GABRIELE GUIDI, PHD
POLITECNICO DI MILANO, ITALY
VISITING SCHOLAR AT INDIANA UNIVERSITY NOV 2017 - OCT 2018

3D IMAGE FUSION

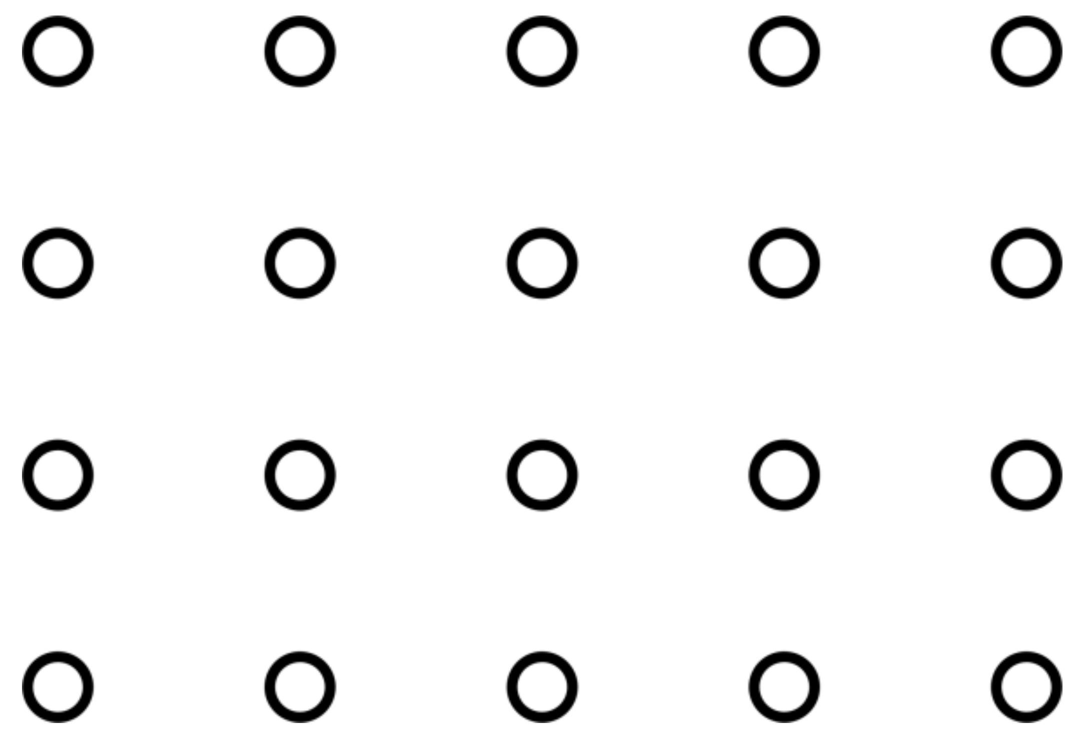
POLITECNICO
MILANO 1863

WHAT A 3D IMAGE IS?

- A cloud of 3D points collected from a 3D sensor by sampling a real scene at a predefined resolution. Each point of the cloud is equivalent to a pixel in a 2D image
- Differently form the latter, the content of each "3D pixel" can be:
  - Pure geometry (x,y,z)
  - Geometry and surface reflectance (x,y,z,R)
  - Geometry and color (x,y,z,r,g,b)

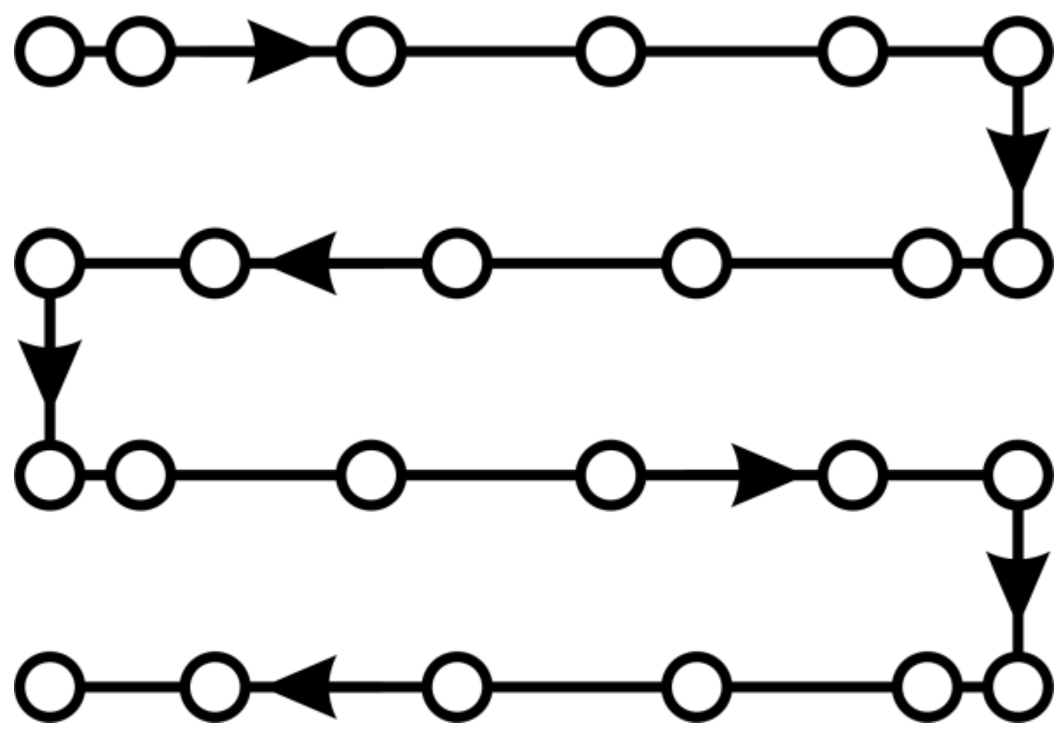
HOW A 3D IMAGE IS ORGANIZED?

- Structured 3D cloud
  - Each 3D point is collected by sensor structured as a matrix
  - The solid angle covered by each pixel is fixed
  - The shape of the 3D image appears like a 2D image where in place of each pixel the geometric and possibly the radiometric information is represented
  - The way such object is allocated in a computer memory is usually a nxm matrix of vectors of 3 (x,y,z), 4 (x,y,z,R) or 6 (x,y,z,r,g,b) components



HOW A 3D IMAGE IS ORGANIZED?

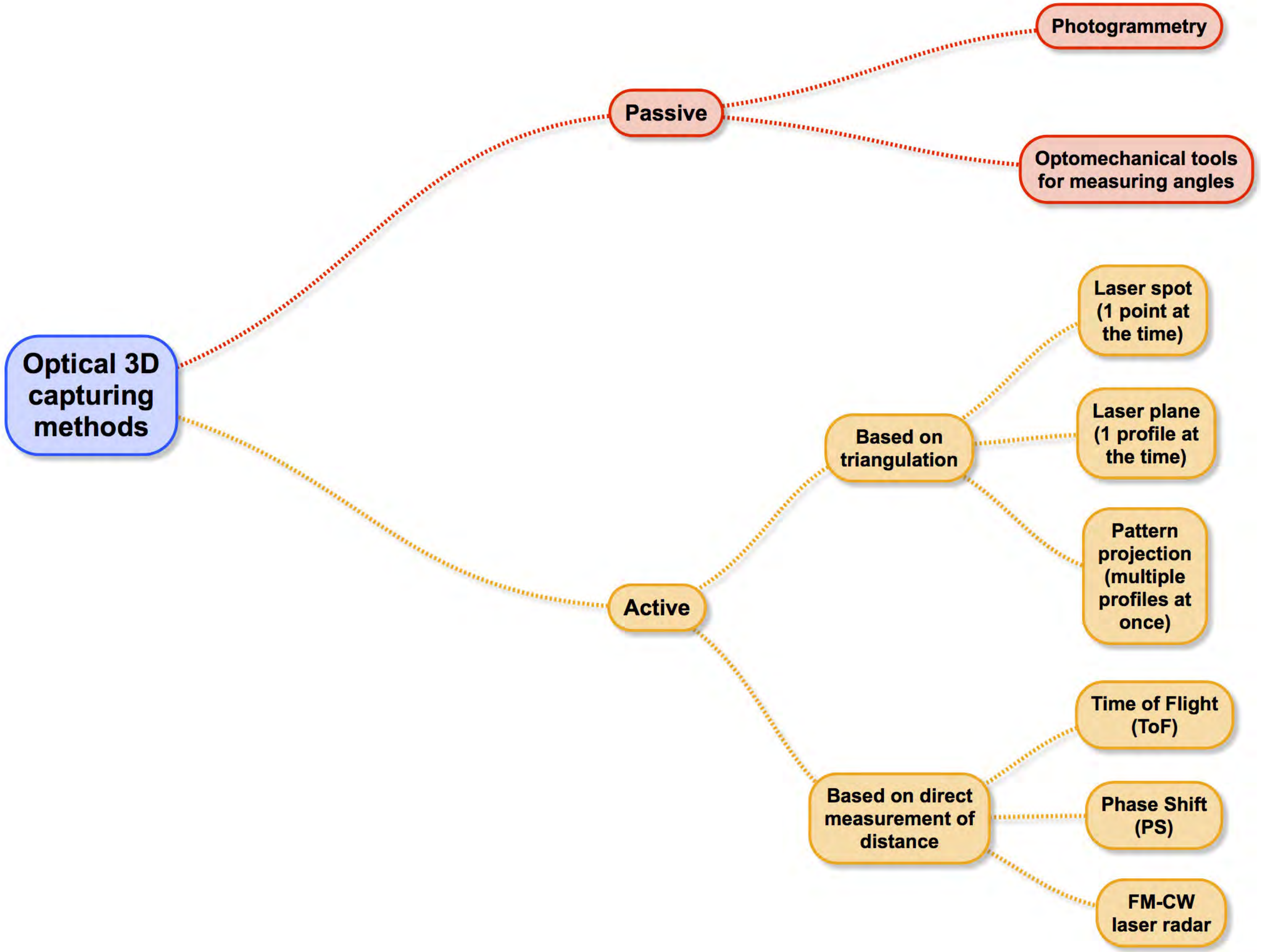
- Unstructured 3D cloud
  - Each 3D point may be collected by single point sensor, scanning the surface of interest line by line through a mechanical rotation of a mirror around two axes, typically horizontal and vertical
  - The sampling frequency is fixed but unrelated with the mechanical movements of the scanner. Points can have a variable density along different scan-lines, so it is not always possible obtain an image arranged as a matrix from the raw data
  - The way such object is stored in a computer memory is a list of vectors of 3 or 4 or 6 components



WHAT IS THE CONTENT OF A 3D IMAGE LIKE?

- Being the result of a measurement process, each 3D coordinate is affected by uncertainty
- Most of the uncertainty is associated to the sensor-to-target distance
- Such uncertainty depends on many factors related to:
  - Working principle of the 3D device
  - Electronic noise of the sensor
  - Light-material interaction

