OMMATIDIA

A NEW LOOK AT LIDAR

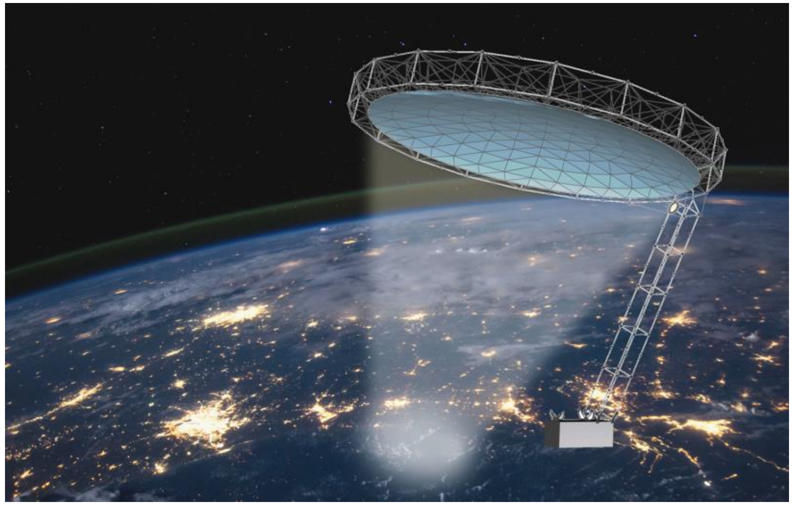
COMET INGENIERÍA

esa

European Space Agency

Final Review

In-Orbit Surface Metrology for Large Deployable Reflectors



Overview of the project

Summary

Project: **IN-ORBIT SURFACE METROLOGY FOR LARGE DEPLOYABLE REFLECTORS**

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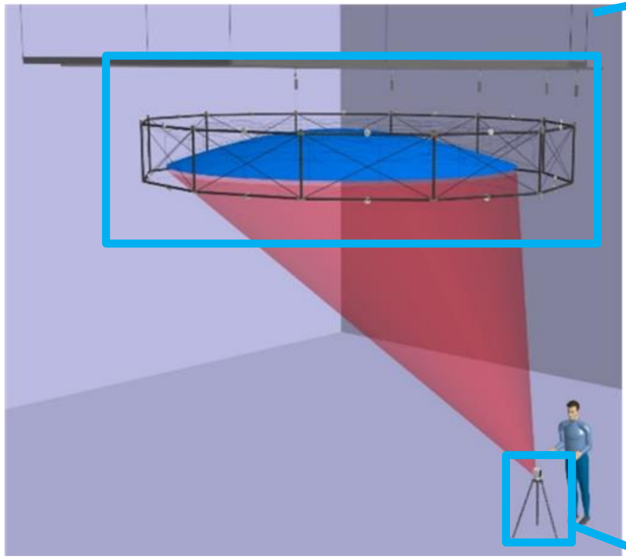
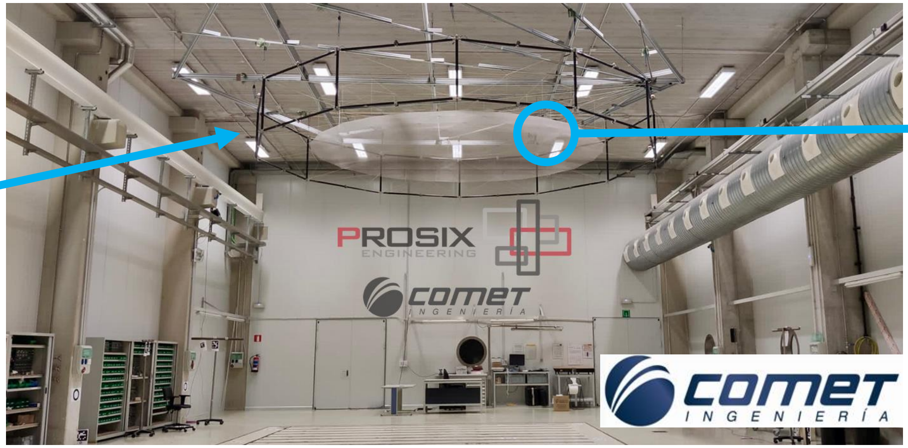
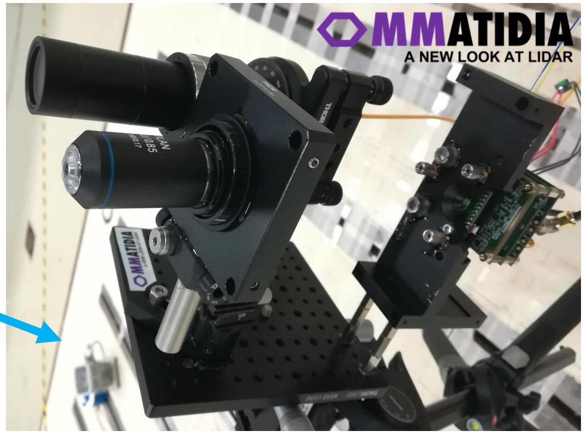
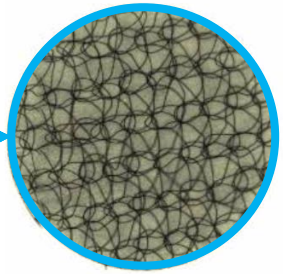


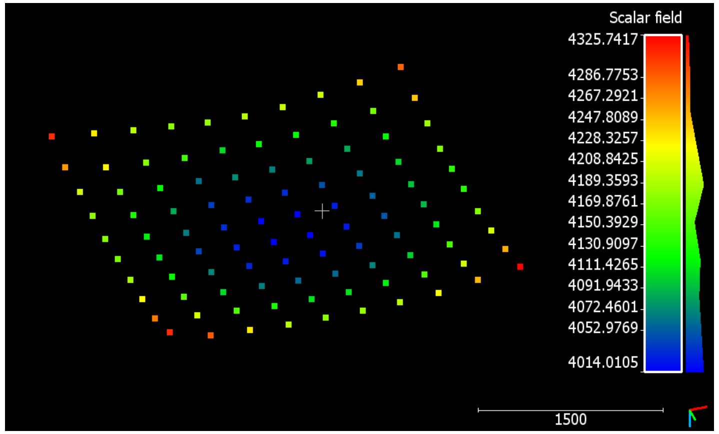
Goal: Metrology system at TRL 4 - 10 µm accuracy @ 10 m for large diameter LDRs







Reflector knitted mesh (L-Band)



Point cloud of the LDR surface

Overview of the project

Outline

STEP 1
Definition of technical requirements

STEP 2
Technology selection

STEP 3
Design and manufacturing

STEP 4
Performance validation

Main Goals

- ✓ Develop a **TRL 4 metrology instrument for space**
- ✓ **In-orbit surface characterization** of LDRs
- ✓ High measurement **accuracy: 10 µm**

Steps towards the main goals

Definition of technical requirements

STEP 1

Definition of technical requirements

Main Goals

- ✓ Develop a **TRL 4 metrology instrument for space**
- ✓ **In-orbit surface characterization** of LDRs
- ✓ High measurement **accuracy: 10 µm**

Technical requirements

Metrology breadboard

Requirements (L-Band)	Value
TRL	TRL 4
Moving parts	NO
Remote measurements	YES
Measurement time	-
Measurement accuracy	10 µm @ 4 m
Mass	<19 Kg
Volume	<1000-8000 cm^3
Measurement range	5 m
Spatial resolution/Minimum marker size	70 mm/5-10 mm
Number of points measured	100 (L-Band)
Power consumption	<30 W

- **Akinetic system for robustness while rocket launching**
- **Non-contact measurements**
- **No technical operator needed**
- **High distance accuracy for LDR going from L-Band to Ka-Band**
- **Compact and low power consumption system allowing transportation in standard launching platforms**

Steps towards the main goals

Technology selection

STEP 1

Definition of technical requirements

STEP 2

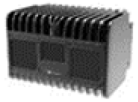
Technology selection

Main Goals

- ✓ Develop a **TRL 4 metrology instrument for space**
- ✓ **In-orbit surface characterization** of LDRs
- ✓ High measurement **accuracy: 10 µm**

Technology selection

Technology review

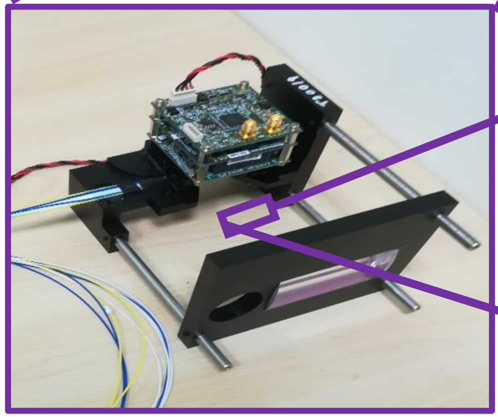
		Metrology Technology									
		Photogrammetry	Laser tracker	Laser scanner	ToF LiDAR	ToF LiDAR	Ommatidia LiDAR	Structured-light projection	Microwave antenna holograhpy	iGPS	Fiber Bragg Gratings
	Company and product	V-STARS/S INCA4 (Geodetic)	Radian Plus (API)	HDS7000 (Leica)	CE30-D (Benewake)	VLP-16 (Velodyne)	Ommatidia LiDAR	N/A	N/A	Nikon (iSpace)	N/A
	Product image							N/A	N/A		N/A
	Mechanical parts	NO	YES (Mechanical scanning)	YES (Mechanical scanning)	NO	YES (Mechanical scanning)	YES/NO	NO	NO	YES (Mechanical scanning)	NO
	Contact Measurements	YES (Retroreflective and/or coded markers)	YES (Retroreflective targets)	NO	NO	NO	Case 1: NO Case 2: YES (film retroreflectors)	NO	NO	YES (Contact sensor)	YES (fibers in contact with antenna)
	Technical operator	YES	YES	YES/NO (can be automated)	NO	NO	NO	YES	NO	YES	NO
Distance accuracy	M.9	4.5 μm + 4.5 μm/m (49.5 μm @10 m)	15 μm + 0.7 μm/m (22 μm @10 m)	100 μm	20 cm	3 cm	10 μm @10 m	-	10-100 μm range	200 μm	10-100 μm range
Mass	M.10	1.5 Kg	10.9 Kg	9.8 Kg	0.33 Kg	0.83 Kg	<5 Kg	>20 Kg	N/A	>20 Kg	<10 Kg (FBG + interrogator)
Volume	M.11	~1,737 cm^3	~16,854 cm^3	~19,205 cm^3	~256 cm^3	~570 cm^3	Case 1: <1000 cm^3 Case 2: <200 cm^3	>size of antenna	N/A	Large setup with many transmitters (theodolites)	Fibers can be long (km) but attached to the antenna
Power consumption	M.17	15 W	60 W	65 W	8 W	8 W	Case 1: <30 W Case 2: <10 W	>10 W	N/A	>10 W per theodolite	<10W

