect	191	151	68
1400 – Indirect	174	137	61
580 – Direct	41	33	15
1400 – Direct	37	29	13

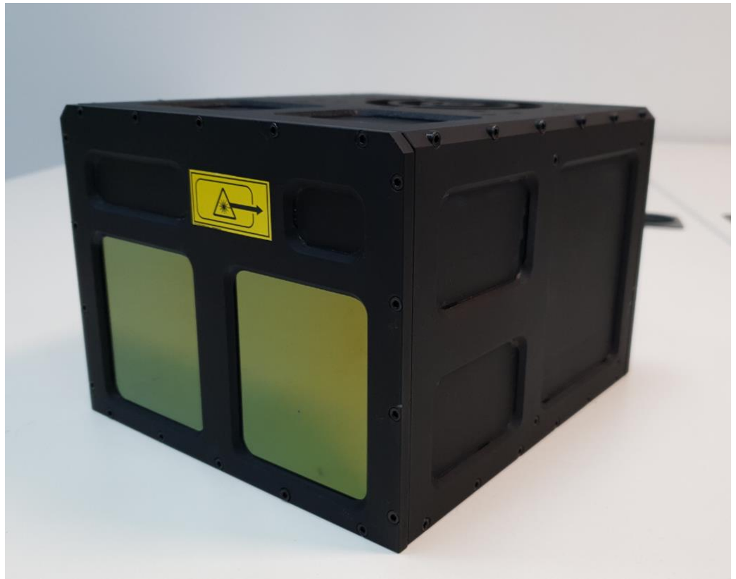
Class 3B

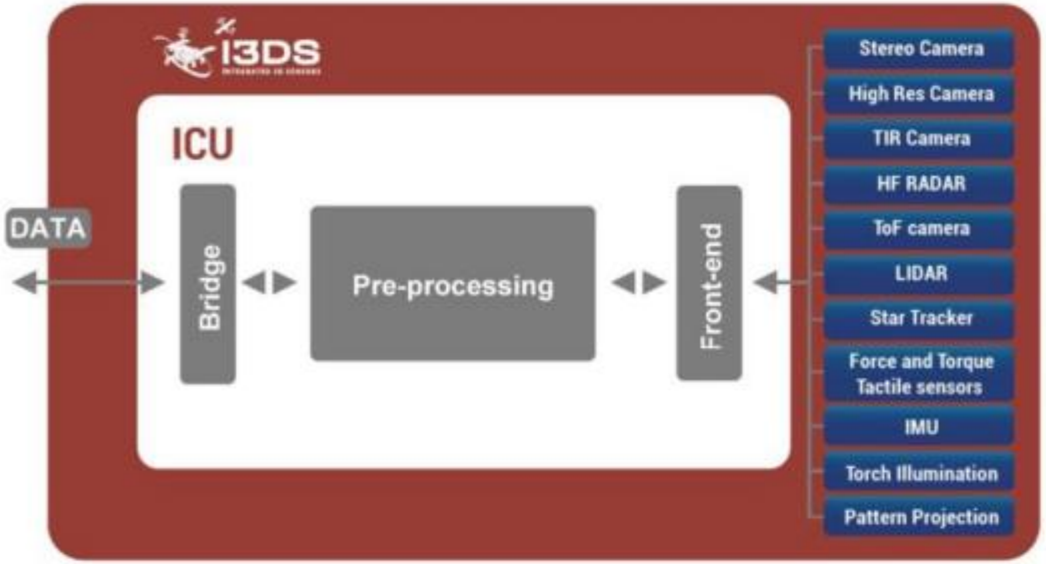
Irradiance (W/m^2)	Range @ 80% refl. (m)	Range @ 50% refl. (m)	Range @ 10% refl. (m)
No sun simulator	659*	586*	268
580 – Indirect	444*	351	157
1400 – Indirect	404	319	143
580 – Direct	96	76	34
1400 – Direct	85	67	30

*The maximum range is limited by the ambiguity distance between two consecutive laser pulses, which is fixed at 426m.

I3DS project

Beamagine collaborated with Thales Alenia Space (France) by providing a custom LIDAR unit for research purposes within the I3DS European project.





SOURCE: V. Dubanchet, S. Andiappane, "*Development of I3DS: An integrated sensor suite for orbital rendezvous and planetary exploration*", I-SAIRAS 2018, Madrid.