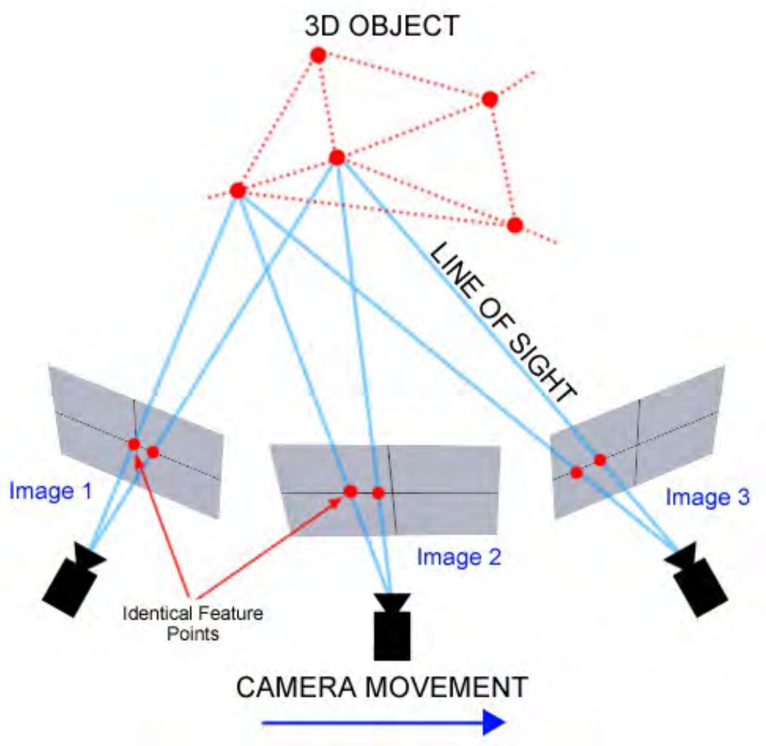
3D CAPTURE WORKING PRINCIPLES

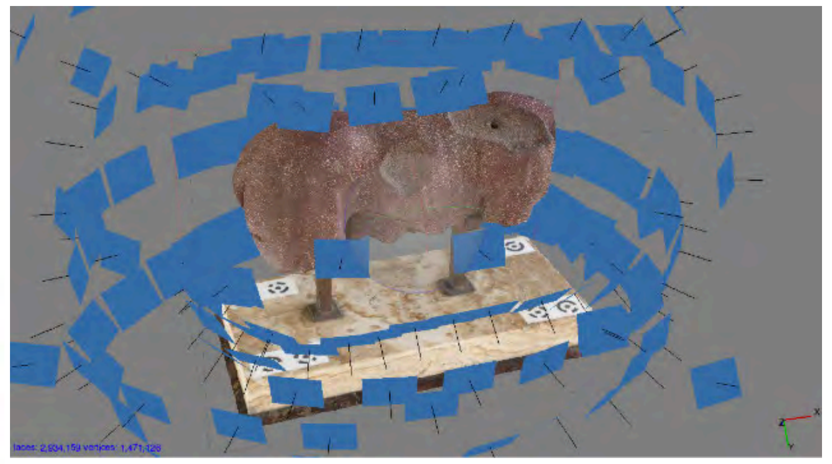


PASSIVE 3D OPTICAL TECHNOLOGIES

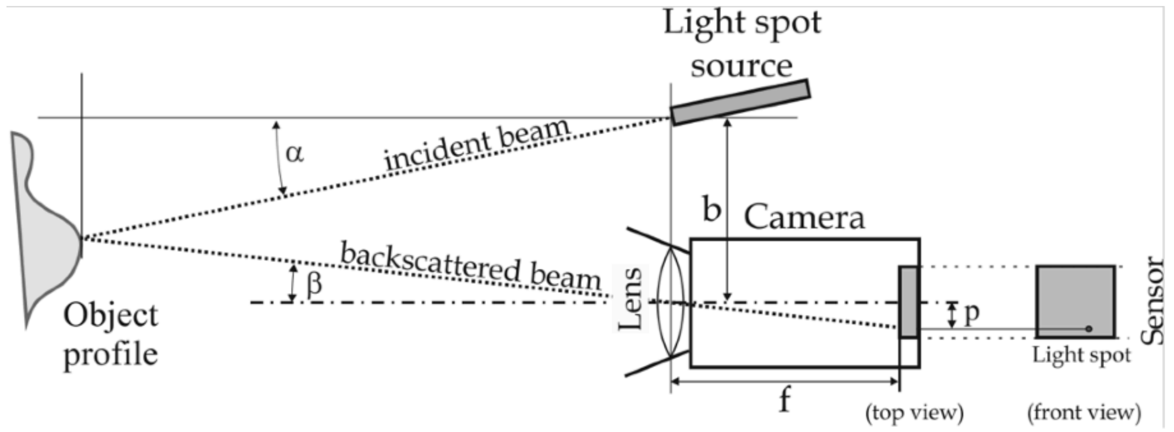
Topographic tools

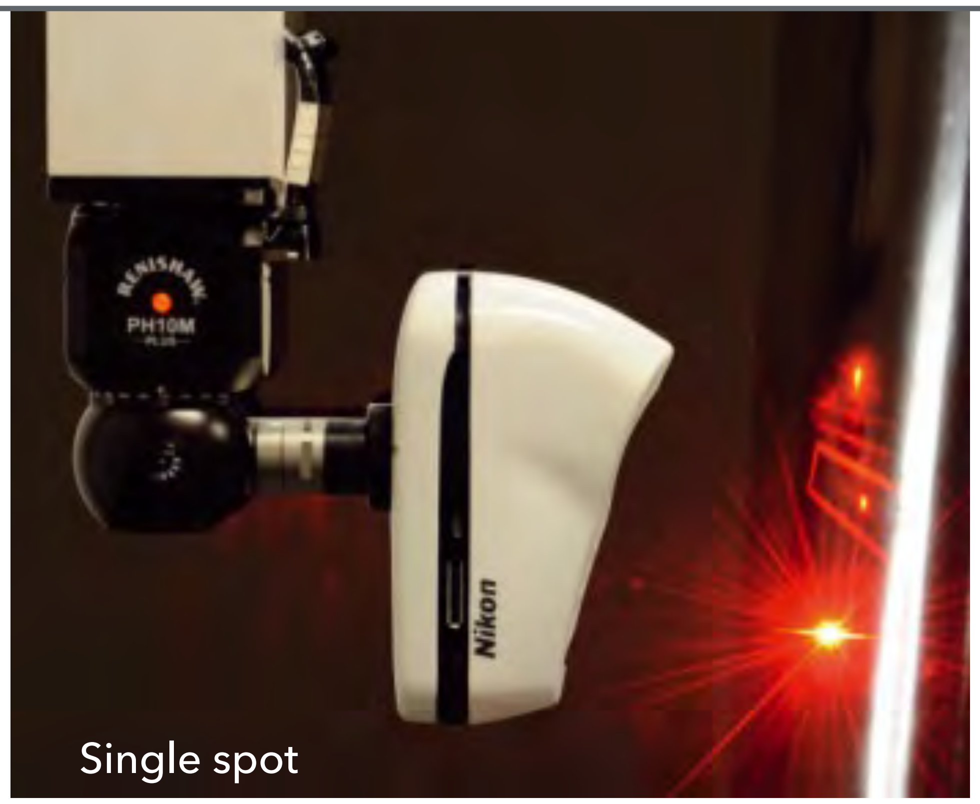
Photogrammetry

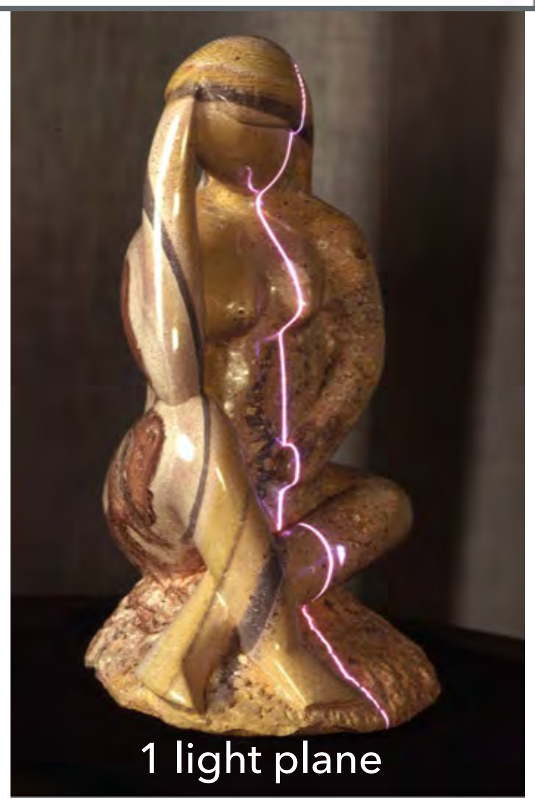


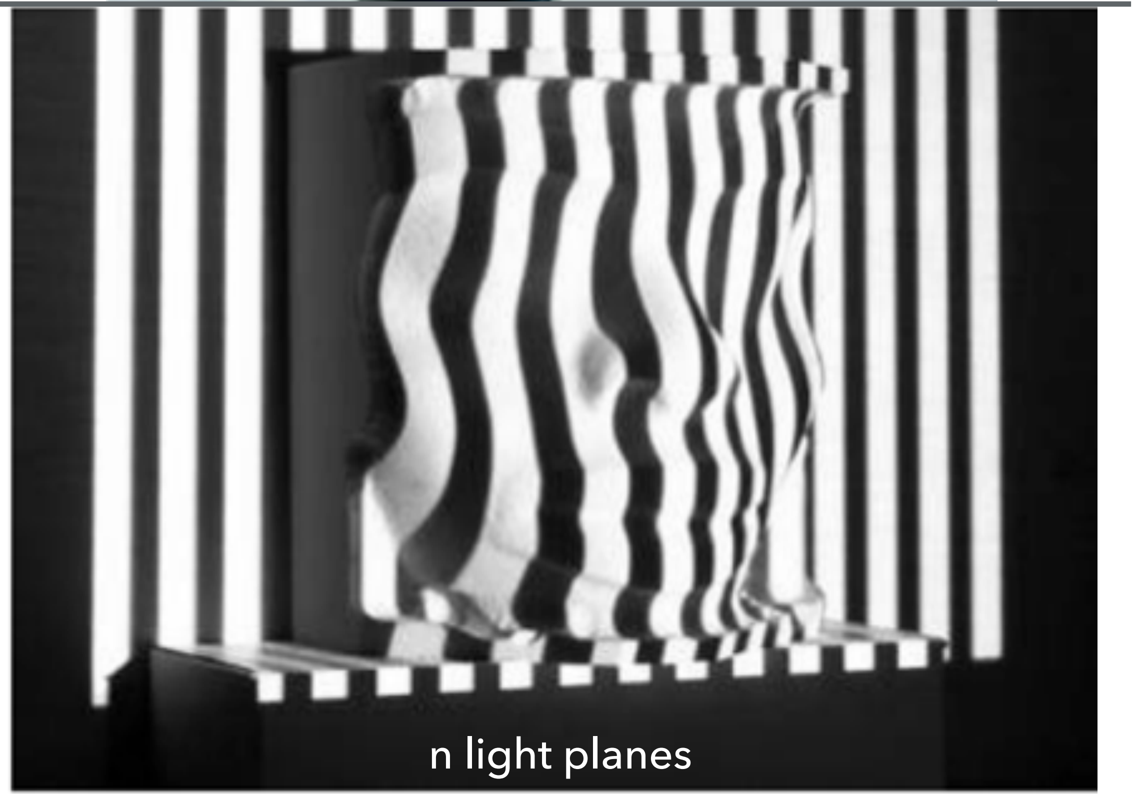


ACTIVE 3D TECHNOLOGIES – TRIANGULATION




Single spot


1 light plane


n light planes

ACTIVE 3D TECHNOLOGIES: DIRECT DISTANCE MEASUREMENT

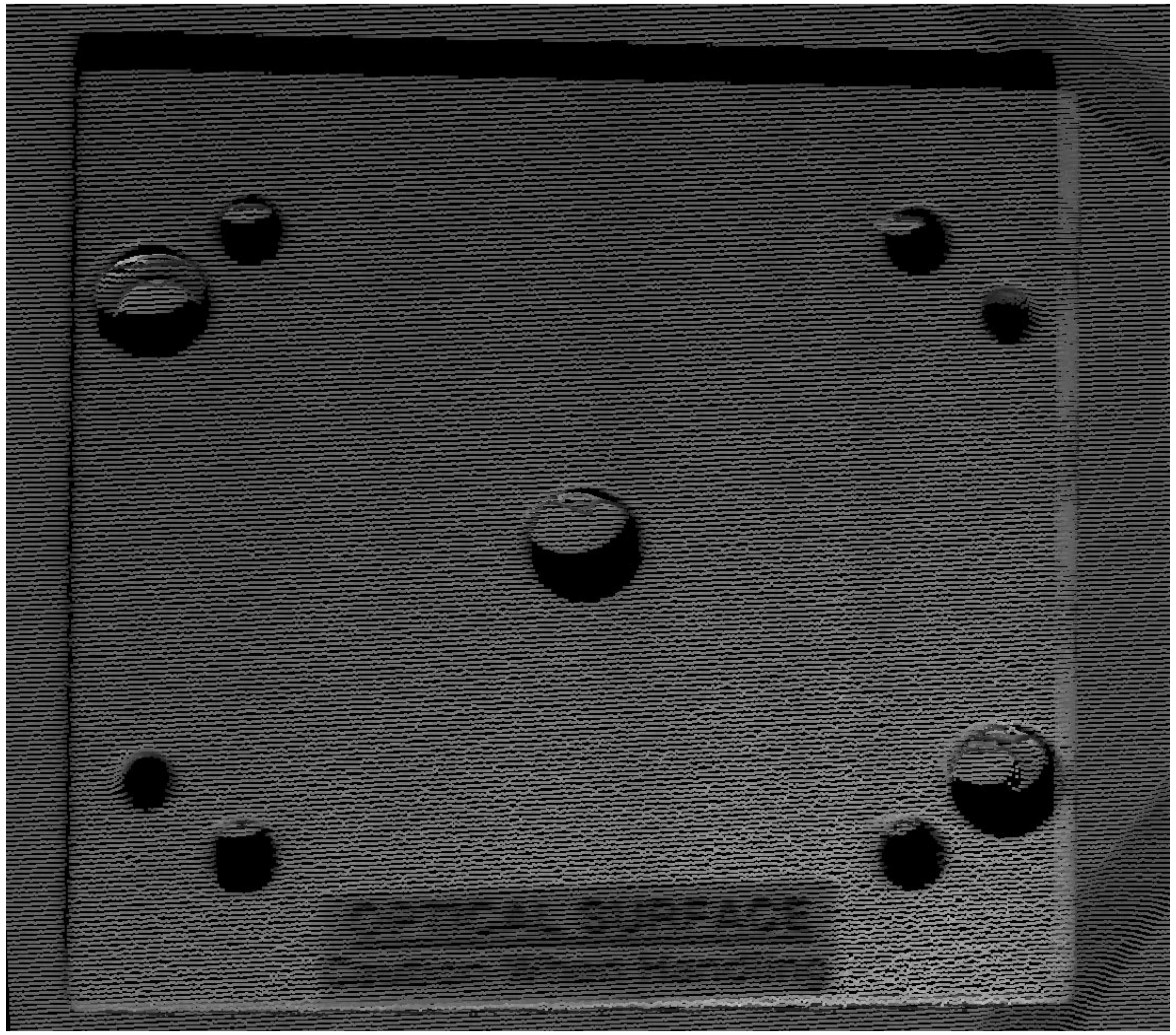
Time of Flight (ToF)

Phase Shift (PS)

Laser Radar

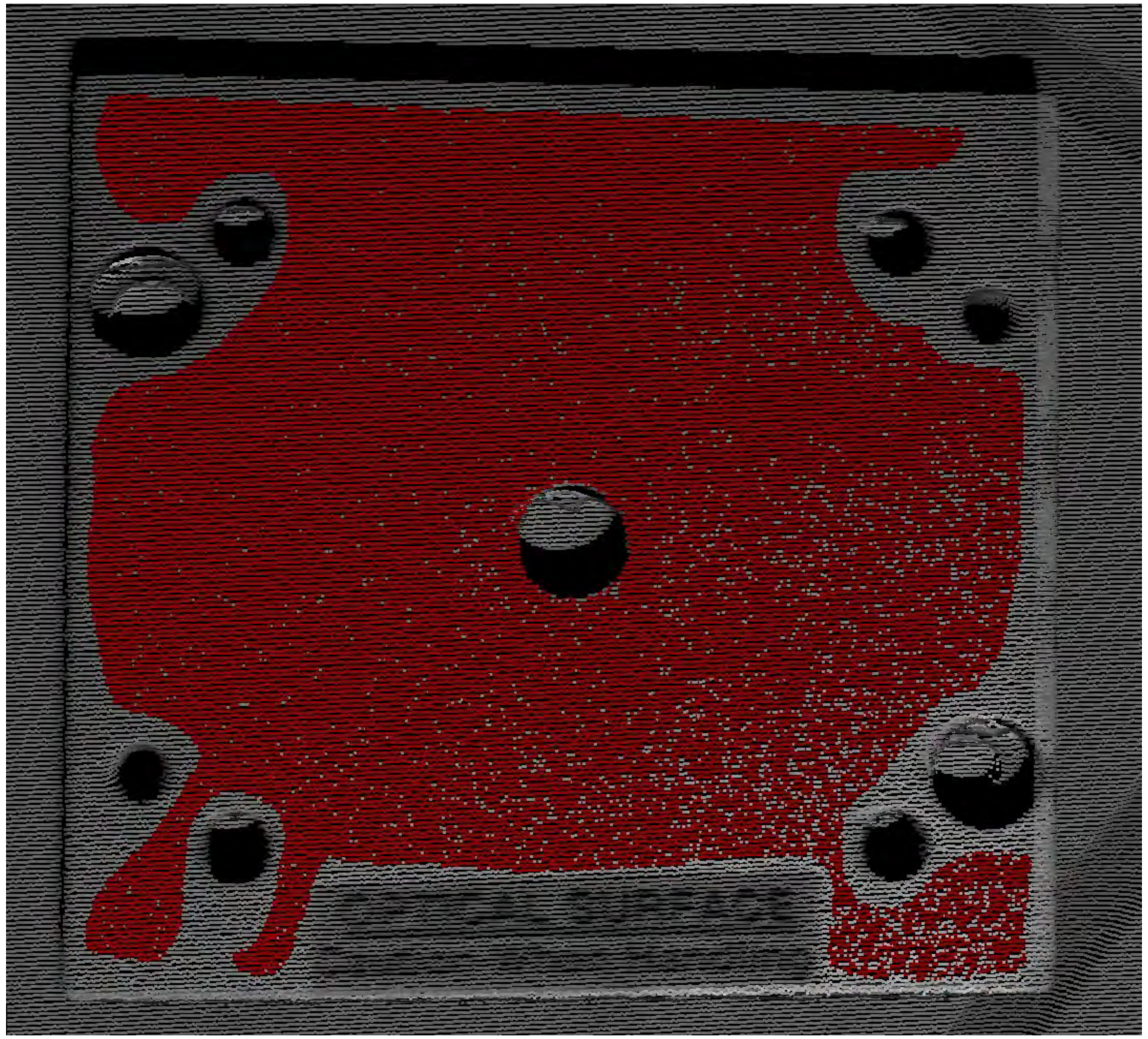
UNCERTAINTY IN 3D IMAGES – HOW TO EVALUATE IT

1. Scan a rectified plane whose deviation from the theoretical plane is at least 5 times lower than the measurement uncertainty that we try to evaluate