Technology selection

Ommatidia LiDAR technology – Ground metrology system

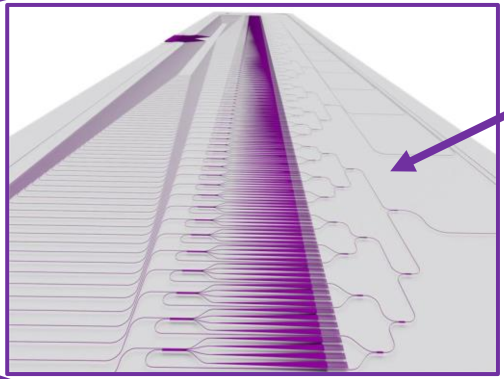
Ommatidia Q1

- Parallel sensing with 128 channels
- Non-contact measurements
- Heart based on integrated photonics
- High accuracy interferometric measurements



Receiver Assembly (~cm)

2D Receiver sensors (~mm)



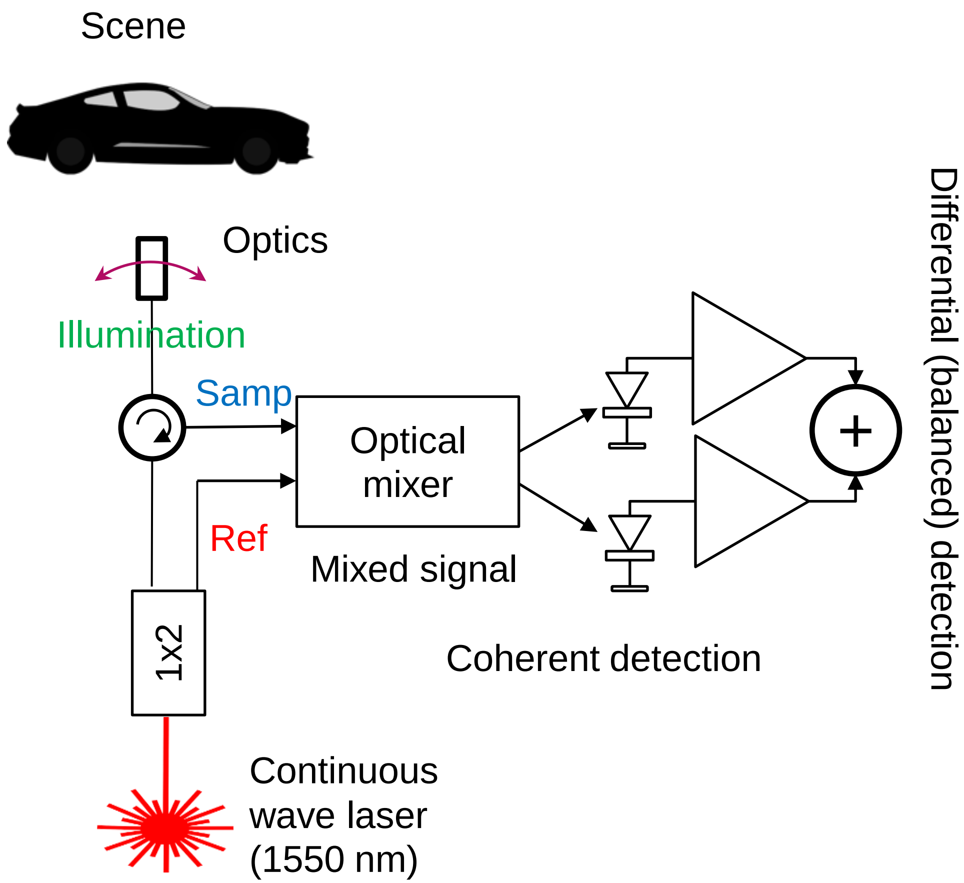
Waveguides (~1µm)

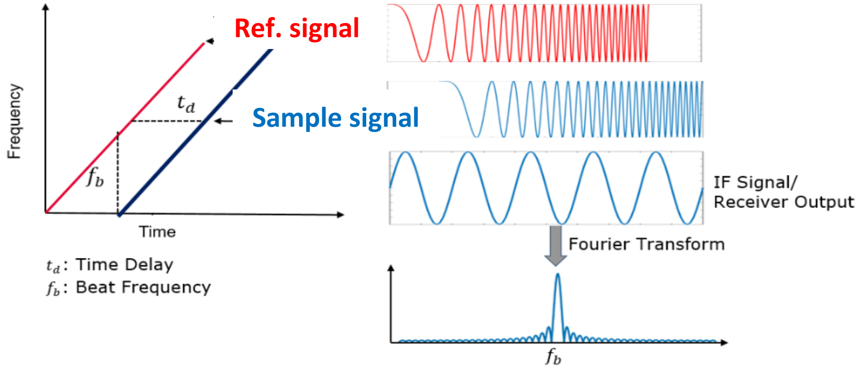
Inside the sensors

Technology selection

Ommatidia LiDAR – working principle

- **Frequency Modulated Continuous Wave (FMCW)**
  - Principle developed in RADAR.
  - Frequency modulated CW laser (**reference signal** – local oscillator + **illumination signal** of the scene)
  - **Sample signal** (back from the scene): delayed signal same freq. modulation
  - **Sample** and **reference** signals are optically mixed inside the sensor → beat frequency → distance information
    - Coherent detection scheme allows for single-photon sensitivity
    - Interferometer-based measurements → μm resolution





Steps towards the main goals

Design and manufacturing

STEP 1

Definition of technical requirements

STEP 2

Technology selection

STEP 3

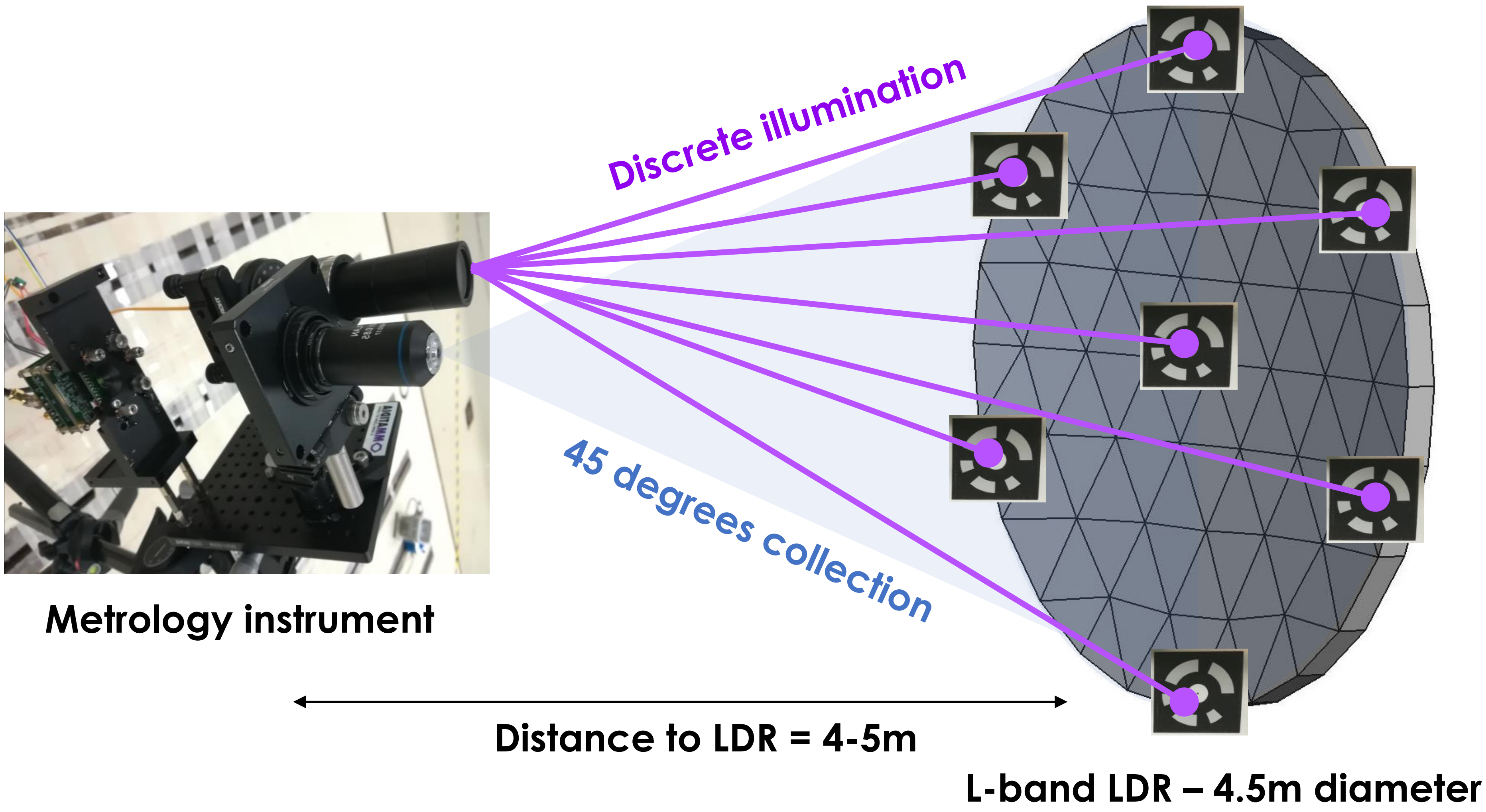
Design and manufacturing

Main Goals

- ✓ Develop a **TRL 4 metrology instrument for space**
- ✓ **In-orbit surface characterization** of LDRs
- ✓ High measurement **accuracy: 10 µm**