I3DS project

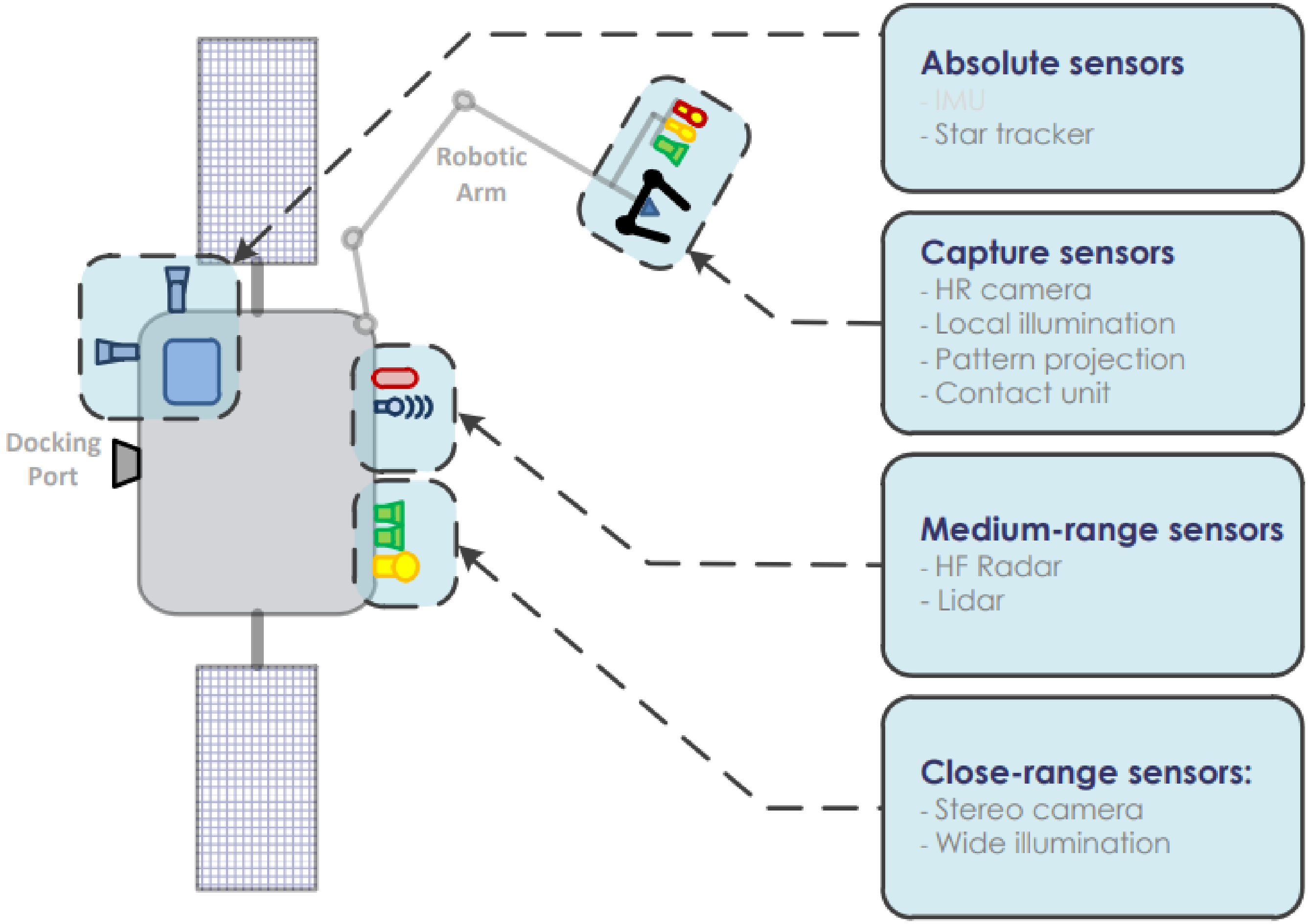


Figure 33 – Sensor configuration of the servicer for the cooperative capture

LIDAR data is the direct result of a physical measure and do not rely on data processing algorithms

SOURCE: http://i3ds-h2020.eu/publications/deliverables File: OG4_I3DS_D1.2-Use_case_Identification_PublicRelease.pdf