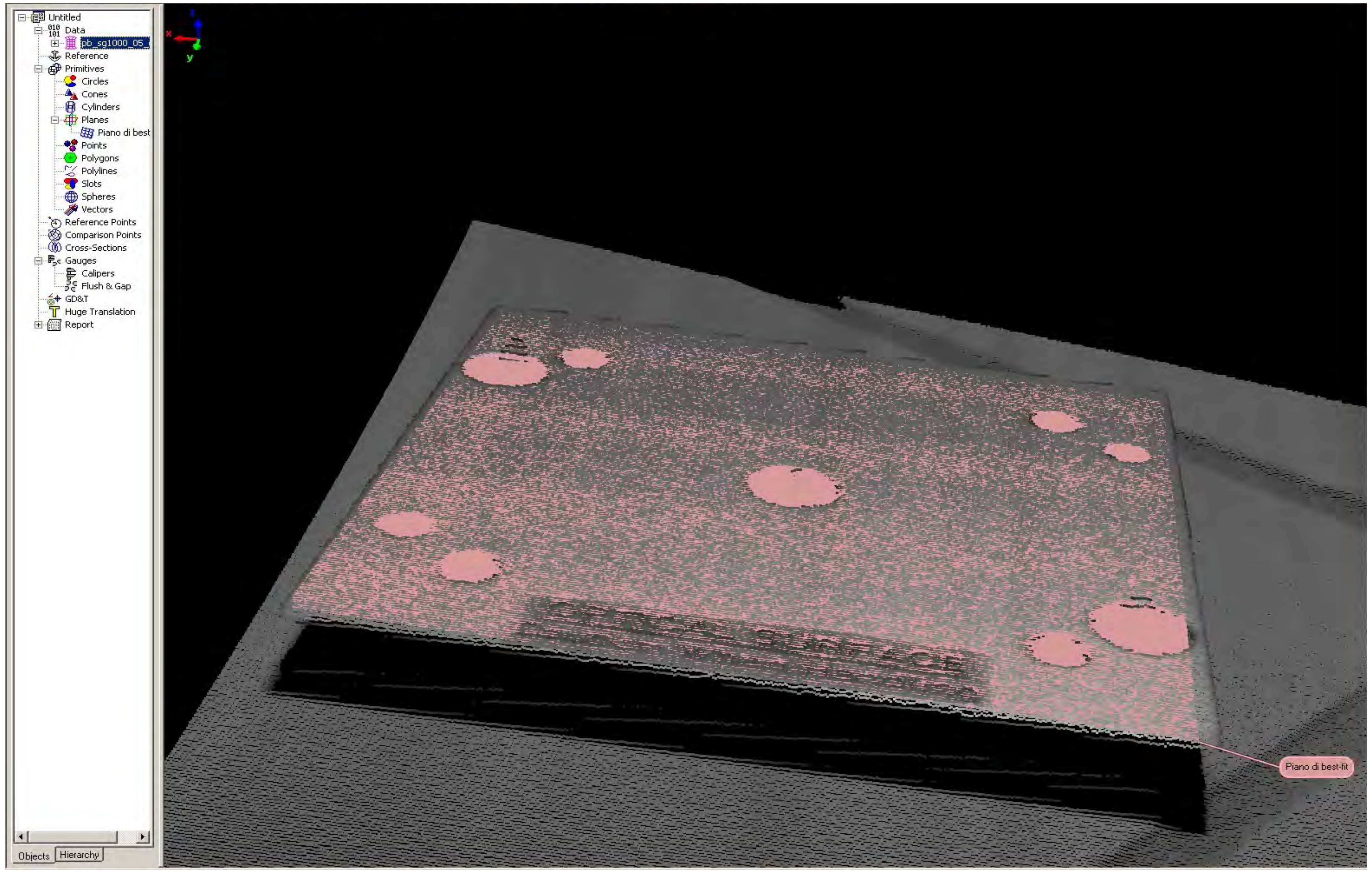
UNCERTAINTY IN 3D IMAGES – HOW TO EVALUATE IT

2. Select points belonging to the same plane



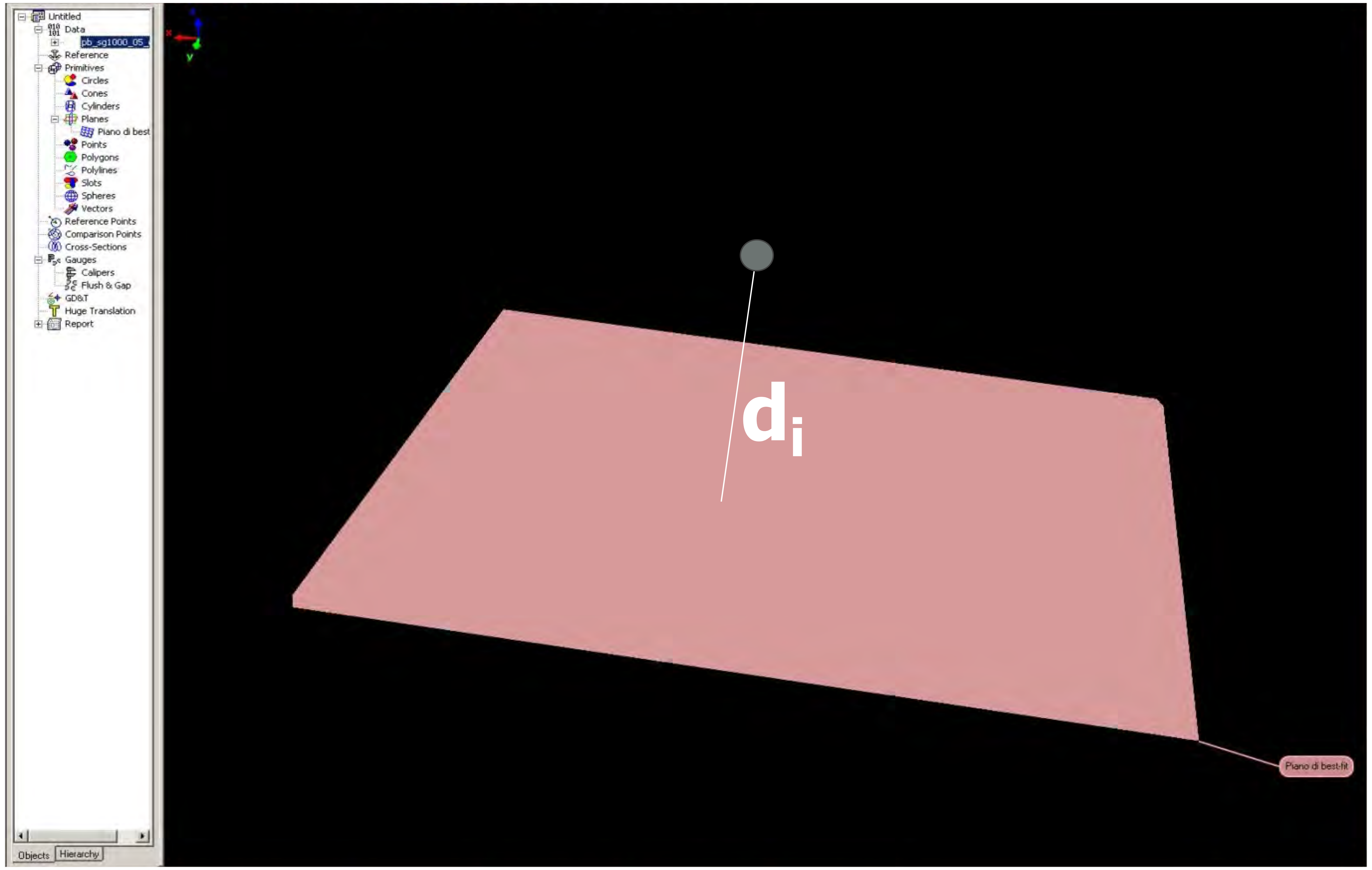
UNCERTAINTY IN 3D IMAGES – HOW TO EVALUATE IT

3. Calculate the best-fitting plane over the selected points



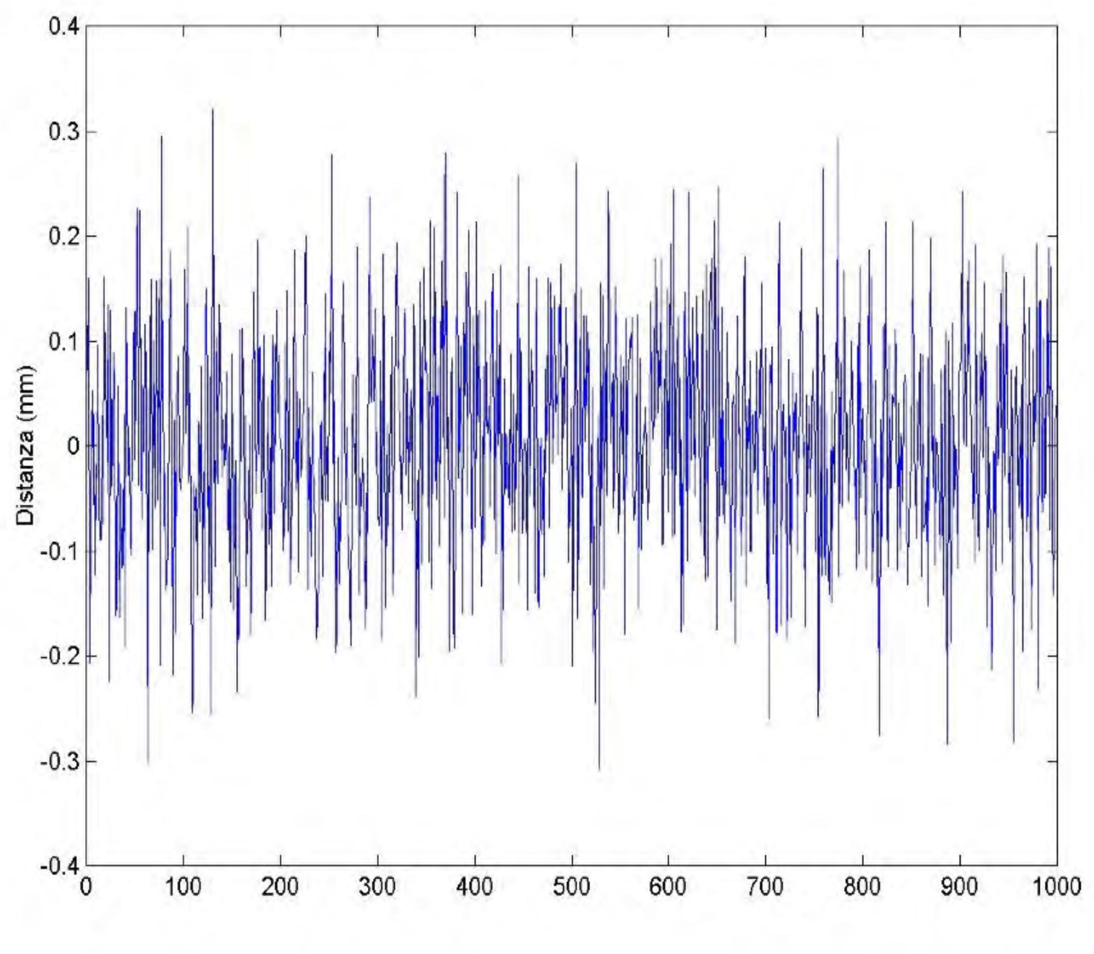
UNCERTAINTY IN 3D IMAGES – HOW TO EVALUATE IT

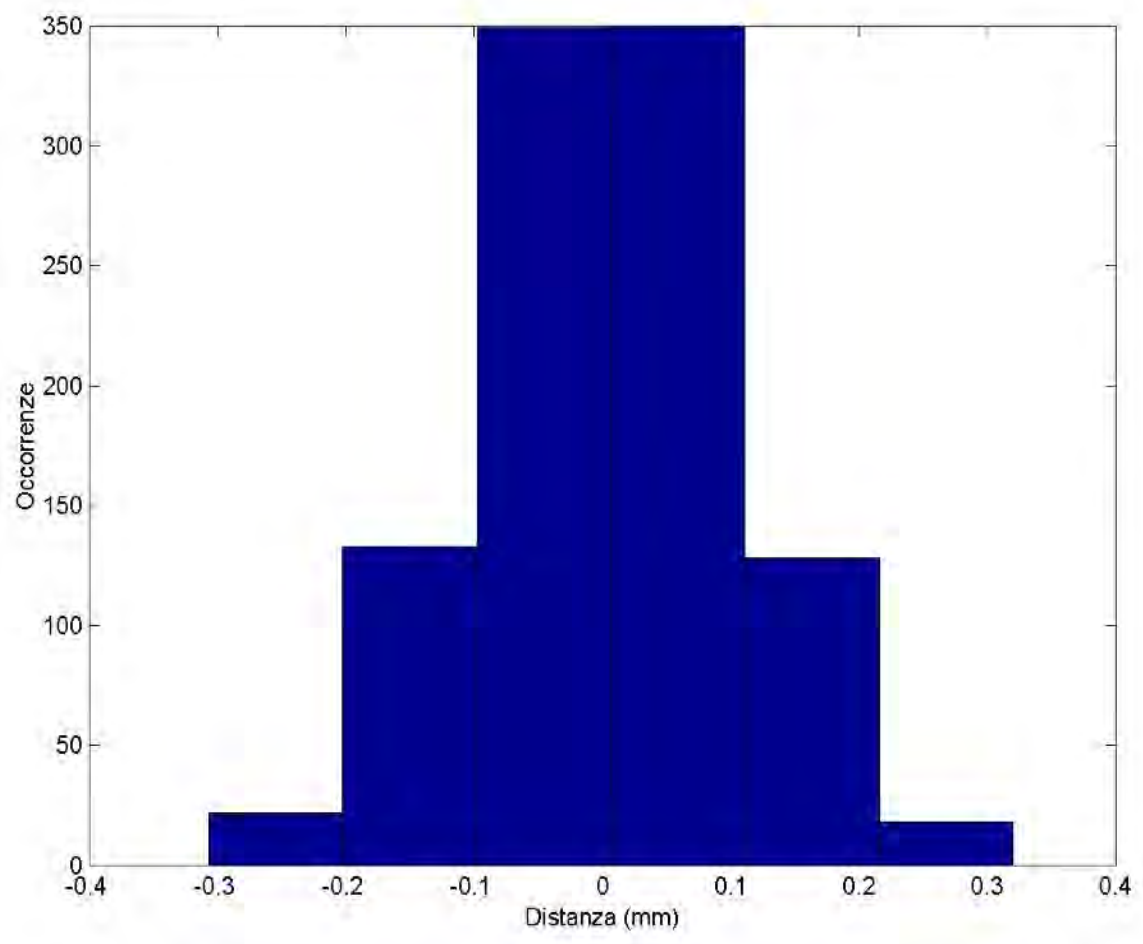
4. Evaluate the residuals between the fitting plane and the actual 3D points