Design and manufacturing

Working principle of breadboard

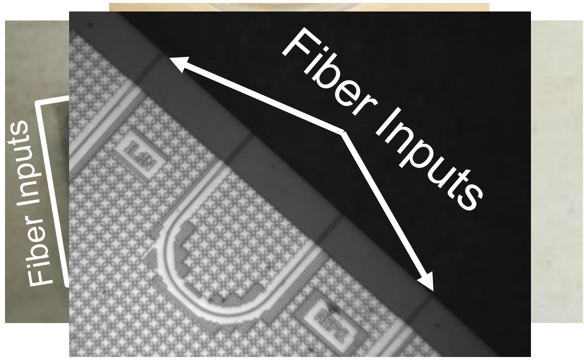


Design and manufacturing

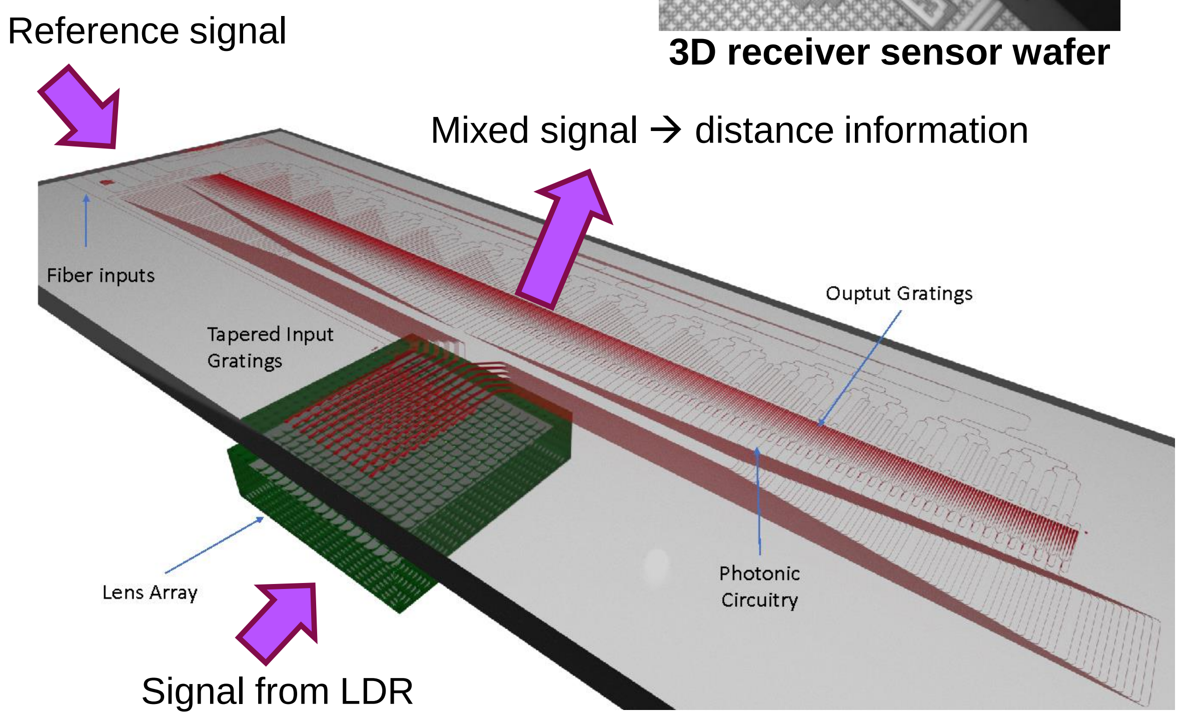
Working principle of the 3D receiver sensor

3D receiver sensor for space applications:

- **Same features based on Ommatidia LiDAR technology…**
  - Parallel sensing with hundreds of channels
  - Non-contact measurements
  - Micrometer accuracy
- **…but adapted for space**
  - Akinetic measurements (redesign of the receiver sensor)
    - Channels distributed in a 10x10 array
  - Outcome: “3D pictures” with 10x10 pixels



3D receiver sensor wafer

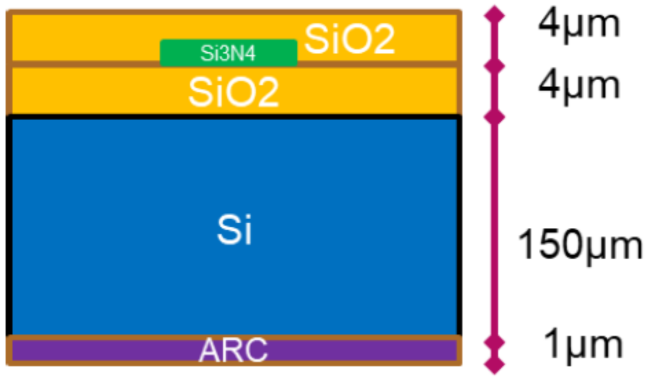


3D receiver sensor design (12 mm x 5mm)

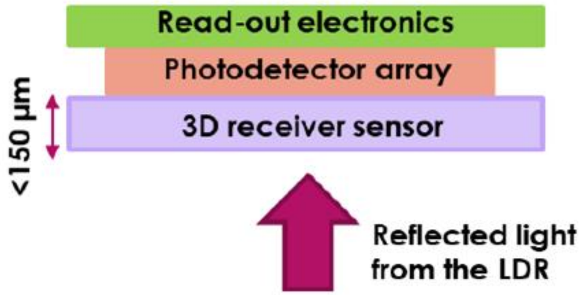
Design and manufacturing

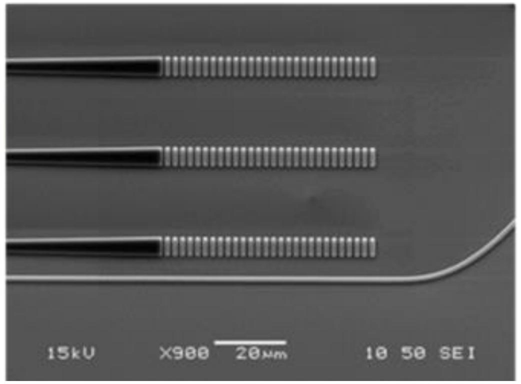
Fabrication of the 3D receiver sensor

- **Silicon Nitride** technology platform to fabricate the photonic integrated circuit (3D receiver sensor)
  - Photonic building blocks designed and optimized for **1550 nm wavelength**
  - **Back-side collection** of the light from the LDR is done **with an array of 10x10 grating couplers + microlens array**
  - Silicon substrate (550 µm) is doped (to avoid undesired signal) and thinned down to 150 µm to allow light reflected back from the LDR get coupled into the 3D receiver sensor



3D receiver sensor – stack of layers

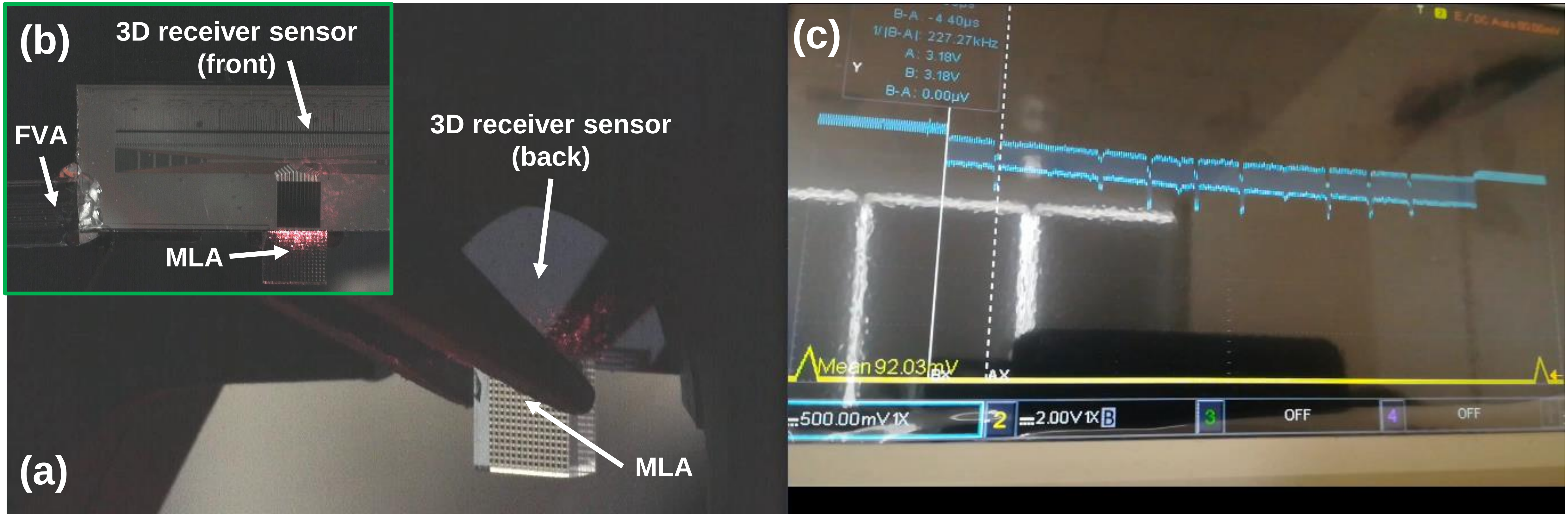




3D receiver sensor – light coupling from the back-side using gratings

Design and manufacturing

Packaging of the 3D receiver sensor



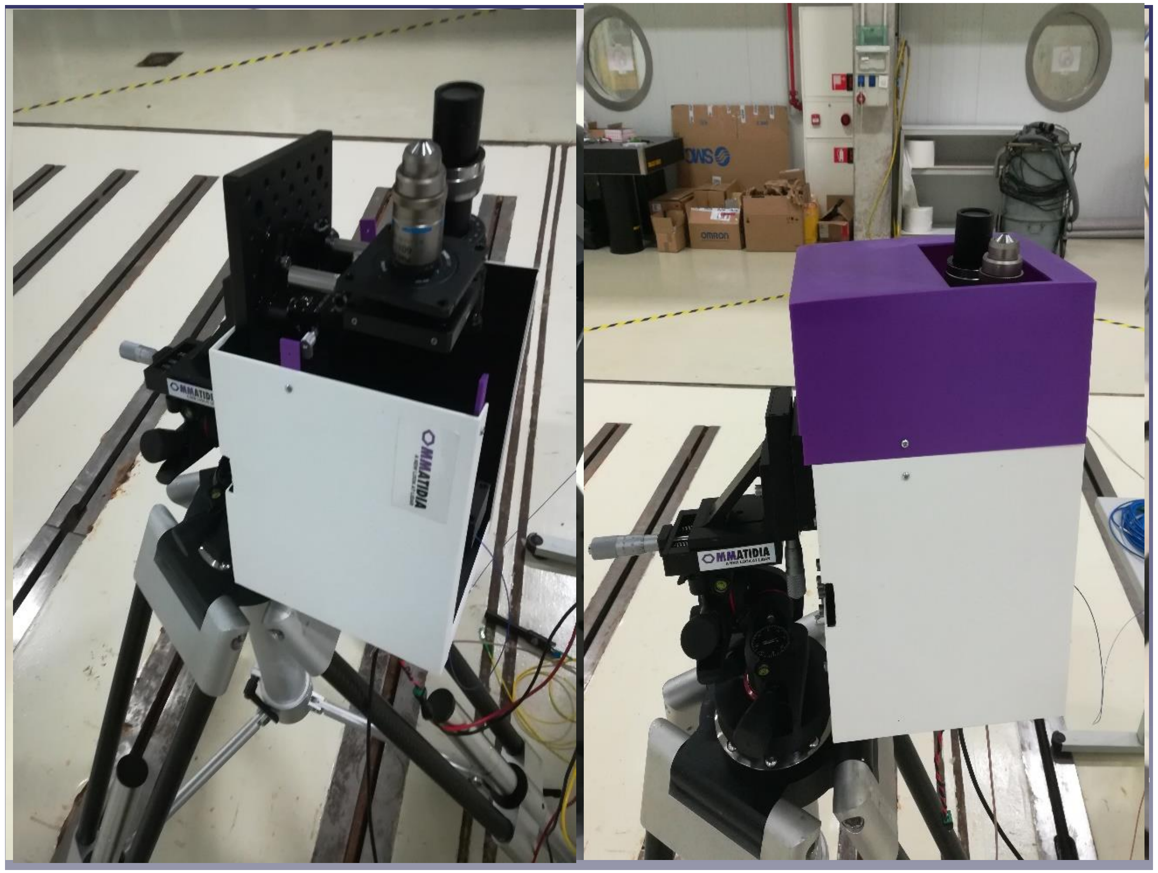
Microlens array alignment. (a) Back view; (b) Front view