Use cases in science missions – Planetary exploration

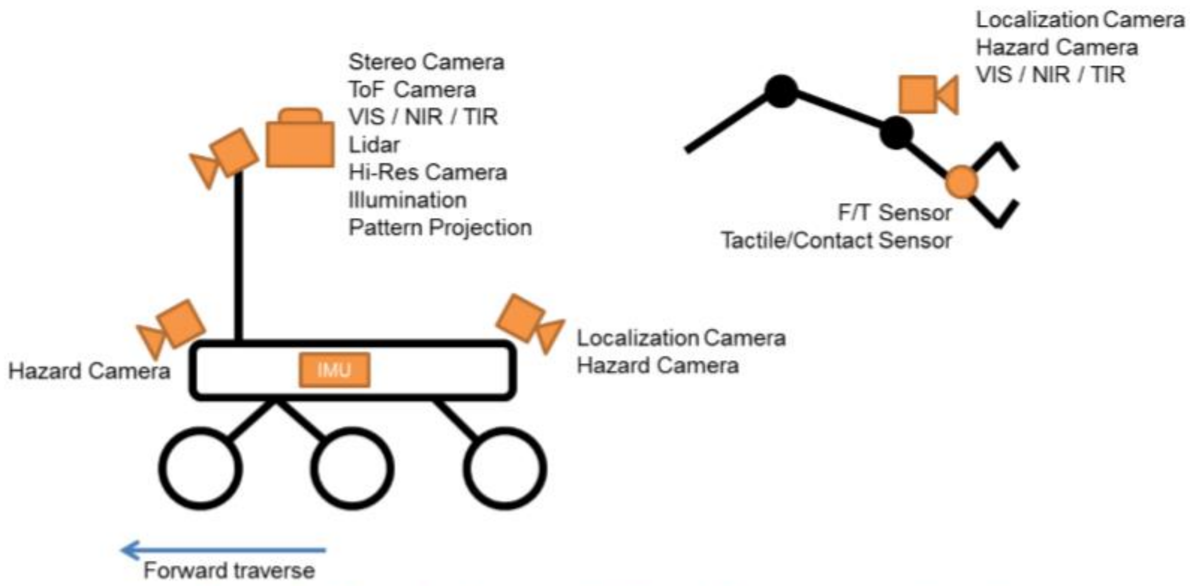


Figure 9 - Example of a potential Rover / Arm sensors allocation

	Suitable sensors by scenario	
Phase	**Mars Equator**	**Moon South Pole**
Depart from / return to a landing spacecraft	Stereo Camera Mono Camera ToF Lidar	Stereo Camera + Illuminator Mono Camera + Illuminator ToF Lidar
Reach towards another planetary asset several kilometres away	Beacon	Beacon
Rendezvous with other planetary asset/s	Stereo Camera Mono Camera ToF Lidar	Stereo Camera + Illuminator Mono Camera + Illuminator ToF Lidar
Science / Sampling site identification	Stereo Camera Mono Camera NIR Camera TIR Camera HR Camera Pattern projector	Stereo Camera + Illuminator Mono Camera + Illuminator NIR Camera TIR Camera HR Camera + Illuminator Pattern projector
Science / Sampling site characterization	Stereo Camera Mono Camera NIR Camera TIR Camera HR Camera ToF Lidar Pattern projector	Stereo Camera + Illuminator Mono Camera + Illuminator NIR Camera TIR Camera HR Camera + Illuminator ToF Lidar Pattern projector

SOURCE: http://i3ds-h2020.eu/publications/deliverables File: OG4_I3DS_D1.2-Use_case_Identification_PublicRelease.pdf