UNCERTAINTY IN 3D IMAGES – HOW TO EVALUATE IT

5. Statistically analyze them

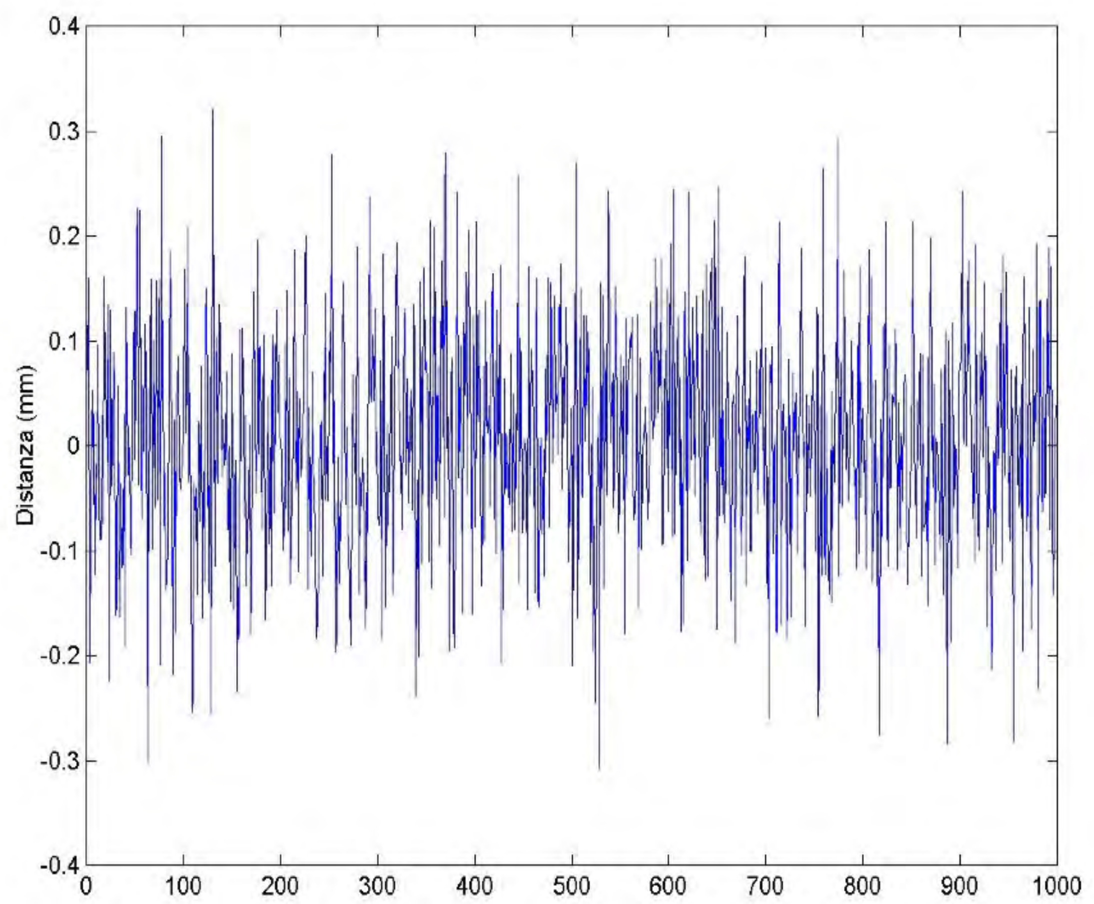


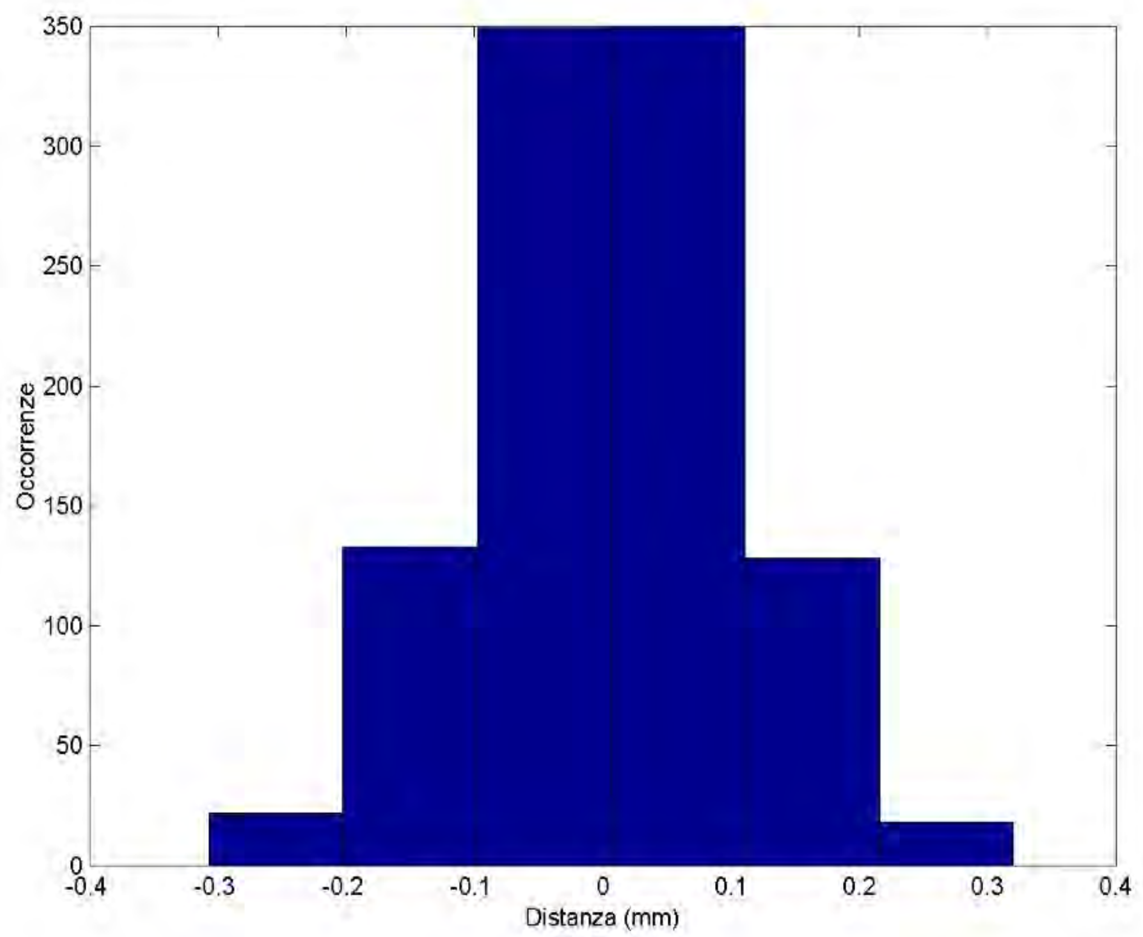


- 1000 points
- 6 classes

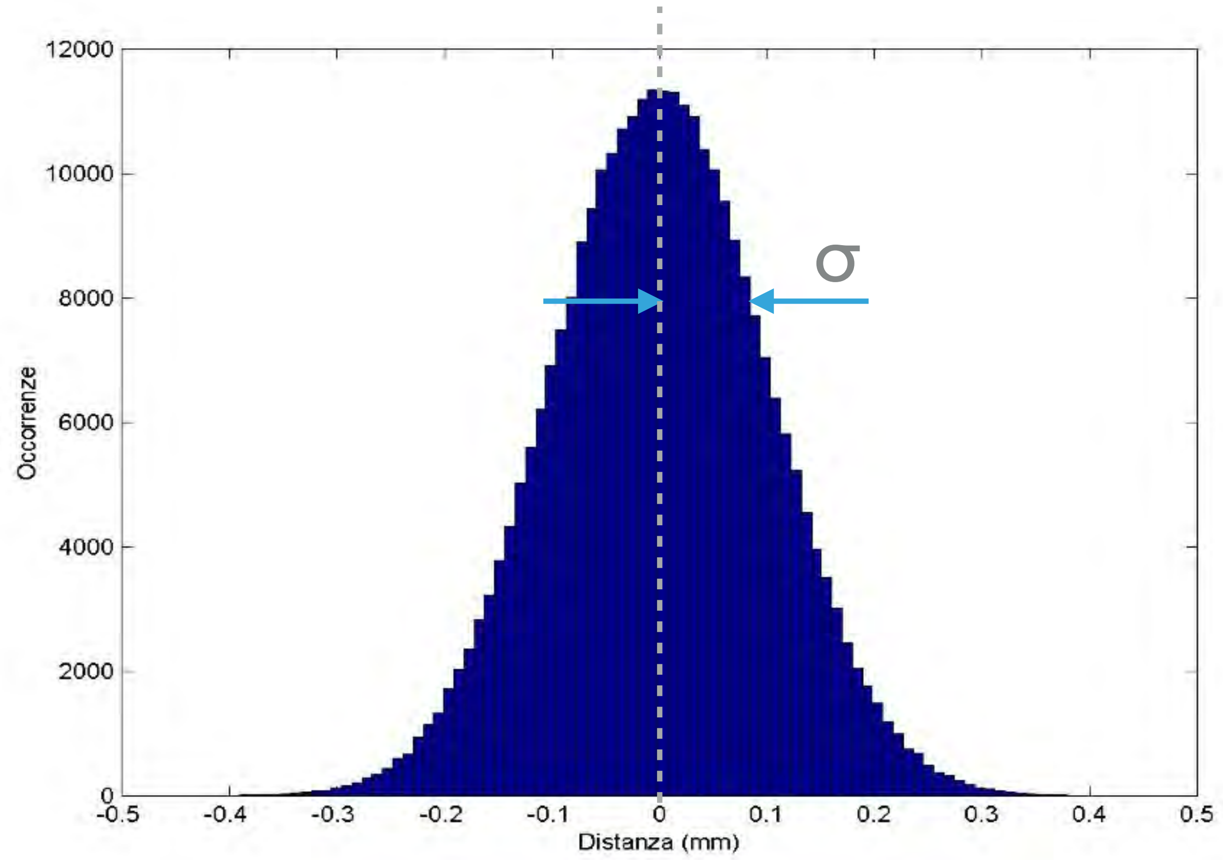
UNCERTAINTY IN 3D IMAGES – HOW TO EVALUATE IT

5. Statistically analyze them





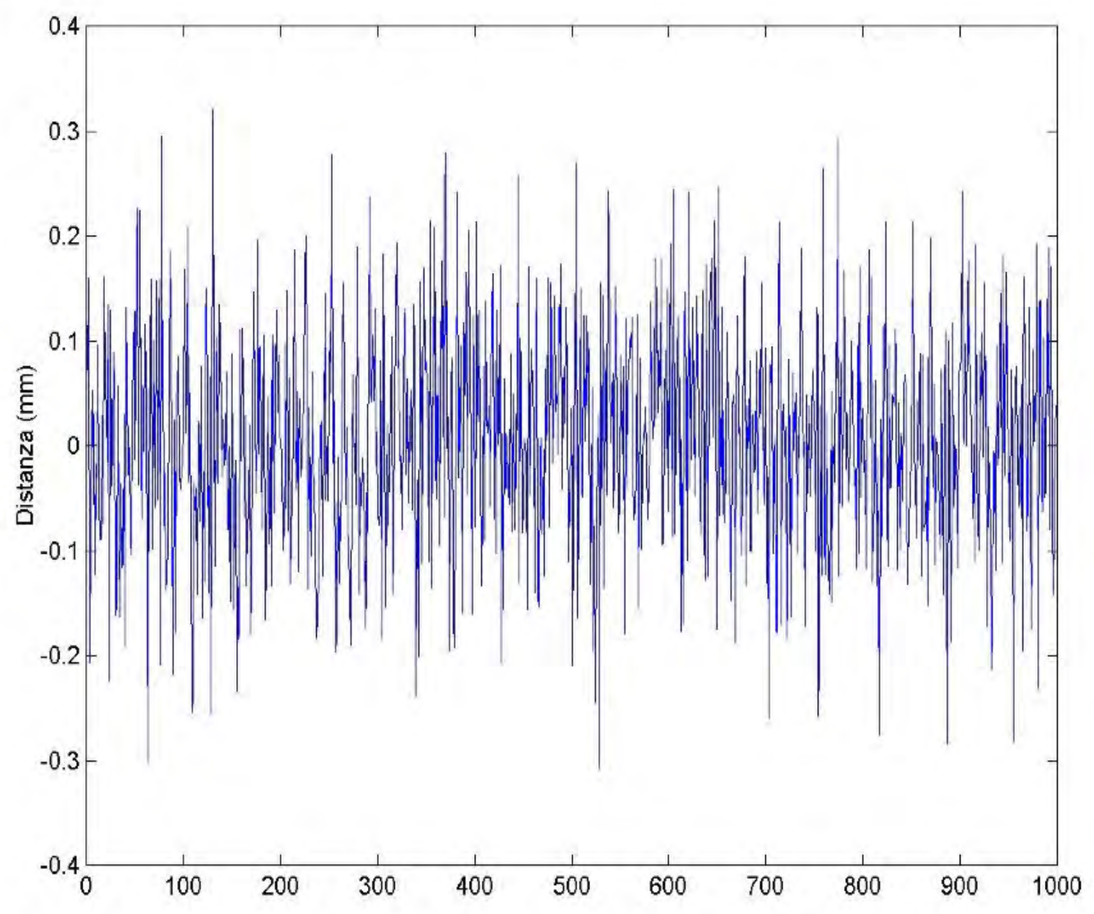
- 1000 points
- 6 classes

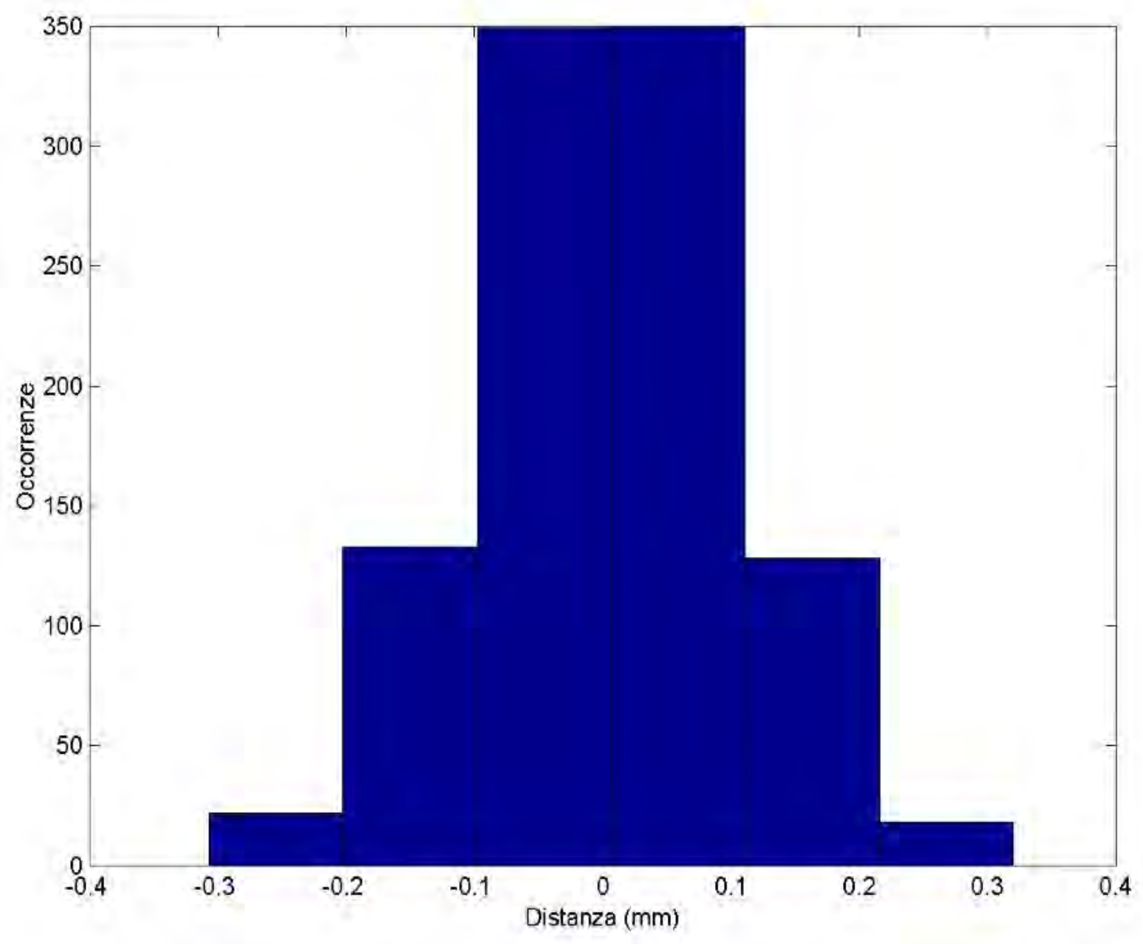


- 300,000 points
- 100 classes

UNCERTAINTY IN 3D IMAGES – HOW TO EVALUATE IT

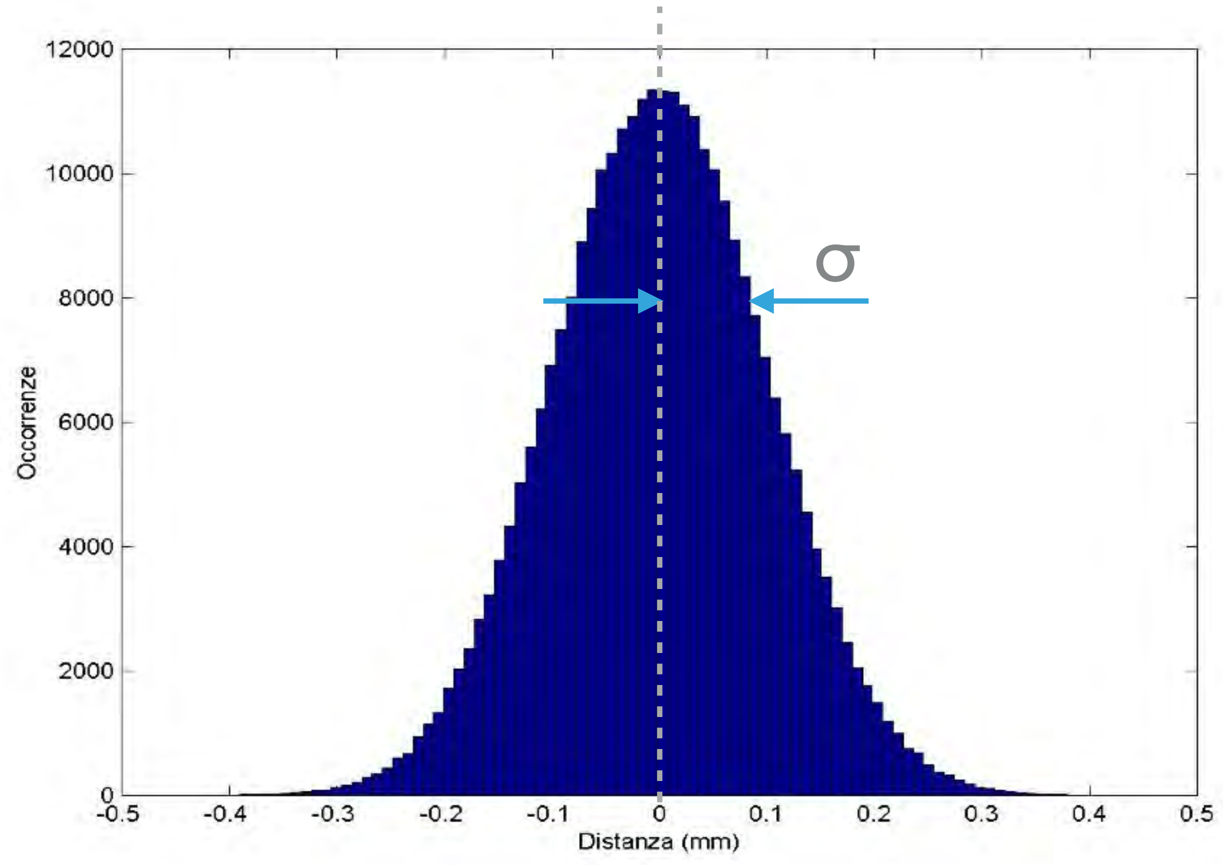
5. Statistically analyze them





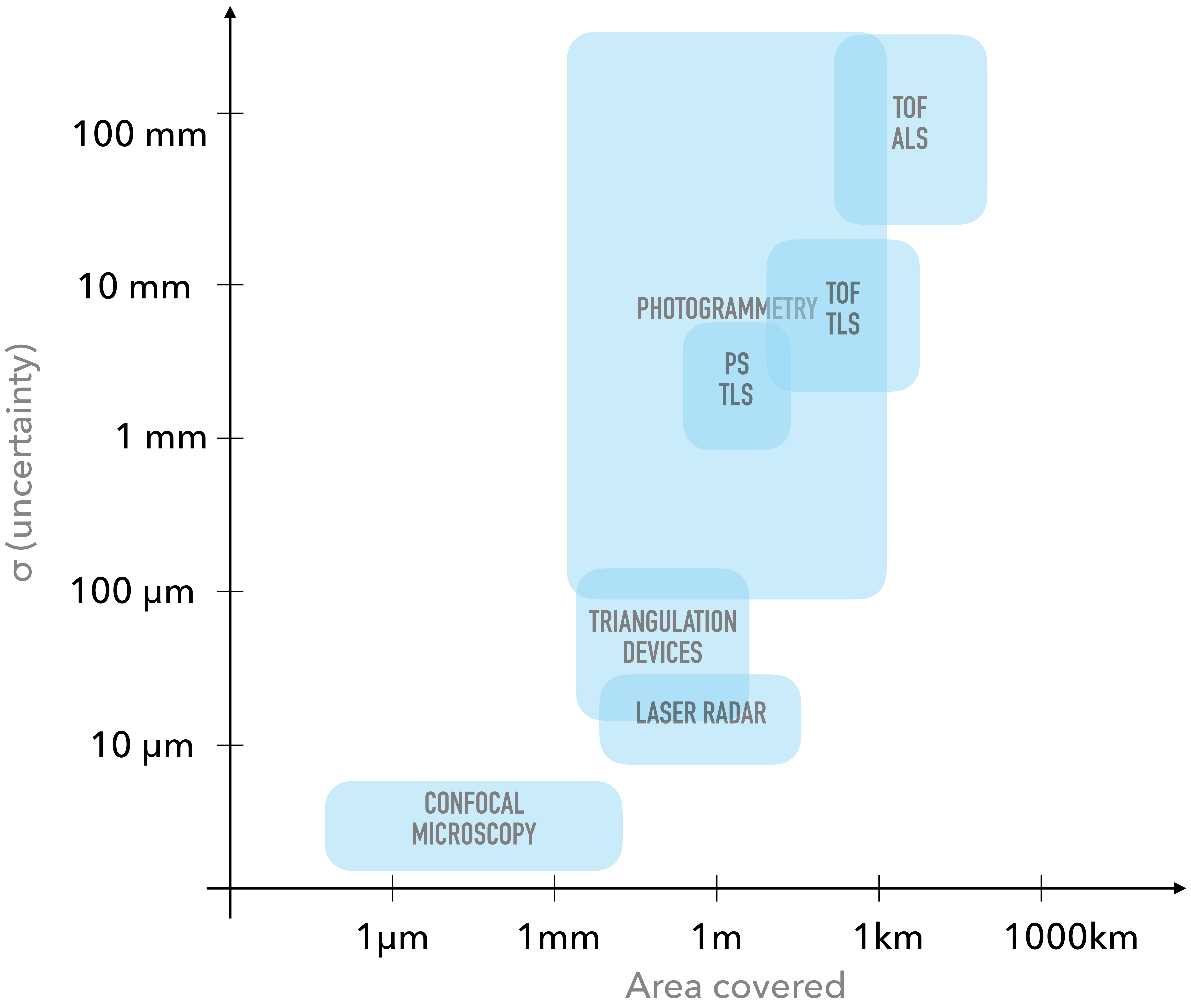
- 1000 points
- 6 classes

- Error with Gaussian distribution
- σ represents an uncertainty estimation



- 300,000 points
- 100 classes

IMAGED AREA VS. MEASUREMENT UNCERTAINTY



DIFFERENT ERROR VS. DISTANCE FOR DIFFERENT TECHNOLOGIES

Technology	σ trend
Active 3D sensors based on **triangulation**	Grows proportionally to the squared distance
Active 3D sensors based on **ToF**	Remains approximately constant with distance
Active 3D sensors based on **PS**	Slightly grows linearly with distance
Photogrammetry	Similar to the triangulation device if the camera-to-camera distance is fixed

3D SENSOR–FUSION MODALITIES

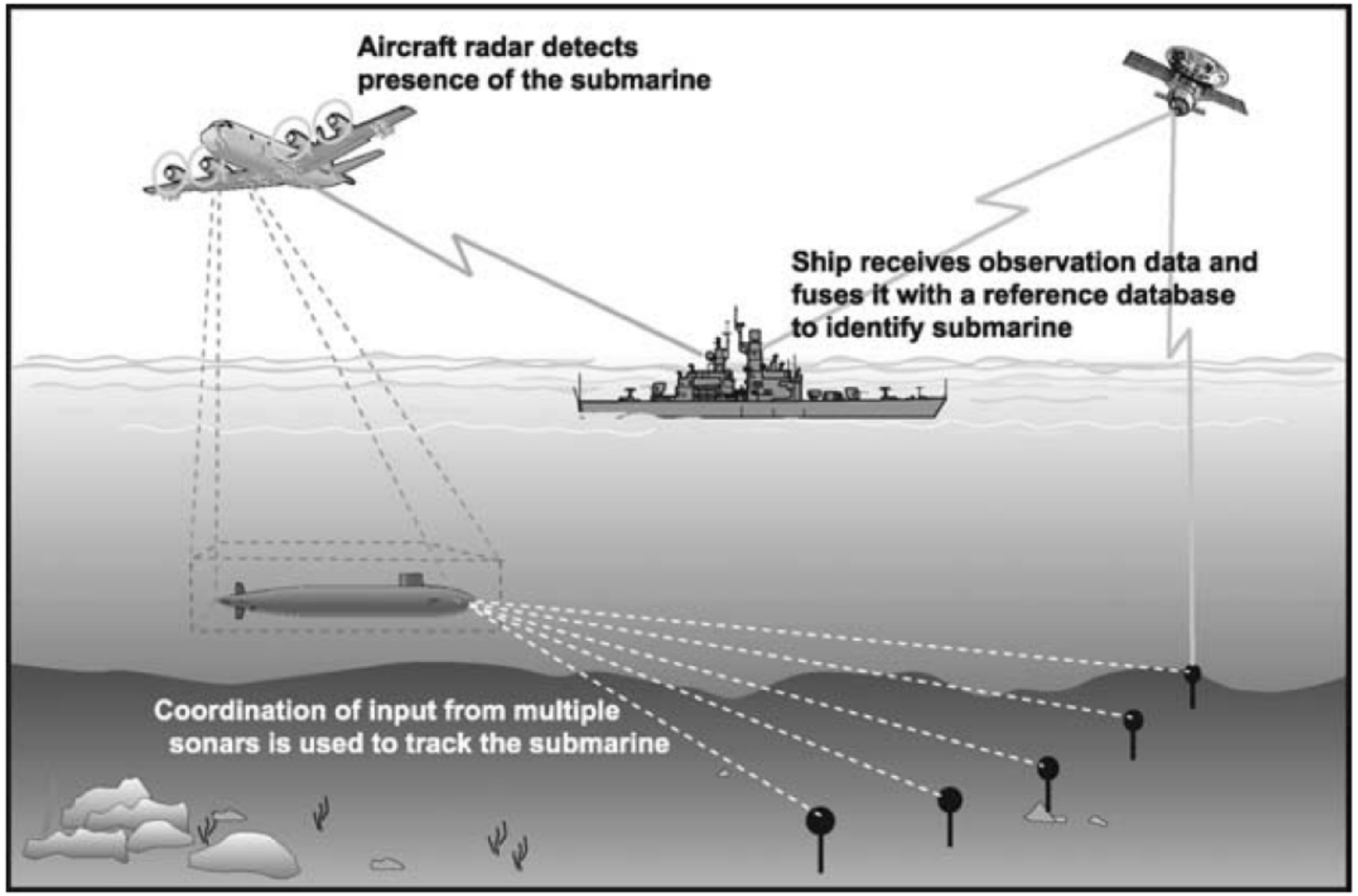
- **Complementary** - each sensor provides independent data about different aspects or attributes of the environment that are used for obtaining a more global view of it