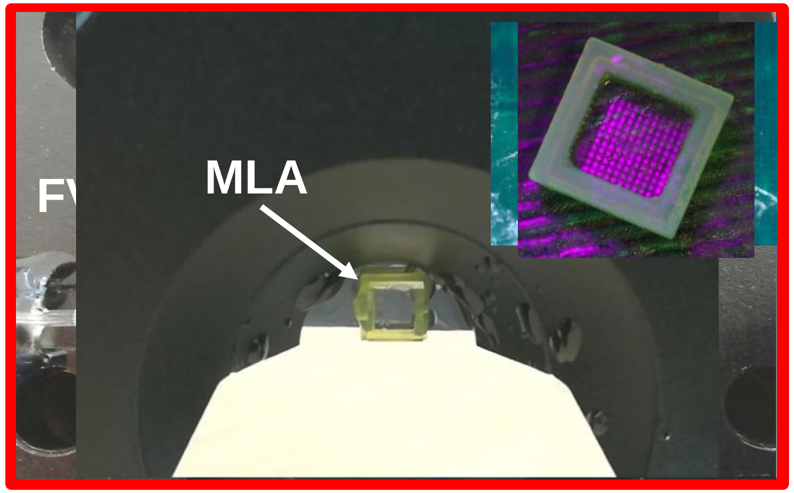
(c) Measured signal in the oscilloscope given by the 1oo gratings while aligning the MLA. Collimated beam incident from the back

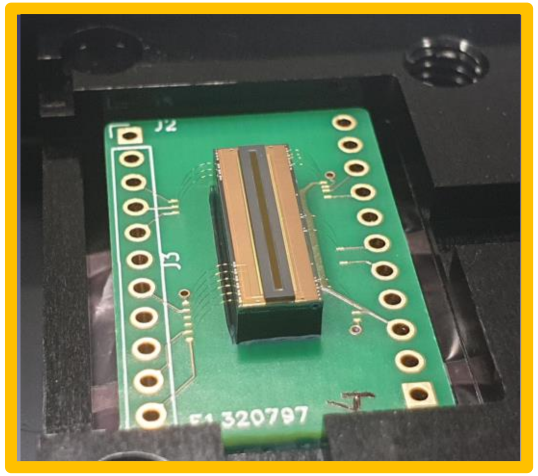
FVA - Fiber array; MLA – Microlens array

Design and manufacturing

Mechanical design and assembly of the breadboard





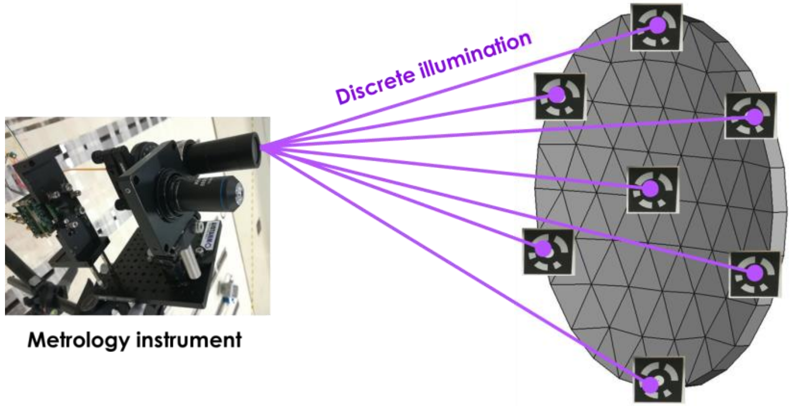


FVA - Fiber array; MLA – Microlens array; DOE – Diffractive optics element

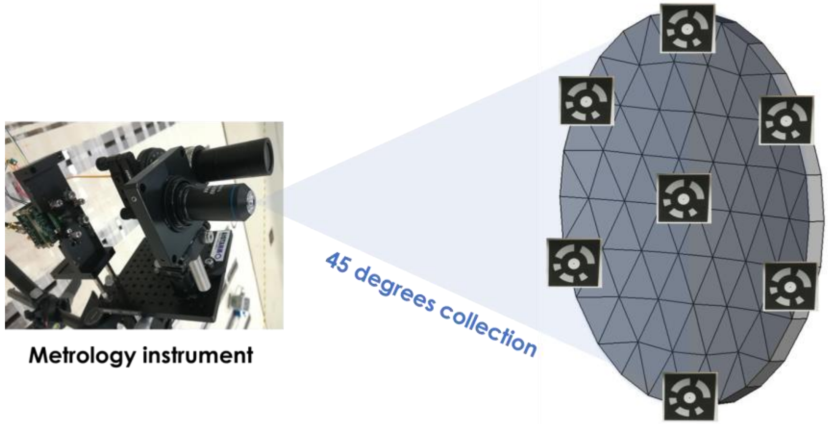
Design and manufacturing

Assembly of the breadboard - Breadboard elements

Illumination path in a matrix of 10x10 discrete points



Receiver side by 3D receiver sensor with adapted FoV

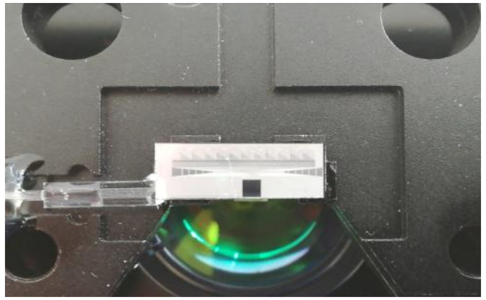


Low noise continuous wave laser at 1550nm

Fiber amplifier of 3 W

Adjustable Collimator + Diffractive optics element

IR objective lens for 45 degrees collection

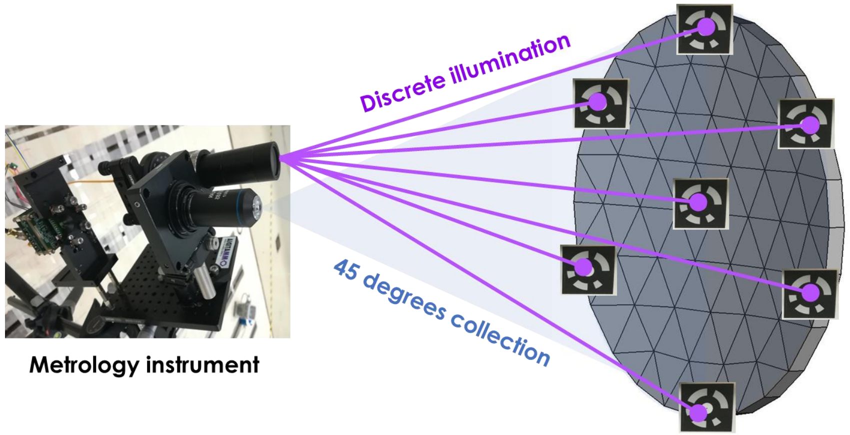


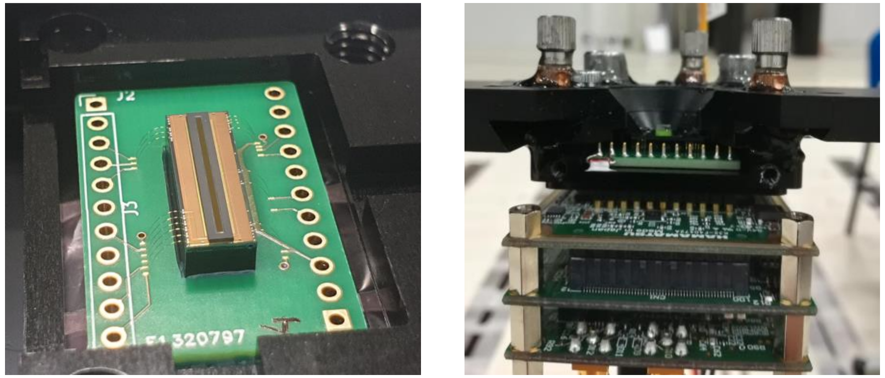
10x10 matrix of gratings in the 3D receiver sensor

Design and manufacturing

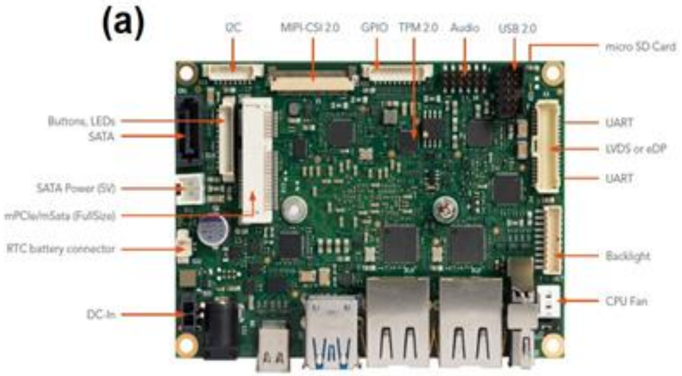
Assembly of the breadboard - Breadboard elements

Mixed signal (reference + sample) read-out, control and processing





Read-out and detection:
Photodetector array + Read-out electronics



Embedded computer (control and processing)

Sensor board for temperature, humidity and pressure

Design and manufacturing
Breadboard improvements during CCN

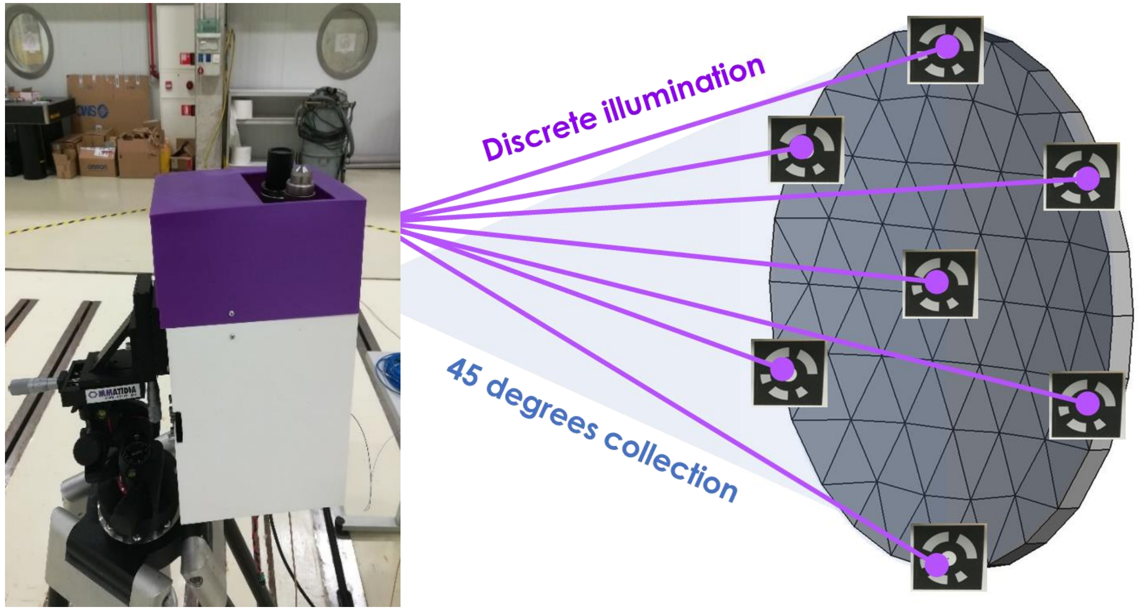
Breadboard main improvements during CCN

- IR objective lens and re-alignment objective-3D receiver sensor
- All-polarization maintaining fibers in reference and illumination paths
- Mechanical changes to make the breadboard more robust against external perturbations
  - Breadboard and metrology tripod → vibrations
  - Enclosure → stray light
- Low noise electronics (custom designed) and cabling
  - Power supply board
  - Digital to analog converter
- Improved waveforms for the laser