Use cases in science missions – Planetary exploration

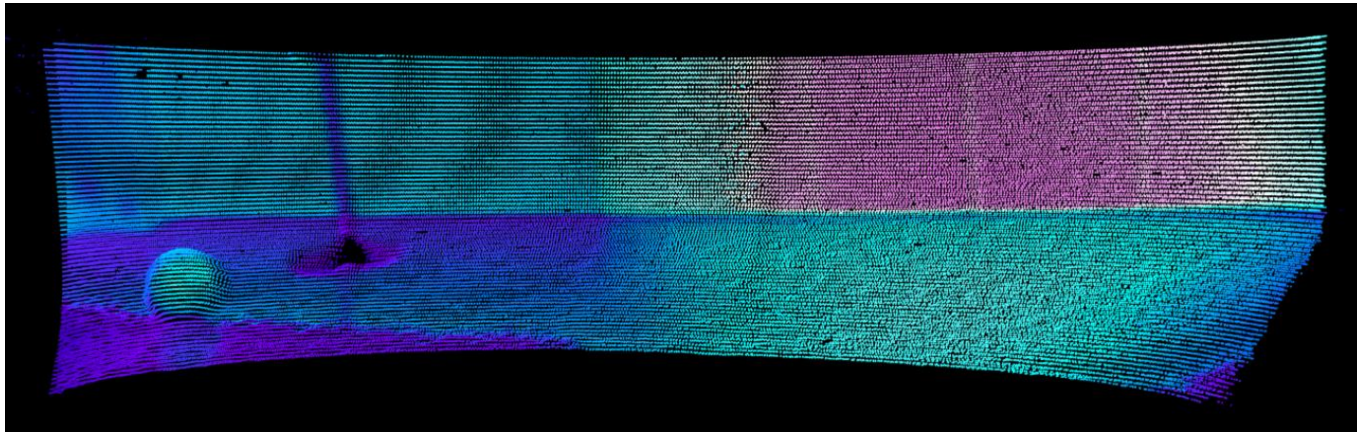
Science site coverage	Stereo Camera ToF Lidar IMU	ToF Lidar IMU
Landmark tracking (long range 50-100m)	Narrow Angle Camera (Stereo)	
Landmark tracking (medium range 10-50m)	Narrow Angle Camera (Stereo) Long-range ToF	Long-range ToF
Landmark tracking (short range 1-10m)	Stereo Camera ToF	Stereo Camera + Illuminator Pattern projector ToF
Sampling site coarse approach (100-10m)	Stereo Camera Long Range ToF	Long Range ToF
Sampling site fine approach (10-0m)	Stereo Camera ToF	Stereo Camera + Illuminator ToF
Sample target / Canister fine approach	Stereo Camera Mono Camera ToF	Stereo Camera + Illuminator Mono Camera ToF
Instrument Positioning for Sampling	Mono Camera on robotic arm Short Range ToF	Mono Camera on robotic arm + Illuminator Short Range ToF
Sampling Execution Monitoring	Mono Camera (CLUPI - Close-Up Imager) F/T Sensor	Mono Camera (CLUPI - Close-Up Imager) + Illuminator F/T Sensor

Stop-and-Go Traverse (without science)	Stereo Camera ToF Lidar IMU Sun Sensor or Mono Camera Contact Sensors	ToF Lidar IMU Sun Sensor or Mono Camera Contact Sensors
Continuous Traverse (without science)	ToF IMU Sun Sensor or Mono Camera Contact Sensors	ToF IMU Sun Sensor or Mono Camera Contact Sensors
Stop-and-Go Traverse (with science)	Stereo Camera ToF Lidar IMU Sun Sensor or Mono Camera Contact Sensors	ToF Lidar IMU Sun Sensor or Mono Camera Contact Sensors
Continuous Traverse (with science)	ToF IMU Sun Sensor or Mono Camera Contact Sensors	ToF IMU Sun Sensor or Mono Camera Contact Sensors
Planetary-referenced mapping of scientific data	Stereo Camera ToF IMU Sun Sensor or Mono Camera	ToF IMU Sun Sensor or Mono Camera
Autonomous science while traversing	Stereo Camera Mono Camera NIR Camera TIR Camera HR Camera Pattern projector ToF Lidar IMU	Stereo Camera + Illuminator Mono Camera + Illuminator NIR Camera TIR Camera HR Camera Pattern projector ToF Lidar IMU