- **Competitive** - each sensor measures independently the same or similar attributes. The data are then combined for improving the quality and the reliability of the measurement
- **Co-operative** - each sensor provides a piece of information that combined with those obtained by other sensors provides the final required information

Chandrasekaran, Balasubramaniyan, Shruti Gangadhar, and James M. Conrad. 2017. **A Survey of Multisensor Fusion Techniques, Architectures and Methodologies**. IEEE SOUTHEASTCON Conference Proceedings

3D IMAGE-FUSION PURPOSES

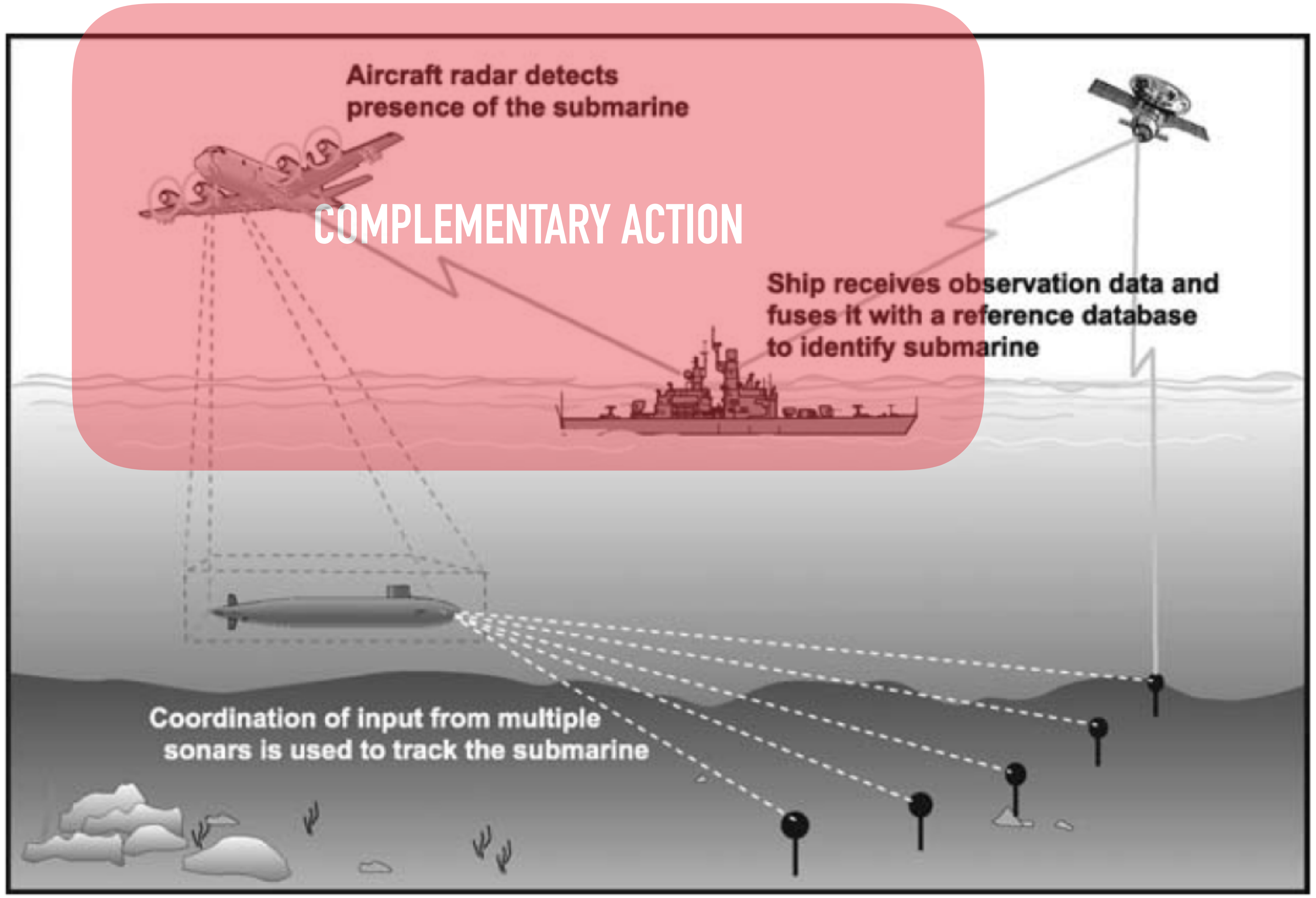
- reducing the measurement uncertainty through redundant 3D images from the same area (competitive)
- creating 3D images by composing the output of several complementary 3D devices (co-operative)
- obtaining a multi-resolution representation of a scenario combining different resolution 3D images (complementary)
- improving the accuracy of the 3D model originated by several 3D images (co-operative)

EXAMPLE OF 3D SENSOR-FUSION IN THE MILITARY FIELD



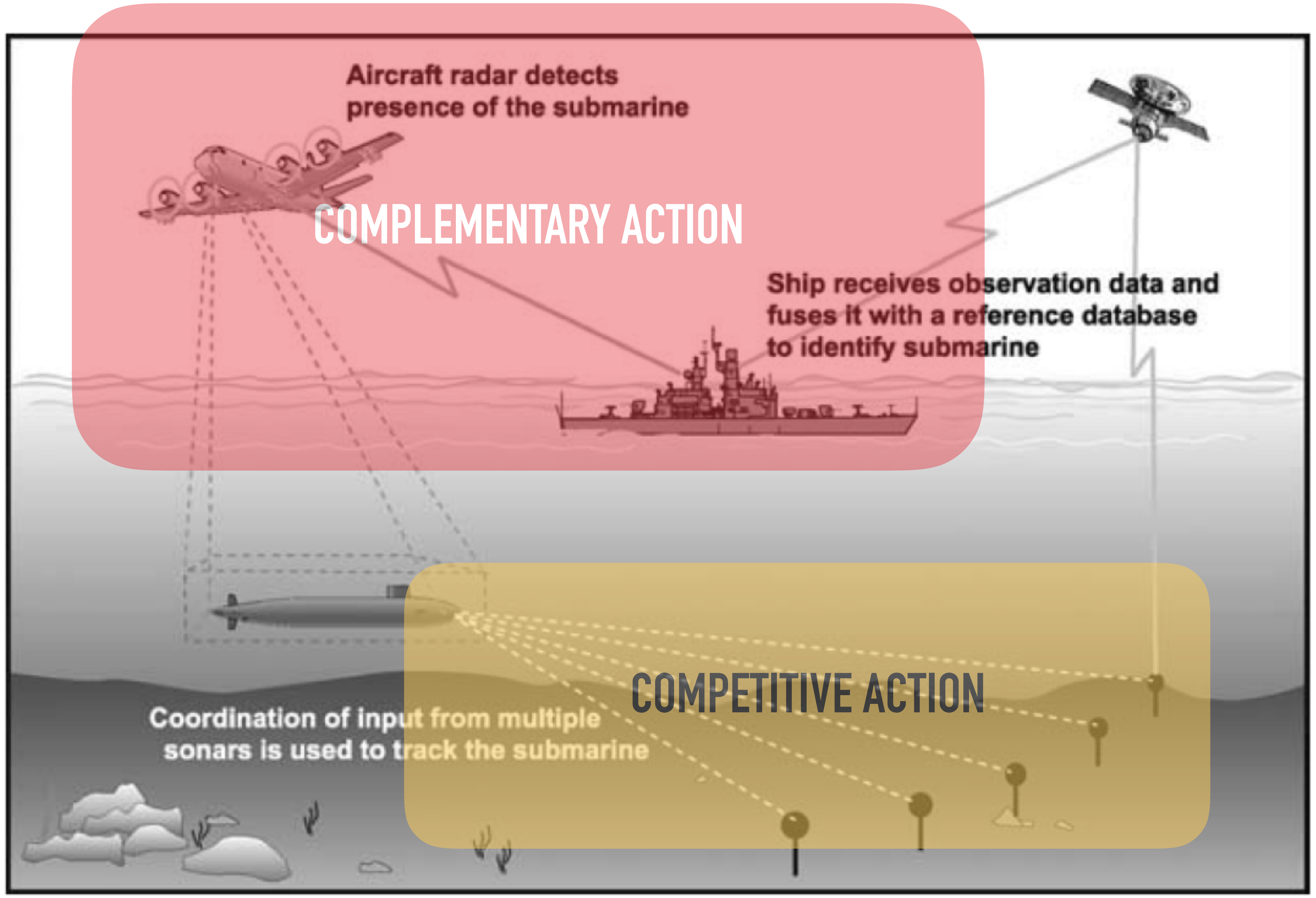
Liggins, Davis L. Hall, and James Llinas. 2008. *Handbook of Multisensor Data Fusion: Theory and Practice*. 2nd edition. Electrical Engineering & Applied Signal Processing 22. CRC Press