Setup for the 2nd measurement campaign (Granted CCN - December 2022)

Design and manufacturing

Breadboard overview and performance



Parameters	Value
Working wavelength	1550 nm
Total output optical power	3 W
Points per frame	100
Output optical power per point	25-30 mW
Field-of-view	45 x 45 degrees
Integration time	1-10 s
Designed working distance	4-5 m
Power consumption	38.4 W
Weight	<10kg
Size	35x20x15 cm^3

Steps towards the main goals

Performance validation

STEP 1
Definition of technical requirements

STEP 2
Technology selection

STEP 3
Design and manufacturing

STEP 4
Performance validation

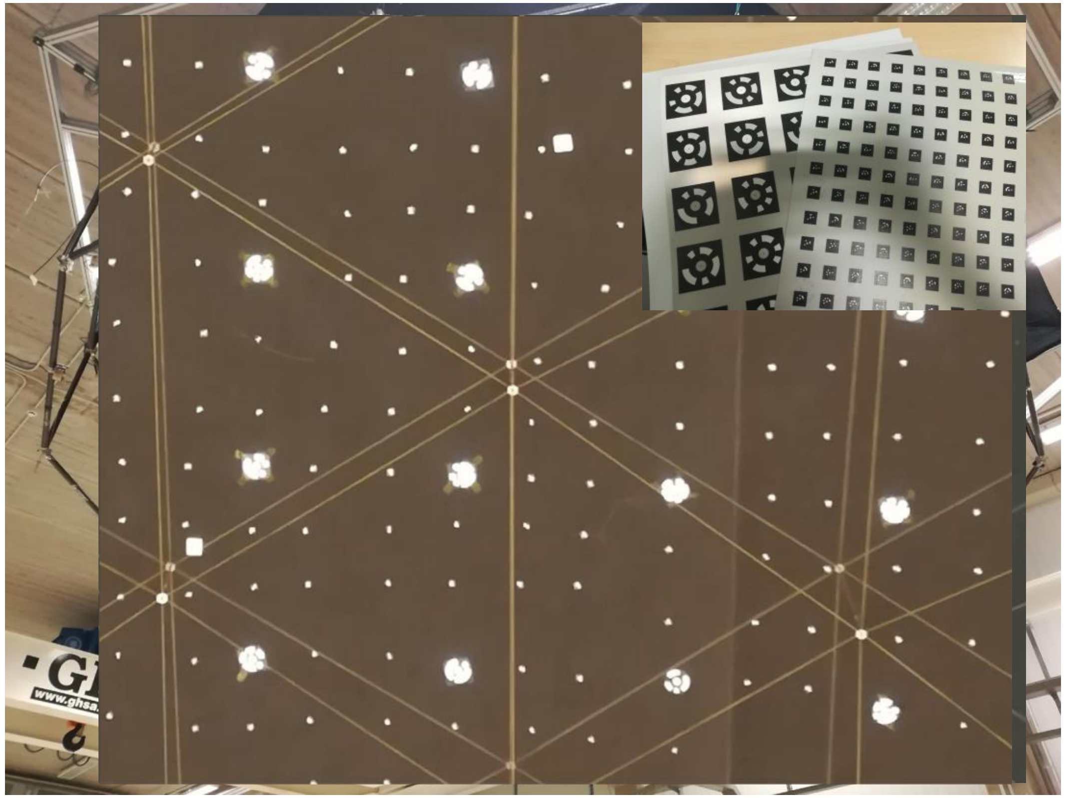
Main Goals

- ✓ Develop a **TRL 4 metrology instrument for space**
- ✓ **In-orbit surface characterization** of LDRs
- ✓ High measurement **accuracy: 10 µm**

Performance validation

Large deployable reflector and retroreflective targets

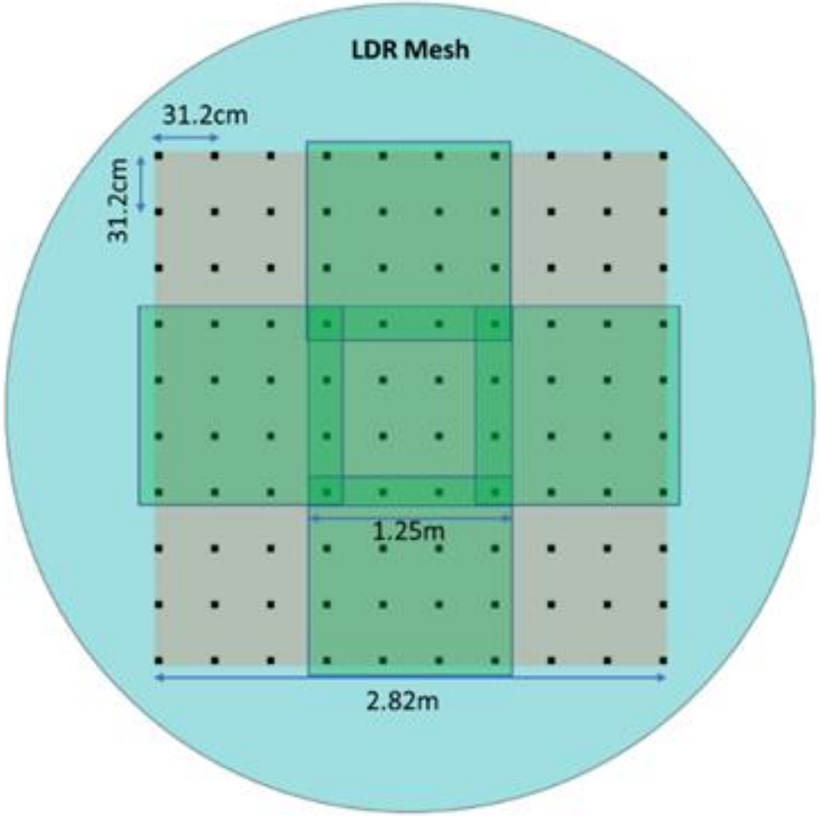
LDR setup – Mesh, ring and structure in the bunker at Tekniker

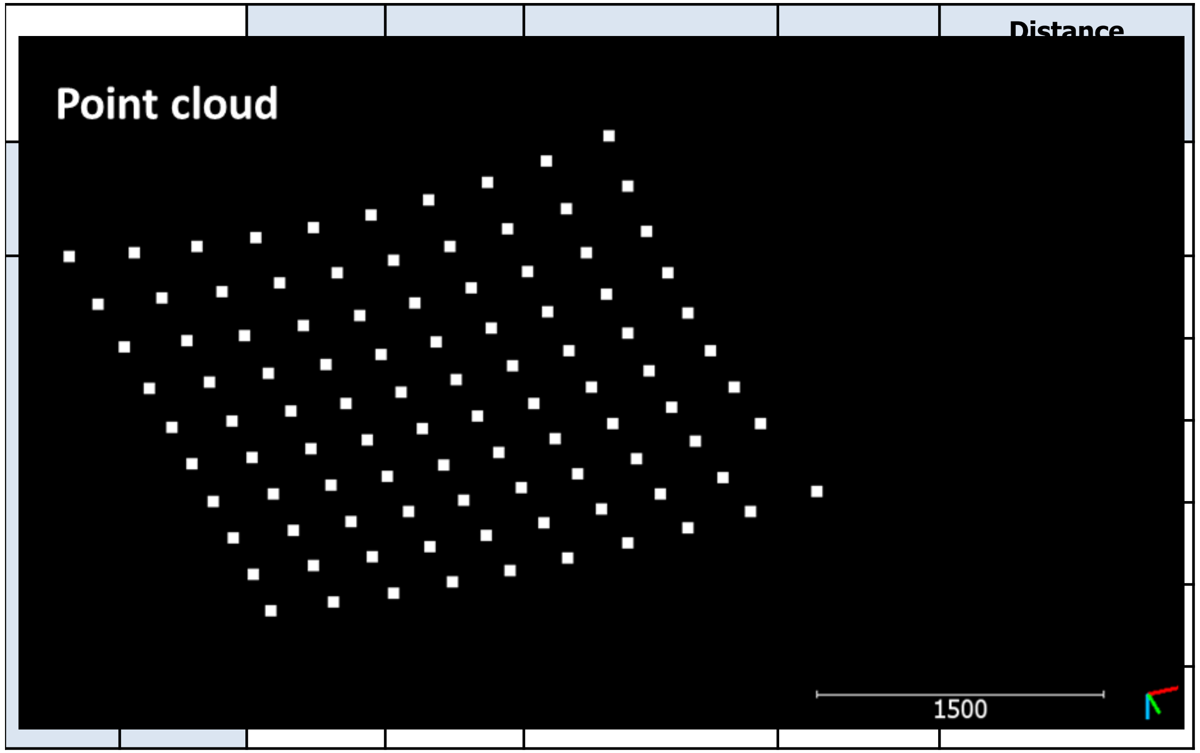


Final LDR setup with film retroreflector targets and absorbing sheet

Performance validation
Photogrammetry campaign and results

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

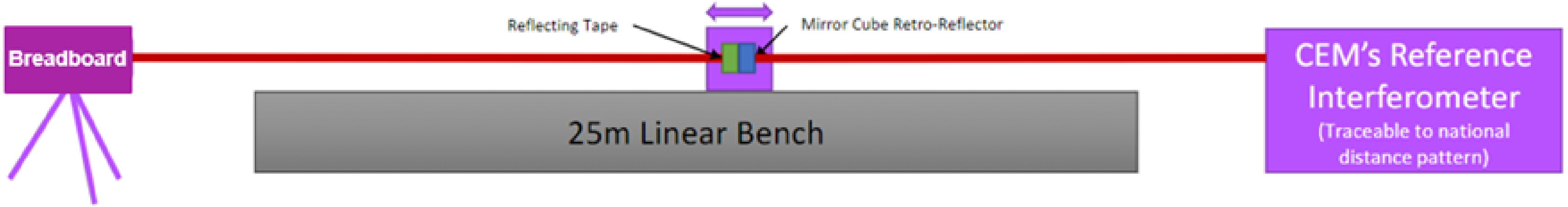




Left: Photogrammetry setup: scale bar, illumination, tripod and camera
Rigth: Measurement strategy