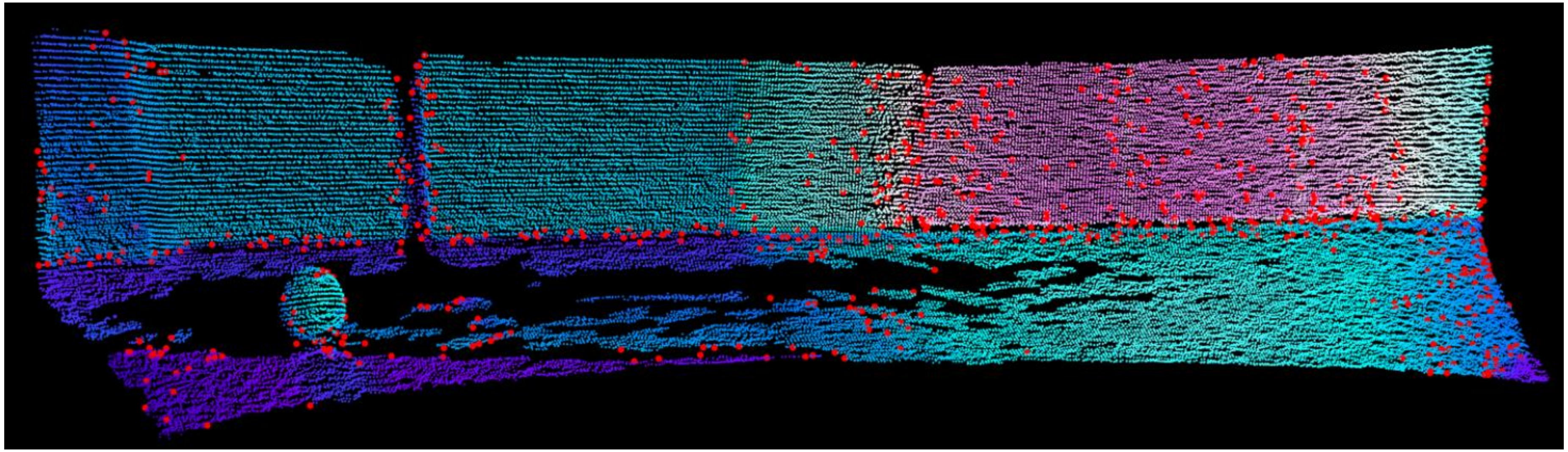
SOURCE: http://i3ds-h2020.eu/publications/deliverables File: OG4_I3DS_D1.2-Use_case_Identification_PublicRelease.pdf

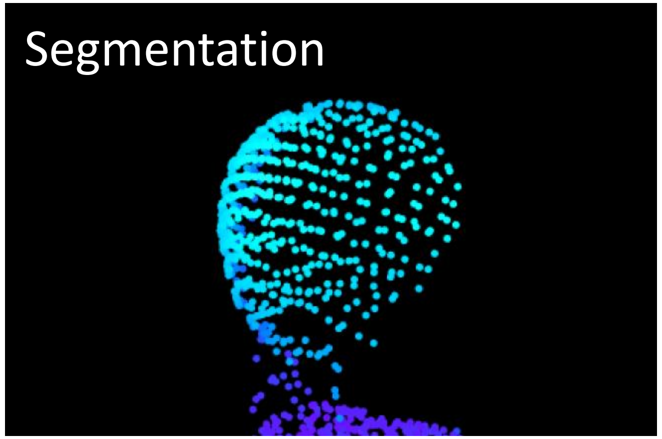
Processing the point clouds

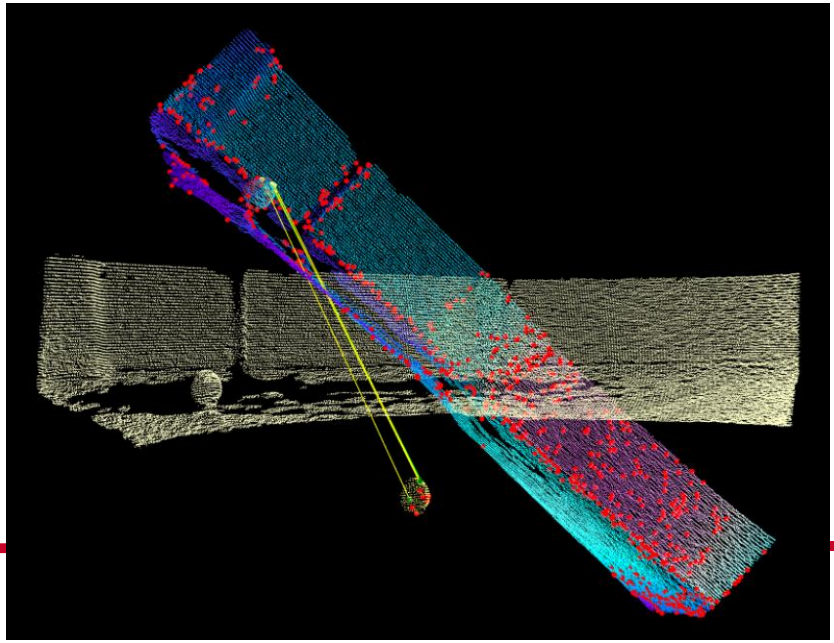
- Since its creation, Beamagine has been focused on the hardware side of the LIDAR sensor. However, we started developing software also for point cloud processing to provide complete solutions to our customers.
- In addition, we stablished a stable collaboration with the Image Processing Group of the Technical University of Catalonia.