EXAMPLE OF 3D SENSOR-FUSION IN THE MILITARY FIELD



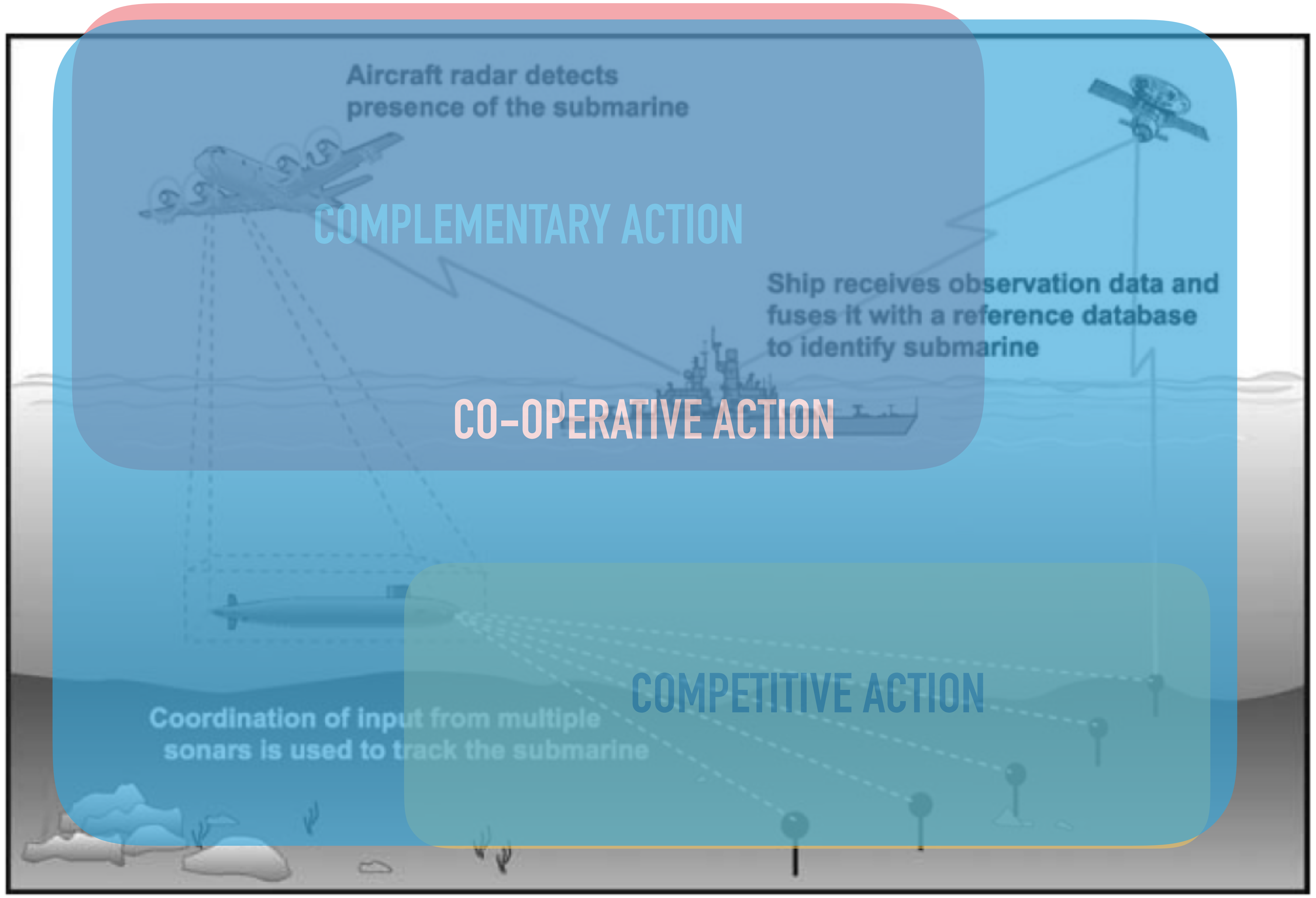
Liggins, Davis L. Hall, and James Llinas. 2008. *Handbook of Multisensor Data Fusion: Theory and Practice*. 2nd edition. Electrical Engineering & Applied Signal Processing 22. CRC Press

EXAMPLE OF 3D SENSOR-FUSION IN THE MILITARY FIELD



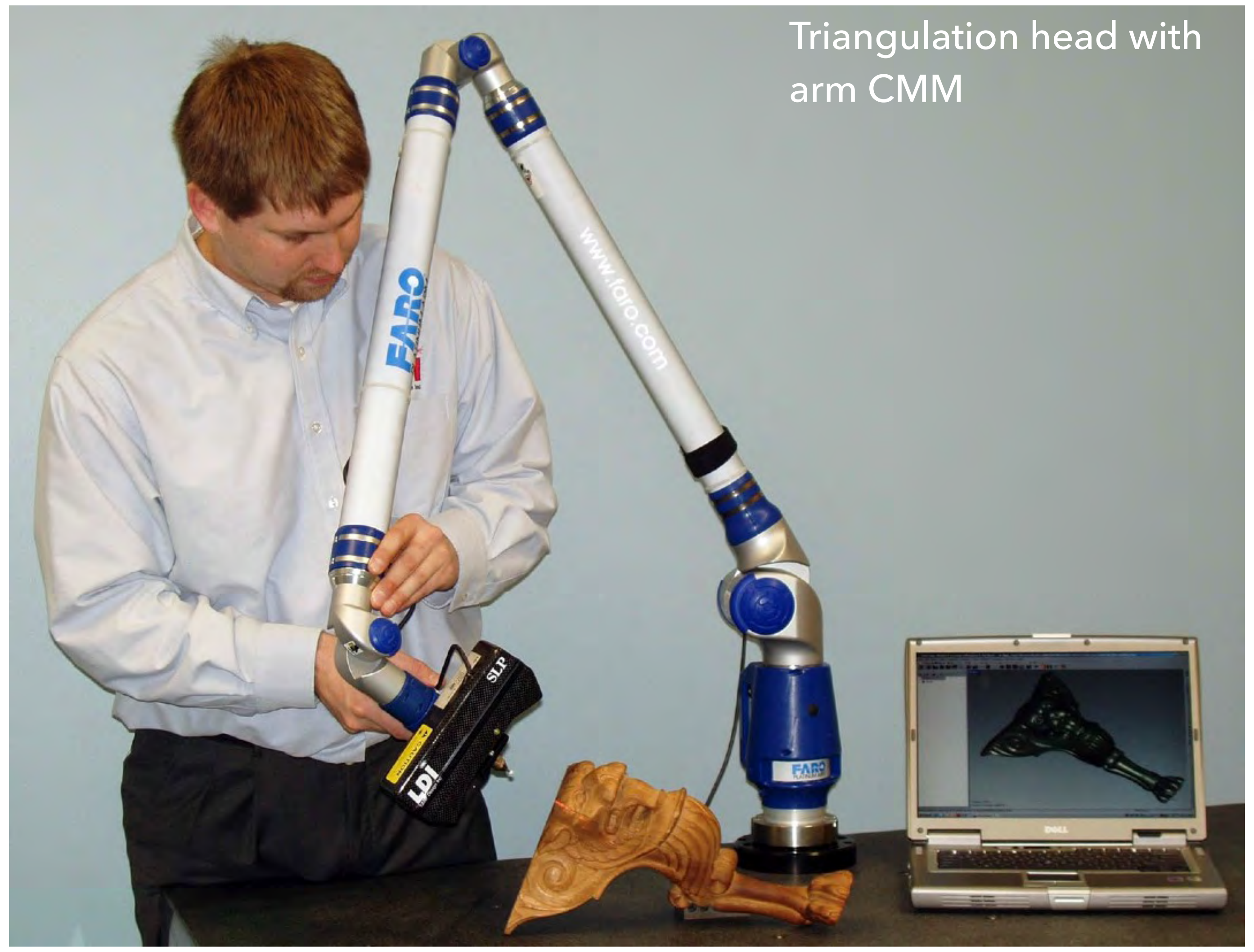
Liggins, Davis L. Hall, and James Llinas. 2008. *Handbook of Multisensor Data Fusion: Theory and Practice*. 2nd edition. Electrical Engineering & Applied Signal Processing 22. CRC Press

EXAMPLE OF 3D SENSOR-FUSION IN THE MILITARY FIELD



Liggins, Davis L. Hall, and James Llinas. 2008. *Handbook of Multisensor Data Fusion: Theory and Practice*. 2nd edition. Electrical Engineering & Applied Signal Processing 22. CRC Press

HANDLED 3D IMAGING SYSTEMS (CO-OPERATIVE)



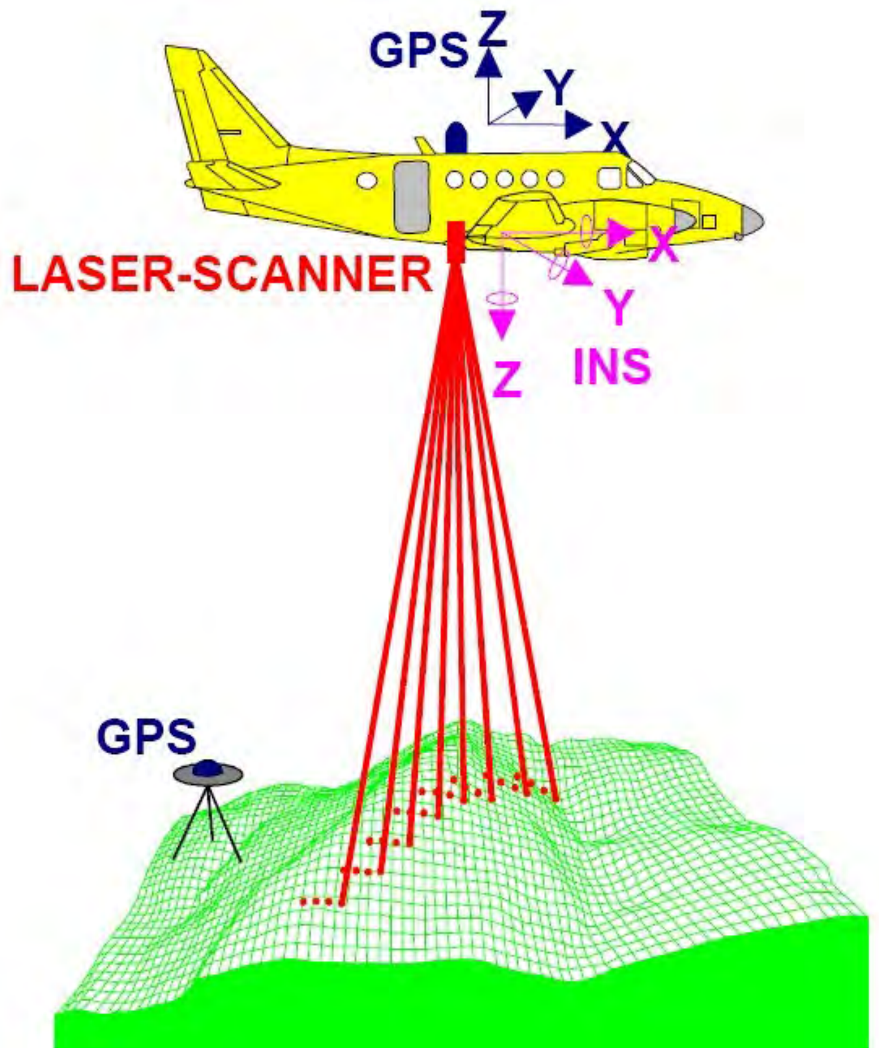
Triangulation head with arm CMM

Triangulation head with laser tracker


Triangulation system with vision system for orientation


Triangulation system with triangulation tracker

ACTIVE SYSTEMS FOR MOBILE MAPPING (CO-OPERATIVE)



Airborn Laser Scanner (ALS)

Laser Scanner on a car

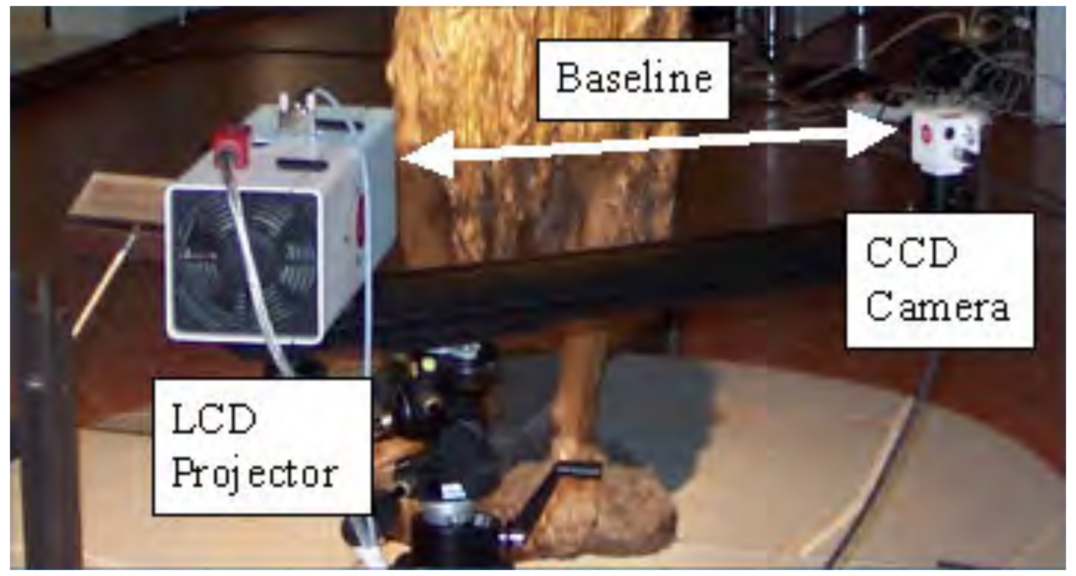
Robot based mobile mapping system

Wearable mobile mapping system

3D DIGITIZATION OF DONATELLO'S MAGDALEN

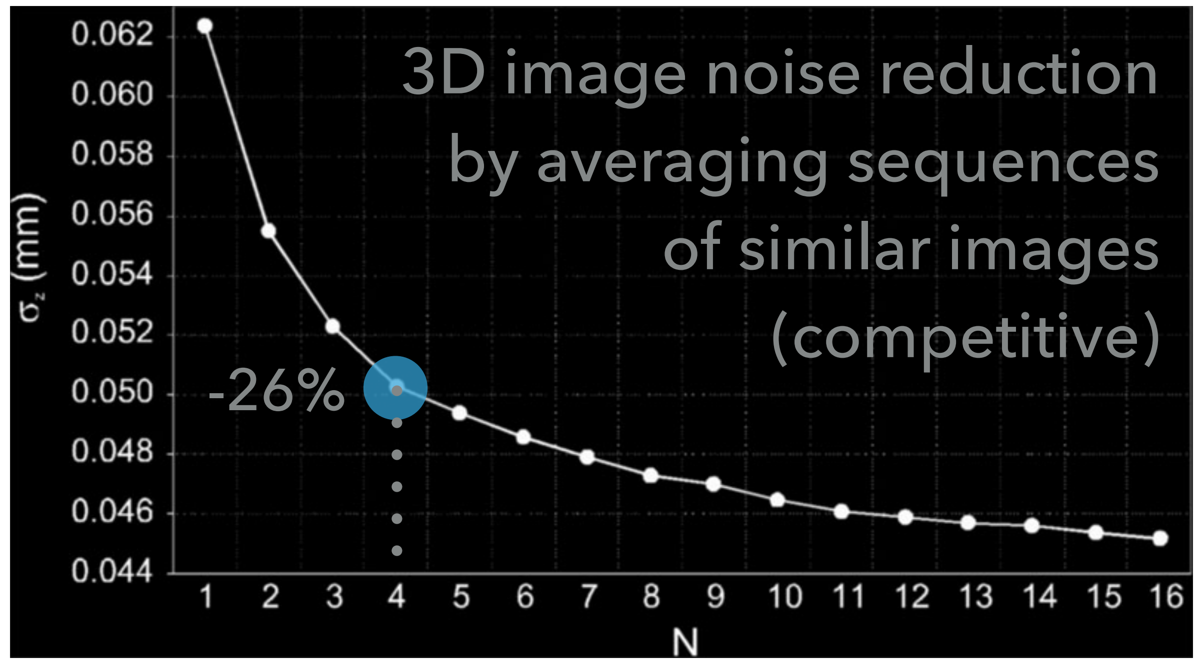
- Sculpted in 1455 approx. and conserved at the "Museo Opera del Duomo" in Florence (Italy)
- Height 180 cm
- Width 40 cm
- Wooden statue originally gold coated: currently dark with reflective spots (optically difficult material)
- Complex shape involving shades and fragmented range maps