Performance validation

Metrology breadboard – Absolute distance calibration at CEM

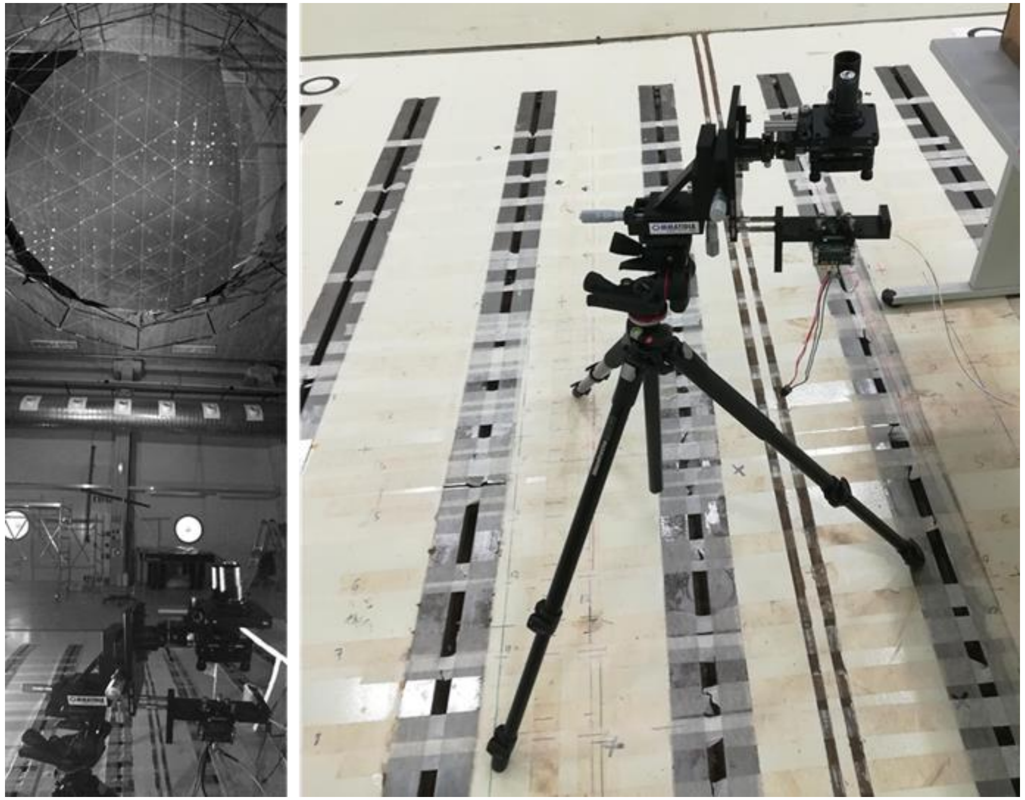


Calibration at the Spanish Metrology Center (CEM)

- Absolute distance calibration against the Spanish standard for distance
- Absolute interferometer in a linear bench of 25 m
- Distance calibration of a single point
  - RMS error of 40 µm at 15 m

Performance validation

Metrology breadboard campaign



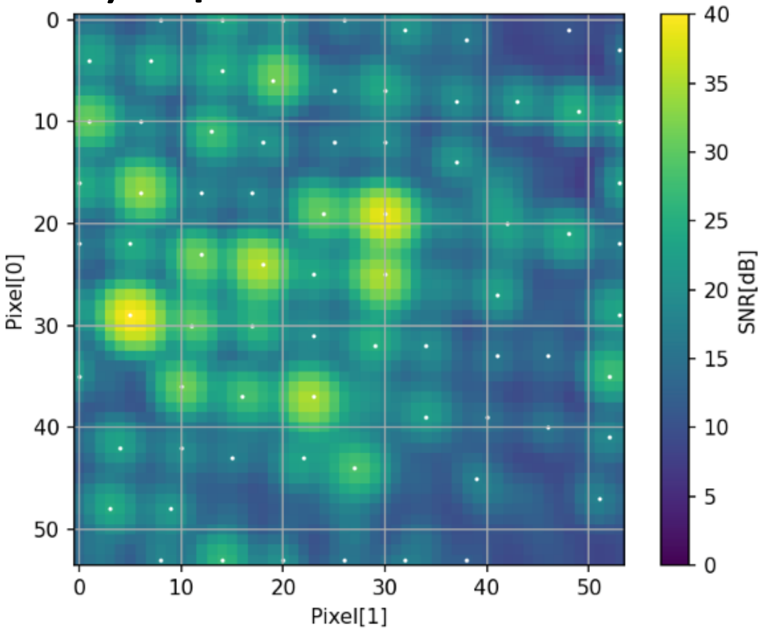
Setup for the 1st measurement campaign
(Main Project - December 2021)

Setup for the 2nd measurement campaign
(Granted CCN - December 2022)

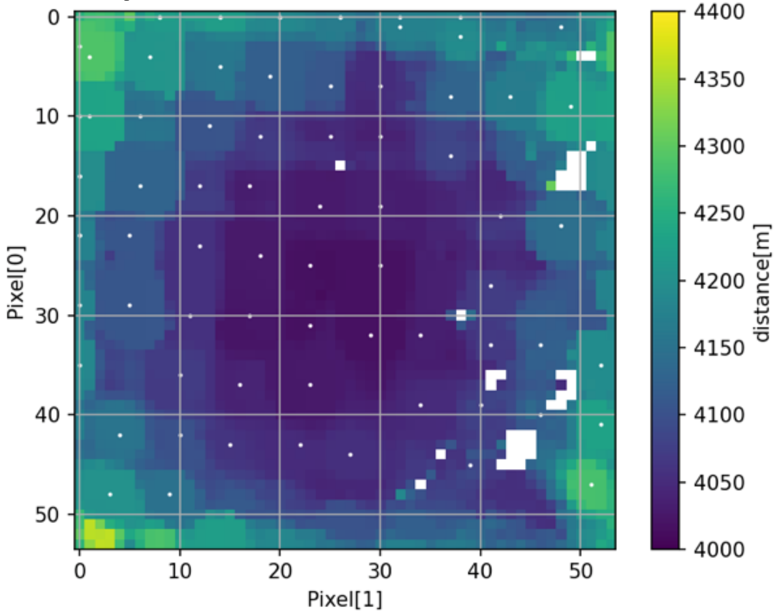
Performance validation

Metrology breadboard campaign and latest results

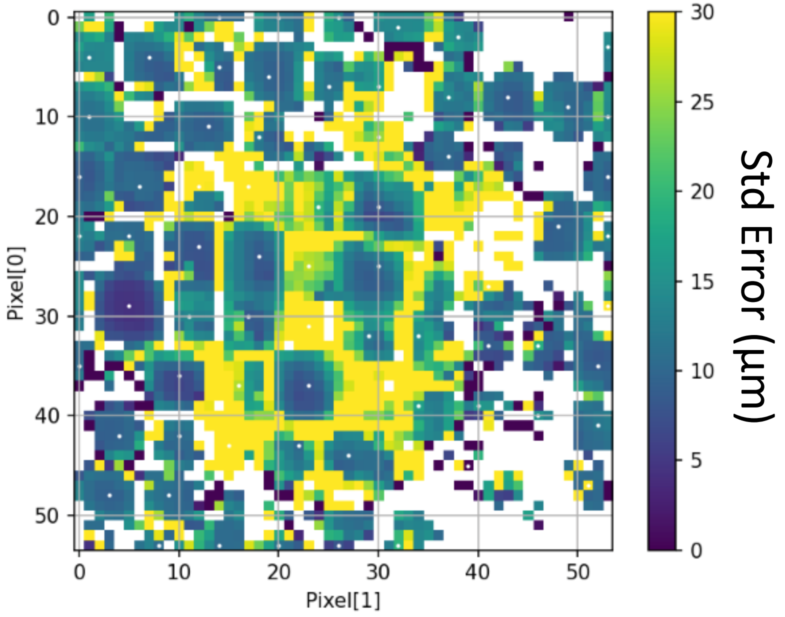
a) 2D plot - SNR



b) 2D plot - Distance



c) 2D plot - Std Dev



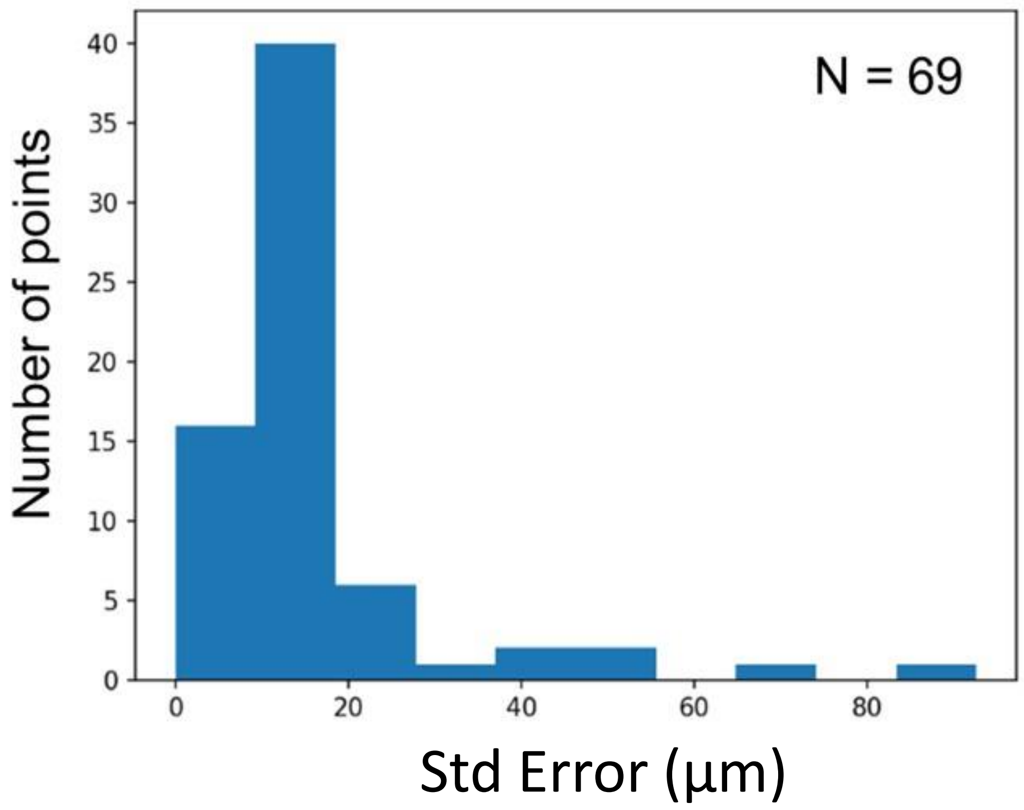
a) Oversampled (54 x 54 pixels) mean intensity over background noise (SNR) of the collected signal by the breadboard. Mean SNR over a sample of 4000 samples acquired every second

b) Mean distance information for each 54x54 pixels → postprocessing (basically FFT of the mixed signal): correspondence frequency-distance

c) Standard error: deviation of the mean distance for each 54x54 pixels. Statistical measure of the dispersion of the distance information → uncertainty of the breadboard measurements