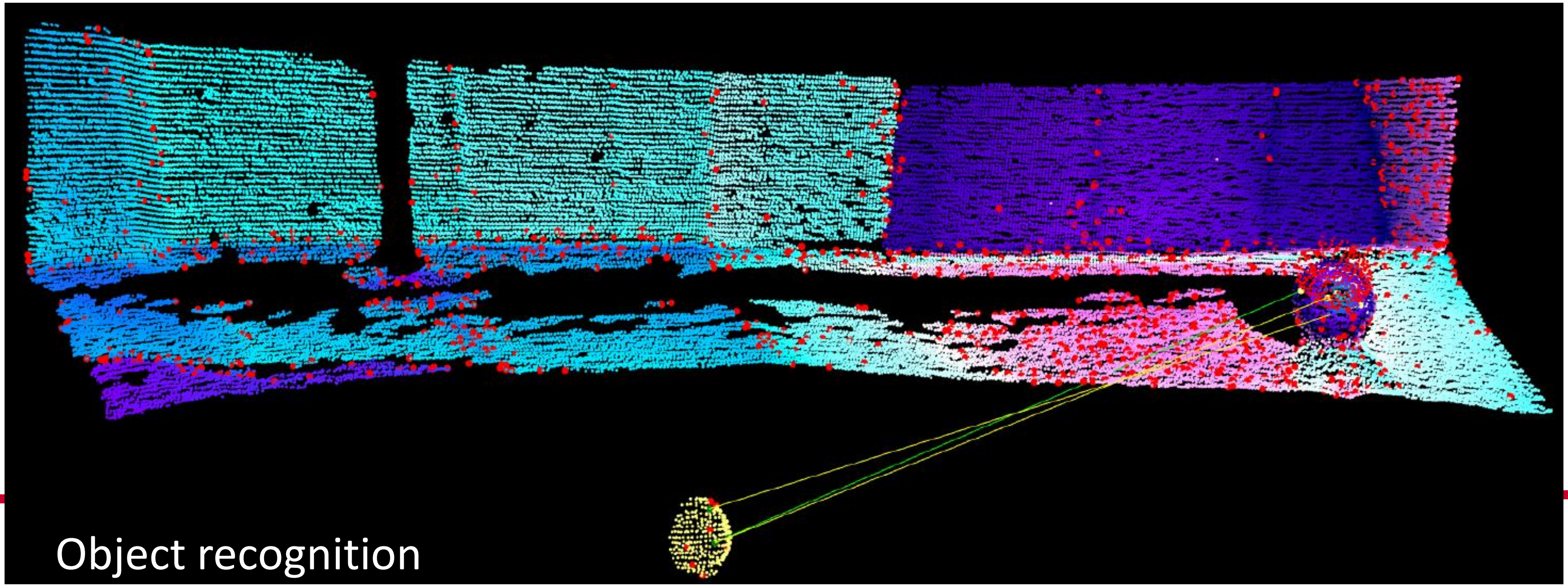


Processing Software









Space product roadmap for New Space future applications

- **Configurable imaging modes**: The image configuration will be fully configurable by the operator that will be able to change between different modes. Then the system will no longer be stacked to a fixed specific resolution / frame rate balance, but will be able to adapt the imaging specs on-demand. Parameters like FOV, image spatial resolution and frame rate will be configurable on-the-fly depending on the application needs in every moment. As an example, some of these modes will enhance image frame rate up to real time (30 frames/s), others will penalize frame rate to enhance image resolution (down to 0.05º of angular resolution), and others will enable the configuration of regions of interest within the FOV dynamically.

- **Cost**: For new space applications, cost matters. The sensor has to be cost-effective for medium size satellite constellations.

- **Size and weight**: A space grade lidar should weight no more than 1Kg.

- **Design for qualification**

THANKS FOR YOUR ATTENTION!

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This presentation was presented at EPIC Meeting on New Space 2019

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