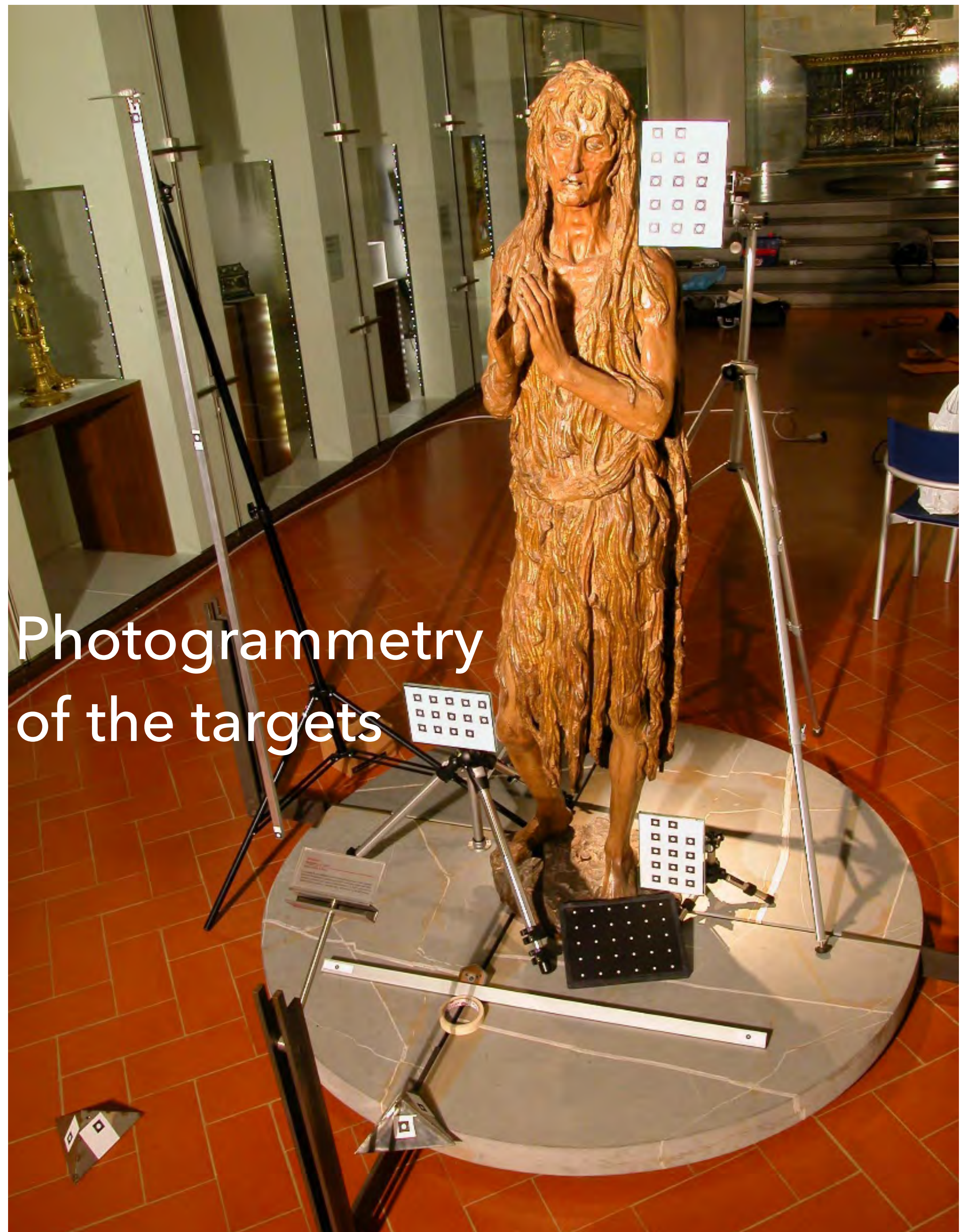
INITIAL 3D PROCESS USED FOR THE MAGDALEN PROJECT

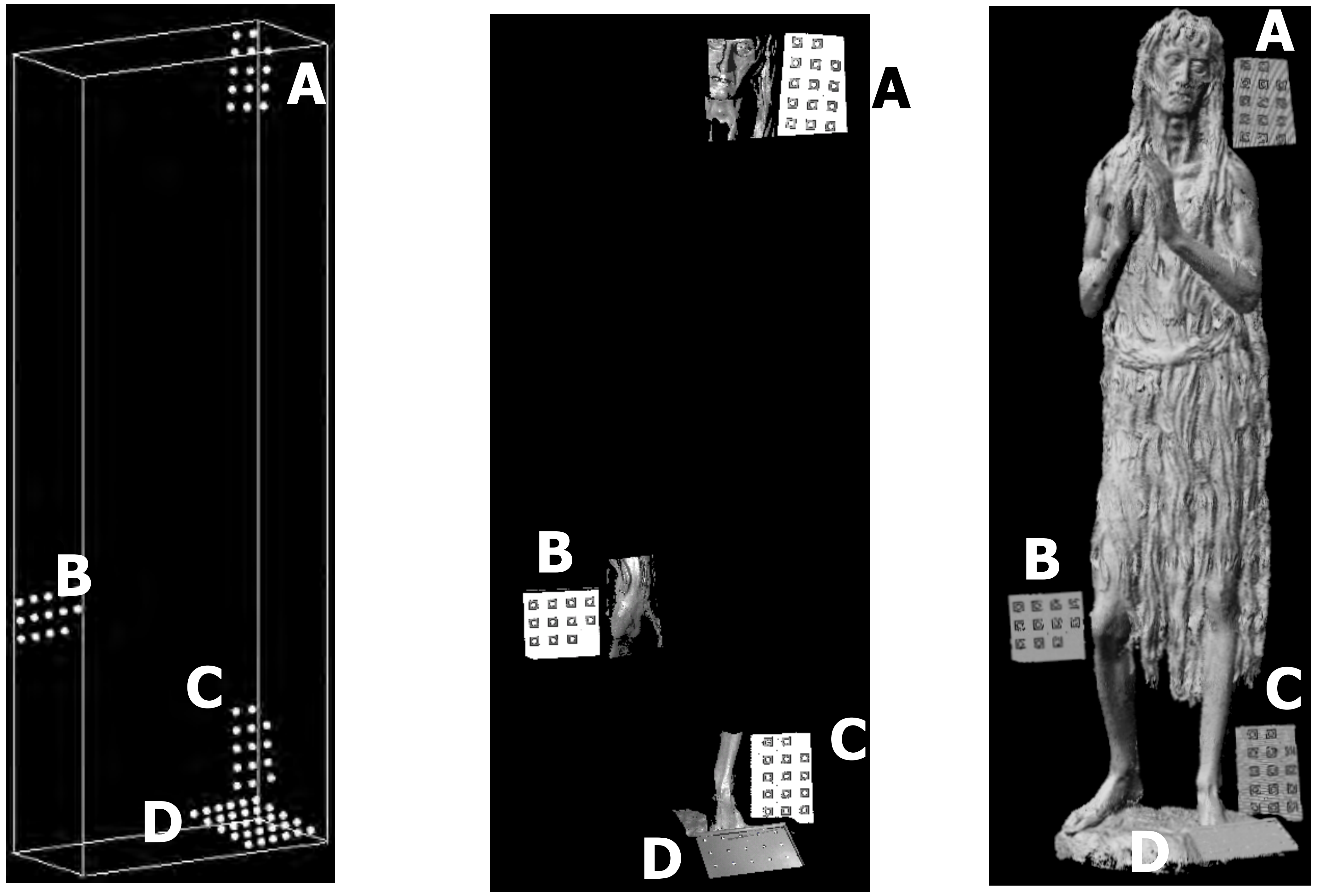


- Pattern projection range device
  - Measuring range: 0.5-1.2 m
  - Measurement uncertainty: 0.05-0.2 mm
  - Measurement resolution: 0.5-0.1 mm
- The 3D model originated by the alignment of 250+ 3D images, resulted to be distorted for the specific process used (ICP)
- An integrated method was developed, by merging passive and active 3D sensing

ENHANCED 3D PROCESS USED FOR THE MAGDALEN PROJECT







Orientation of few key 3D images according to photogrammetry and alignment of all the sculpture to these constrained 3D images (co-operative)

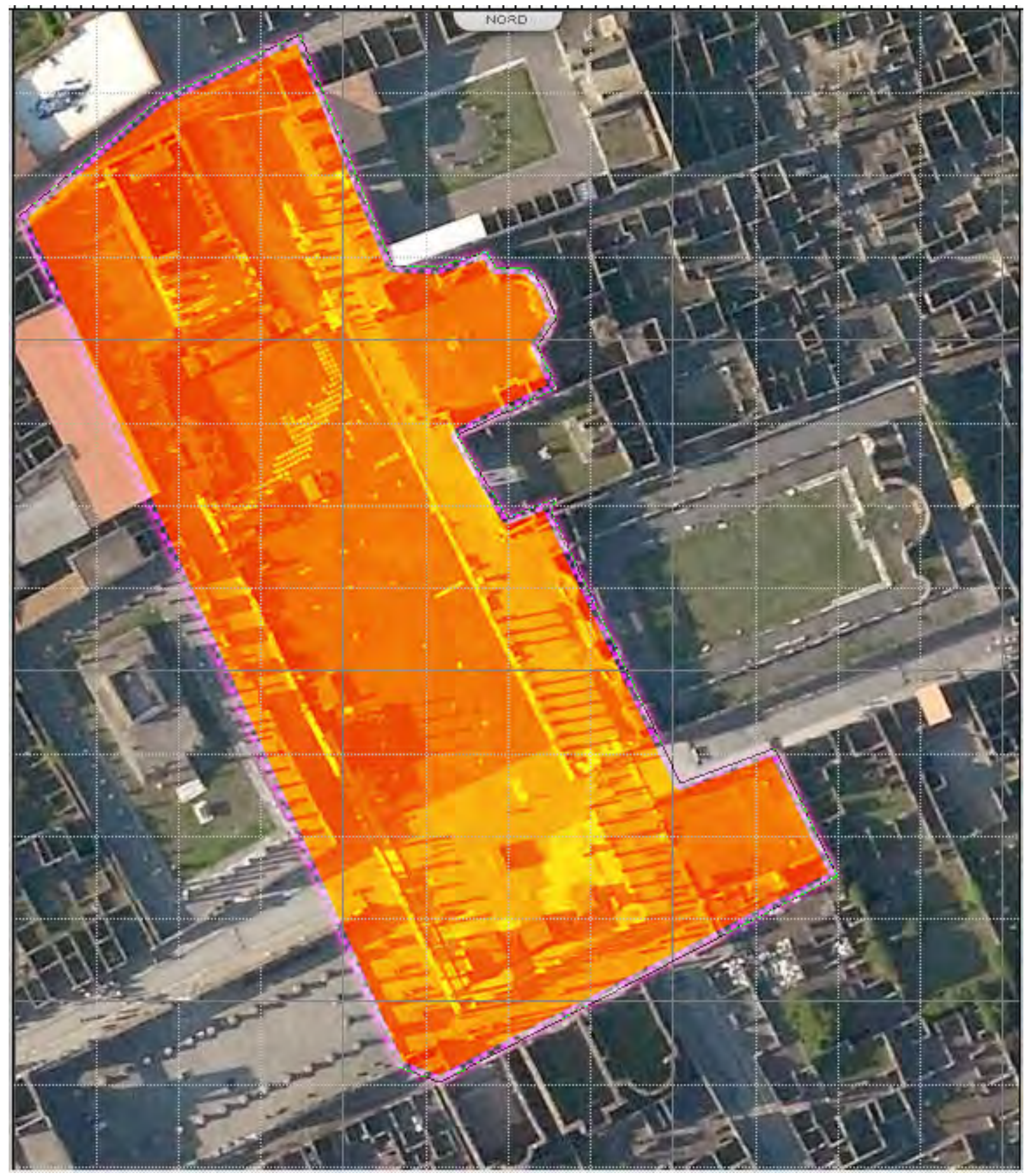
The final check revealed a correction of lateral deformations up to 18.9 mm

Guidi, Gabriele, Jean-Angelo Beraldin, and Carlo Atzeni. 2004. **High-Accuracy 3-D Modeling of Cultural Heritage: The Digitizing of Donatello's 'Maddalena**. IEEE Transactions on Image Processing 13 (3): 370–380.