Performance validation

Metrology breadboard campaign and latest results - uncertainty

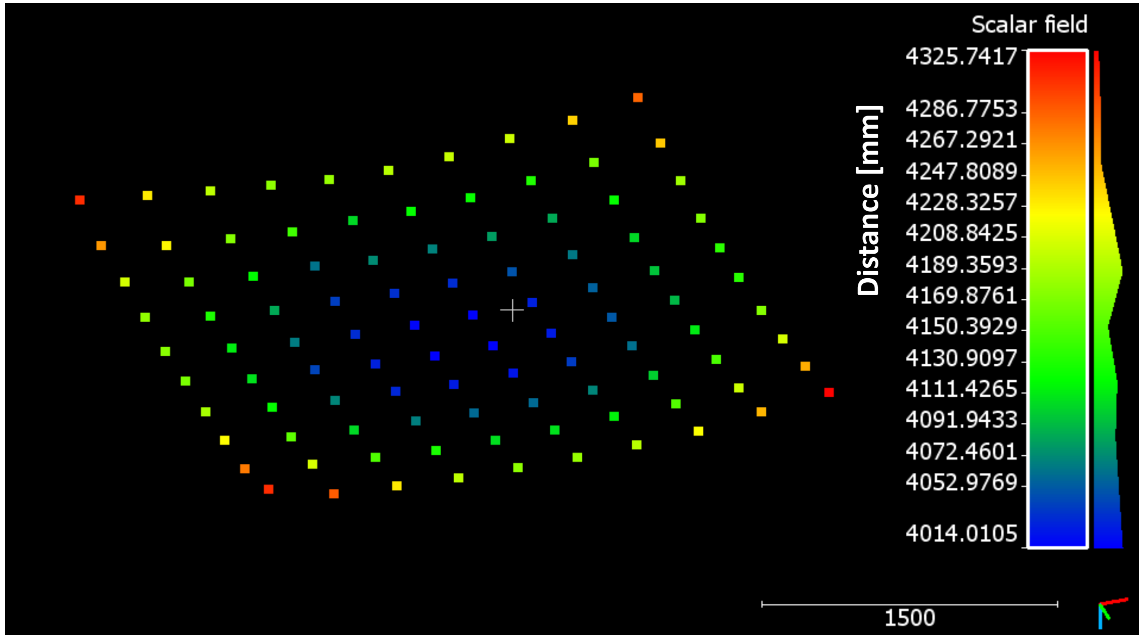


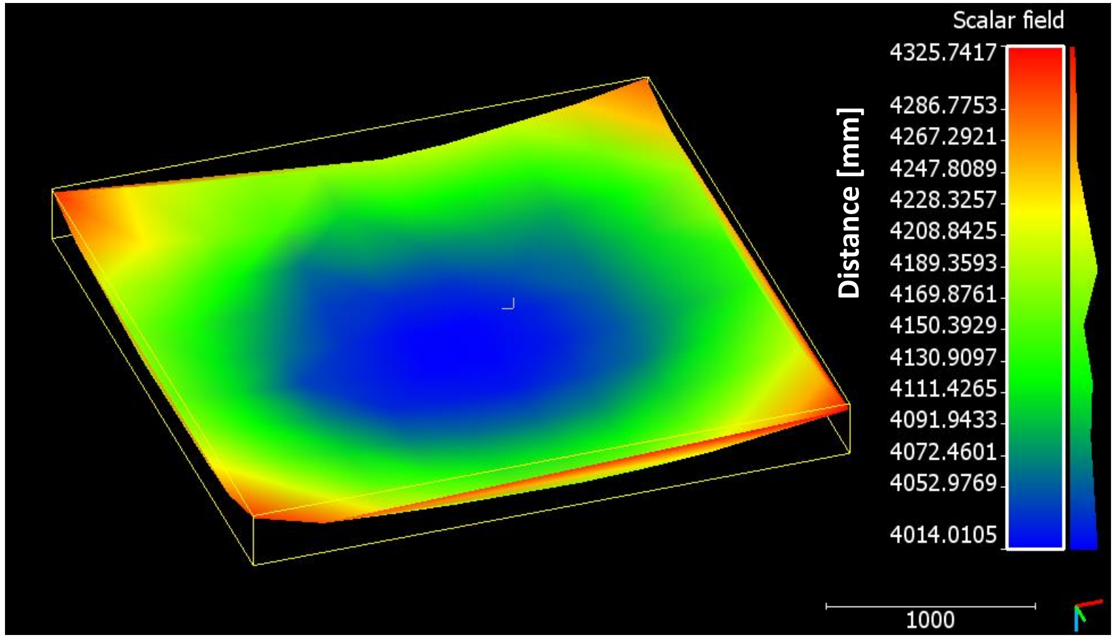
Results

- Maximum (center) intensity in each measured point (cluster of pixels) is taken → 100 points with their uncertainty
- Uncertainty of **69 out of 100 points** is **below 80 µm**
  - **55 out of 100 below 20 µm**
- Measurements having **less than 100 µm uncertainty** over the LDR can be acquired in **2 min for 50 points**
  - For this setup, we have a trade-off between having a minimum uncertainty in a higher number of points and the measurement time

Performance validation

Metrology breadboard campaign and latest results – point cloud

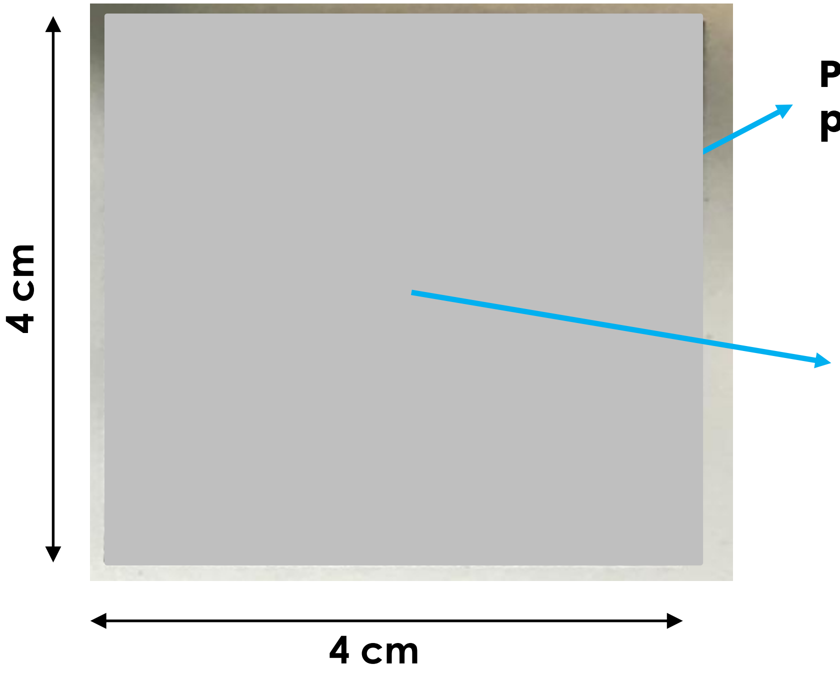




Point cloud obtained with the metrology breadboard and Surface reconstruction

Performance validation

Limitations of the comparison with the baseline photogrammetry

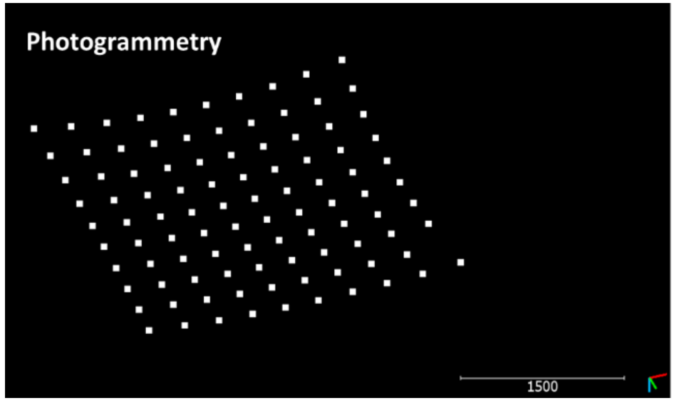


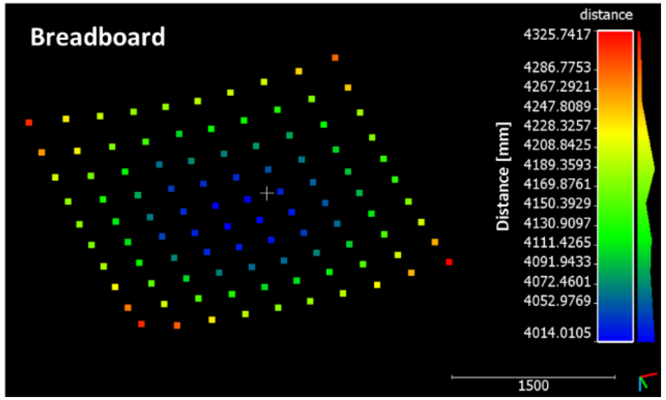
Conclusions

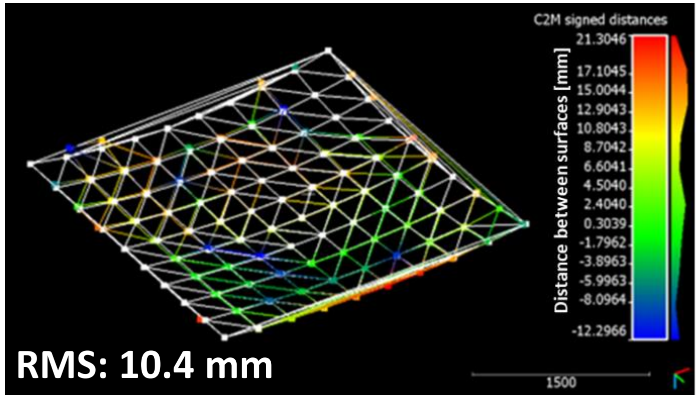
- Constraints in the setup result in **photogrammetry not** been **able** to provide a **baseline measurement**
  - Position of the points measured on the target are different for both techniques
    - Could result in errors of more than 2 cm
  - Other sources of error include:
    - Photogrammetry was not repeated during CCN (1 year between measurements)
    - Corners of the retroreflective targets detaching from the mesh

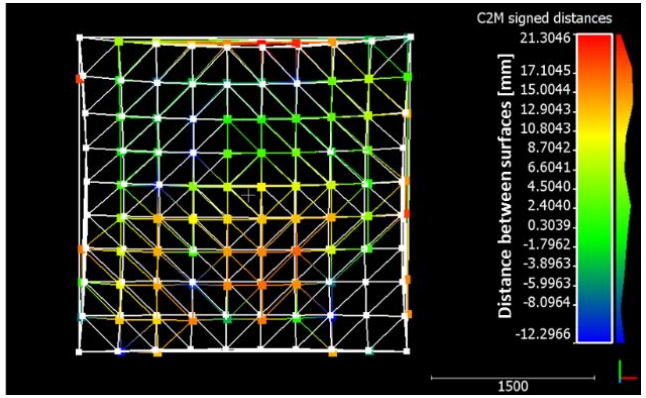
Performance validation

Comparison between baseline









Conclusion: The breadboard functions well, but difficult to establish a credible baseline to compare measurements against

Results

- Triangulated surface (mesh is made of flat triangles) generated from both point clouds
- Computed distance between both surfaces
  - Expected errors in the cm range given by the constraints in the measurement setup
- **Constraints in the setup gives no conclusive results from the surfaces comparison**
- **Other approaches are needed for validation over 100 points** → Nikon/CMM at ESTEC TBD

Conclusions

Summary of achievements

Requirements (L-Band)	Value	Achieved with the breadboard
TRL	TRL 4	TRL 4
Moving parts	NO	Akinetic system ("3D camera" – 10x10 pixels)
Frame time	-	1-10 s
Measurement accuracy	10 µm @ 4 m	Uncertainty: <80 µm in 69% of the points Absolute accuracy for individual points: 40 µm at 15 m Absolute accuracy for 100 points: Not conclusive. Extra measurements at ESTEC to compare with CMM or Nikon instruments TBD
Mass	<19 Kg	<10 Kg (with amplifier)
Volume	<1000-8000 cm^3	35x20x15 cm^3 (10500 cm^3)
Measurement range	5 m	4-20 m
Spatial resolution/Minimum marker size	70 mm/5-10 mm	30 cm @5 m (suitable for L-Band)/10 mm
Number of points measured	100 (L-Band)	100 per frame
Power consumption	<30 W	38.4 W

Future perspective

Performance under space conditions

Expected performance of the breadboard under space conditions

- Vacuum environment: on-ground distance measurements need to be corrected by the refractive index of air under measurement conditions (temperature, humidity and pressure). This may not be needed for measurements in space
- Mechanical vibrations: on-ground measurements need to be performed in a “quiet” environment free of vibrations. Breadboard uses a strategy to minimize them. Microvibration environment would need to be assessed at spacecraft level to understand the performance. Also, spacecraft launch environment needs to be checked to ensure payload continues to function after sine vibration, random vibration (acoustic noise) and shock loading. This can be assessed at breadboard level as for other payloads
- Thermal management: 3D receiver sensor + read-out electronics need thermal control in space due to the large temperature variations in space
- Radiation: Testing of all the components needed → TRL5-6

Future perspective

Towards higher TRL maturity

- Breadboard was designed with the space compatibility in mind (within the limitations)
- Effort will be put in the critical function testing of individual components and redesign
  - 3D receiver sensor
  - Laser
  - Optics
  - Electronics (read-out and control) → alternative: COTS components

Thanks for your attention

IN-ORBIT SURFACE METROLOGY FOR LARGE DEPLOYABLE REFLECTORS

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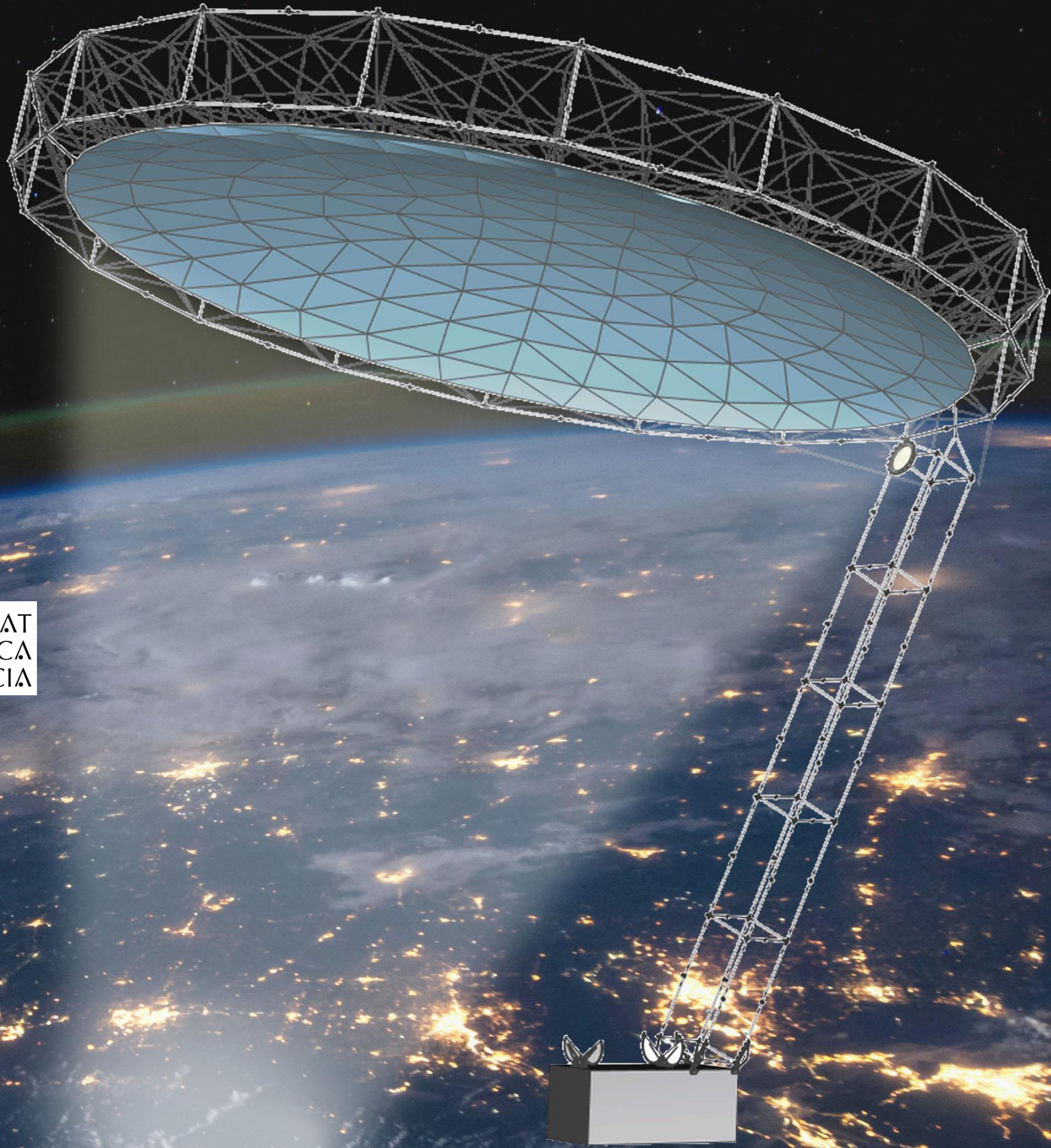
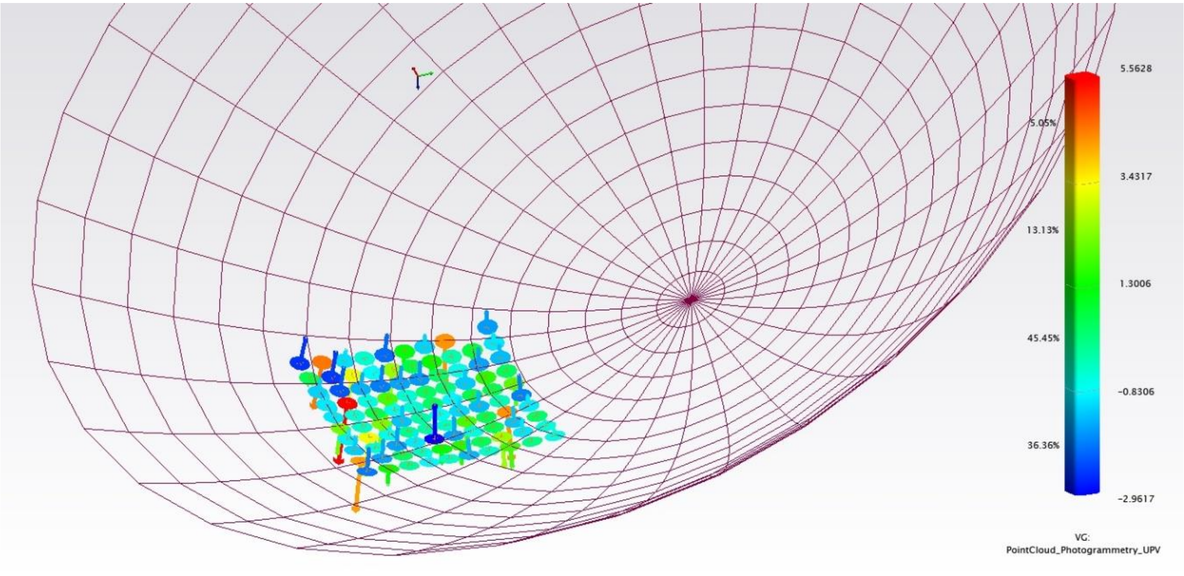
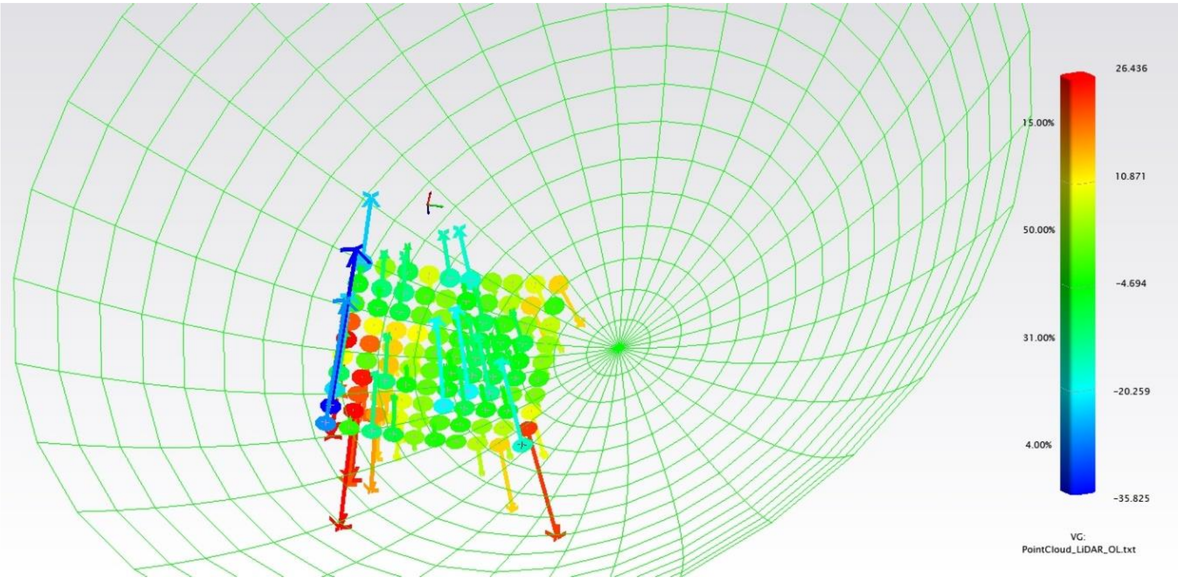


Performance validation

Surface comparison with photogrammetry – Steven Sablerolle



Paraboloid best-fit to photogrammetry point cloud



Best fit of breadboard point cloud to previous paraboloid