3D IMAGING OF THE POMPEI FORUM

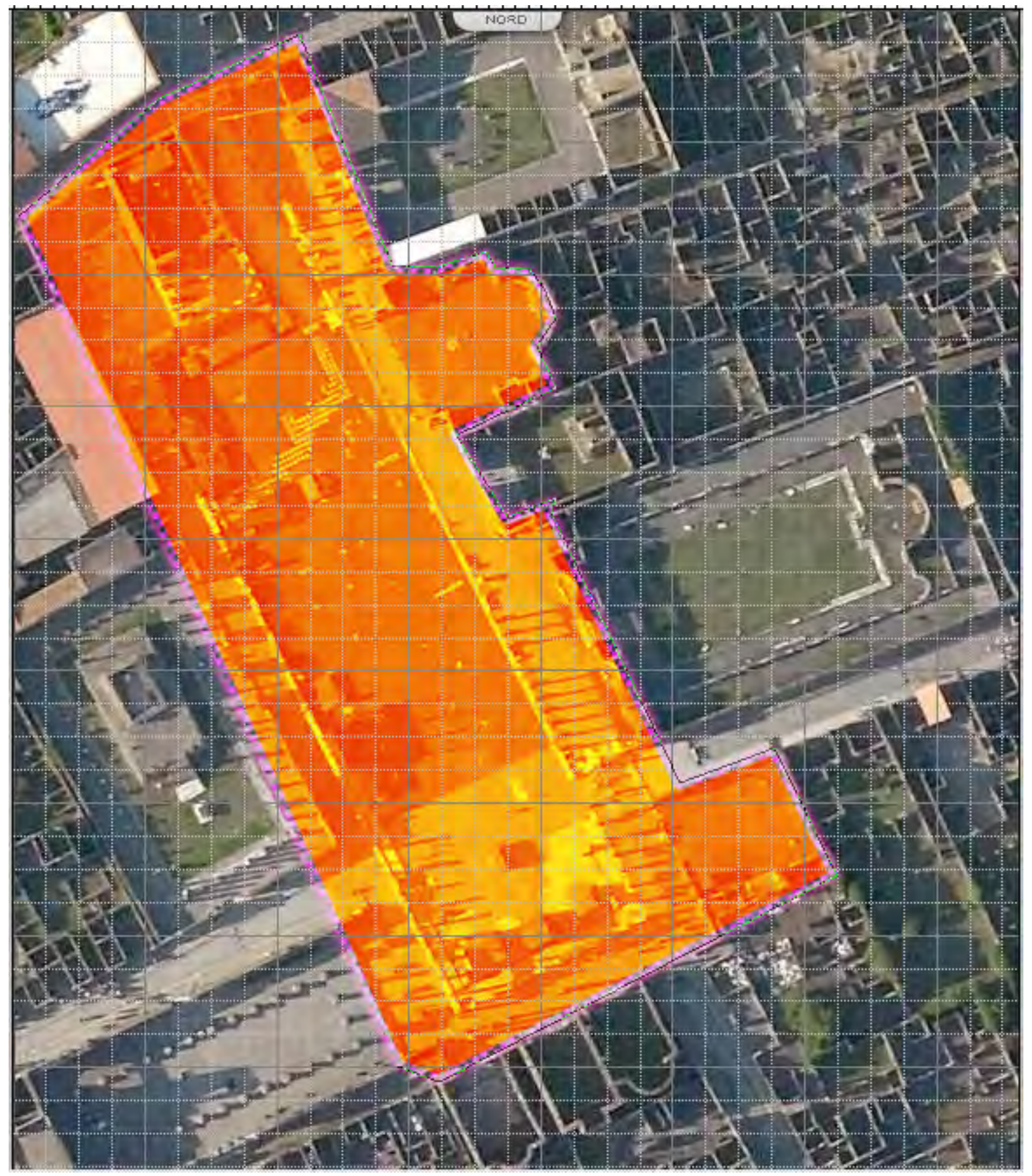
SEVERAL DIFFERENT LEVEL OF DETAIL REQUIRED FOR GATHERING THE NEEDED 3D REPRESENTATION OF THE FORUM

MULTIRESOLUTION INTEGRATED APPROACH



Low resolution (1 to 0.25 m)

- Aerial Images
- GPS
- Traditional topography



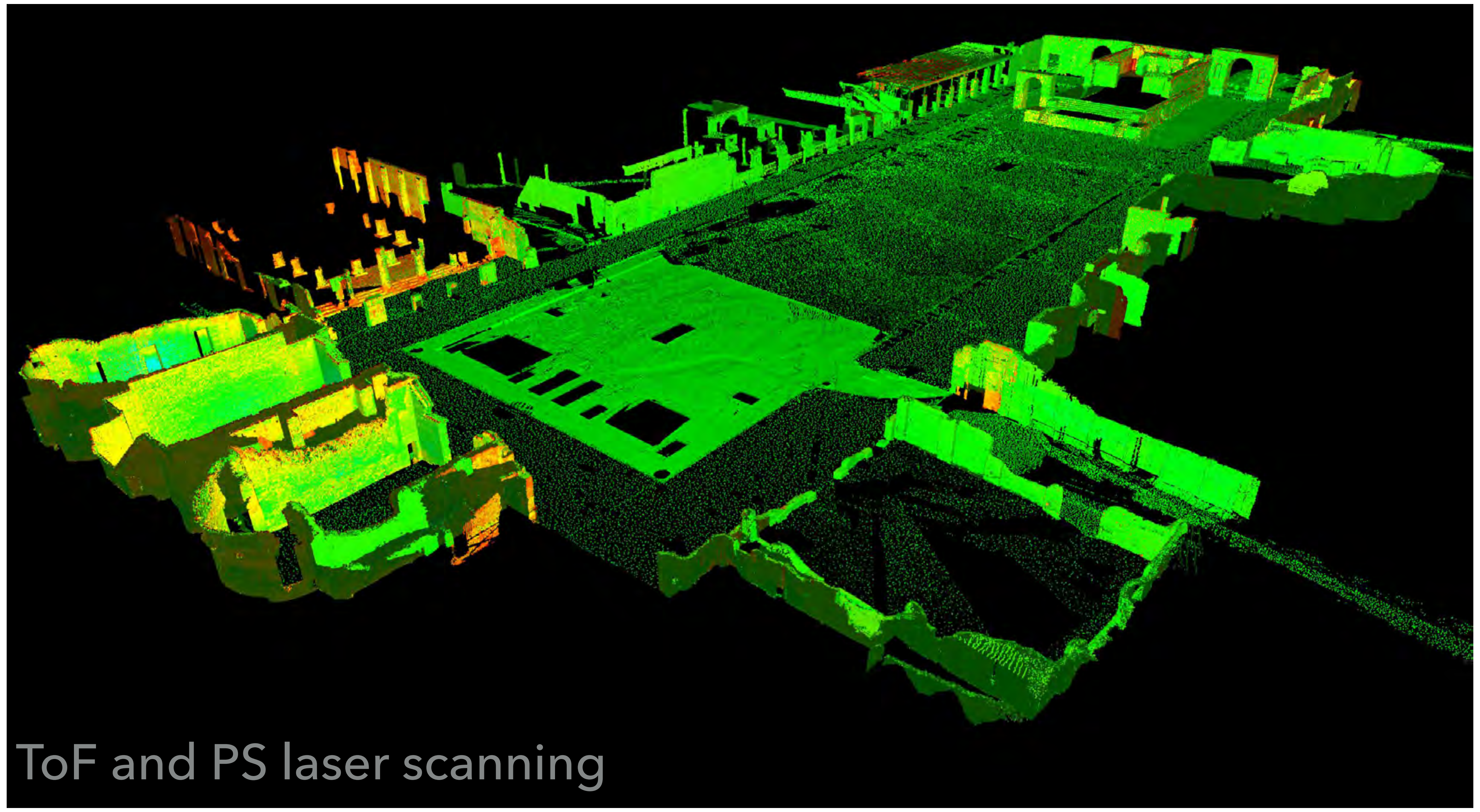
Medium resolution (20 to 5 mm)

- ToF laser scanning
- PS laser scanning
- Traditional photogrammetry

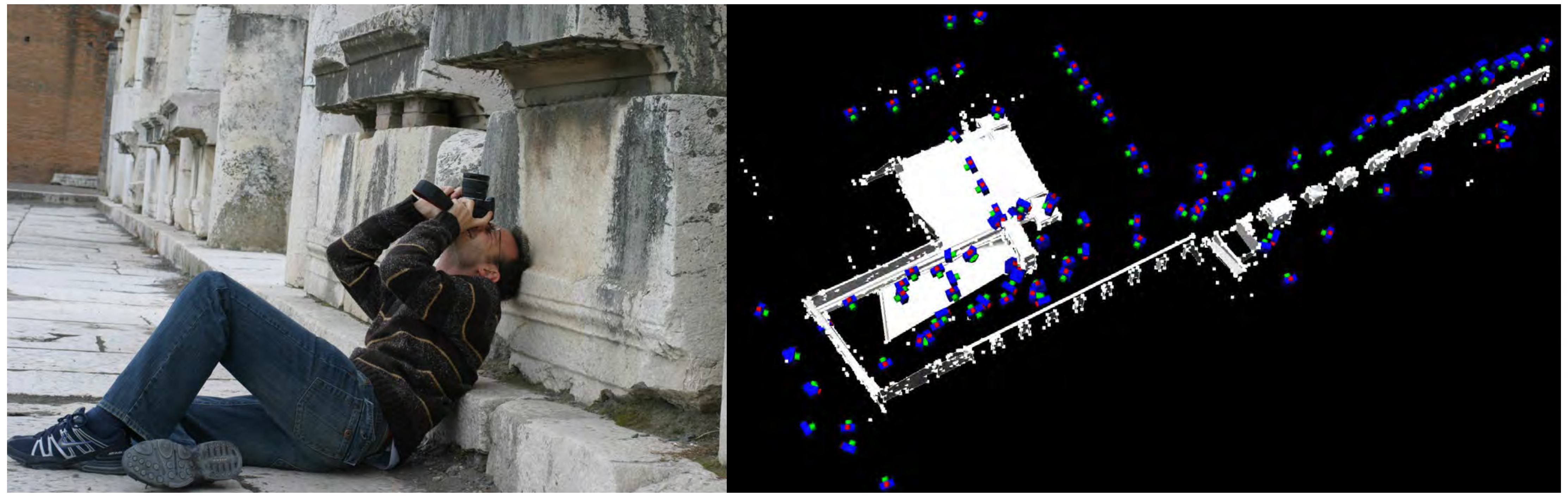
High resolution (up to 0.5 mm)

- Automatic photogrammetry with Structure from Motion (SfM) and Image Matching (IM)

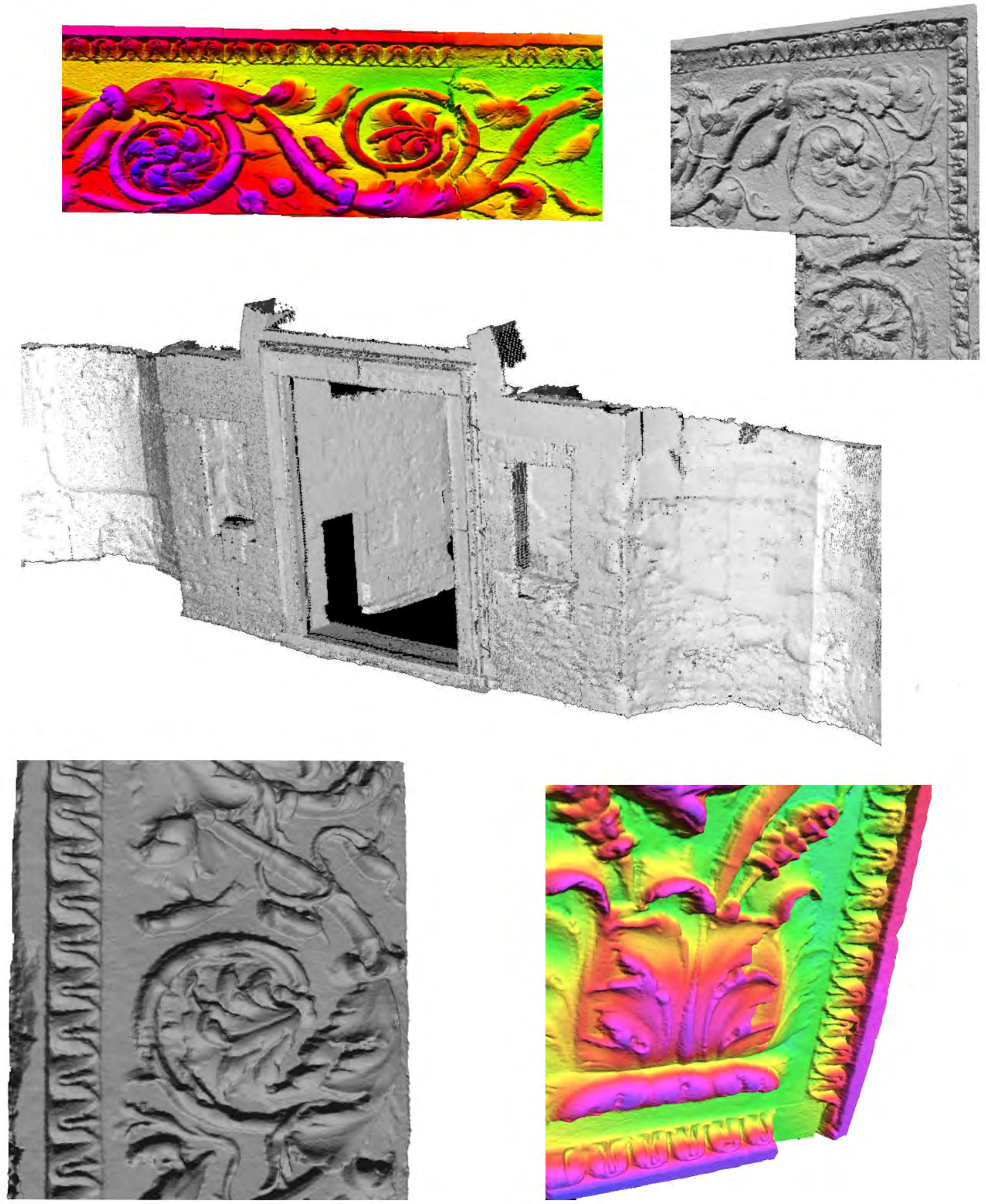
3D TECHNOLOGIES IN ACTION



ToF and PS laser scanning



Traditional photogrammetry



SFM/IM photogrammetry

3D RESULTS

Traditional photogrammetry models

Laser scan + image texturing models

Automatic photogrammetry model

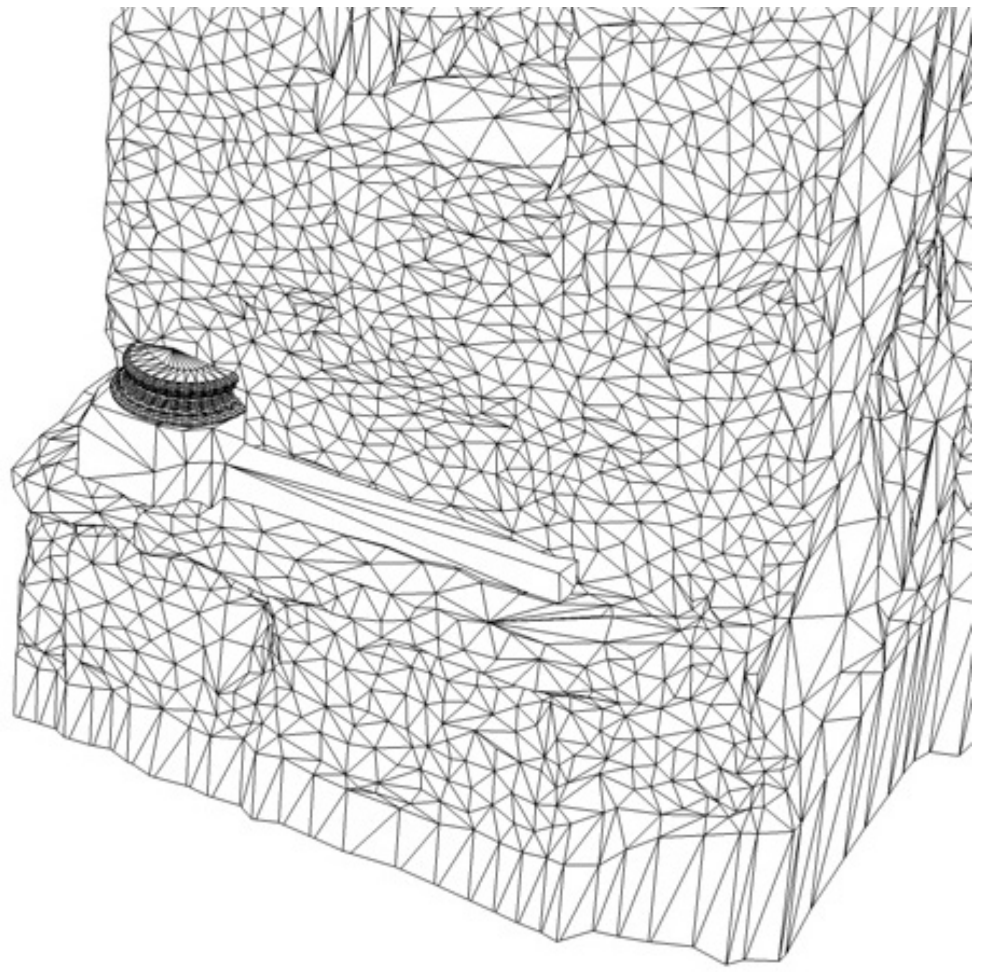
DIFFERENT 3D RESOLUTION

Laser scan + image texturing model

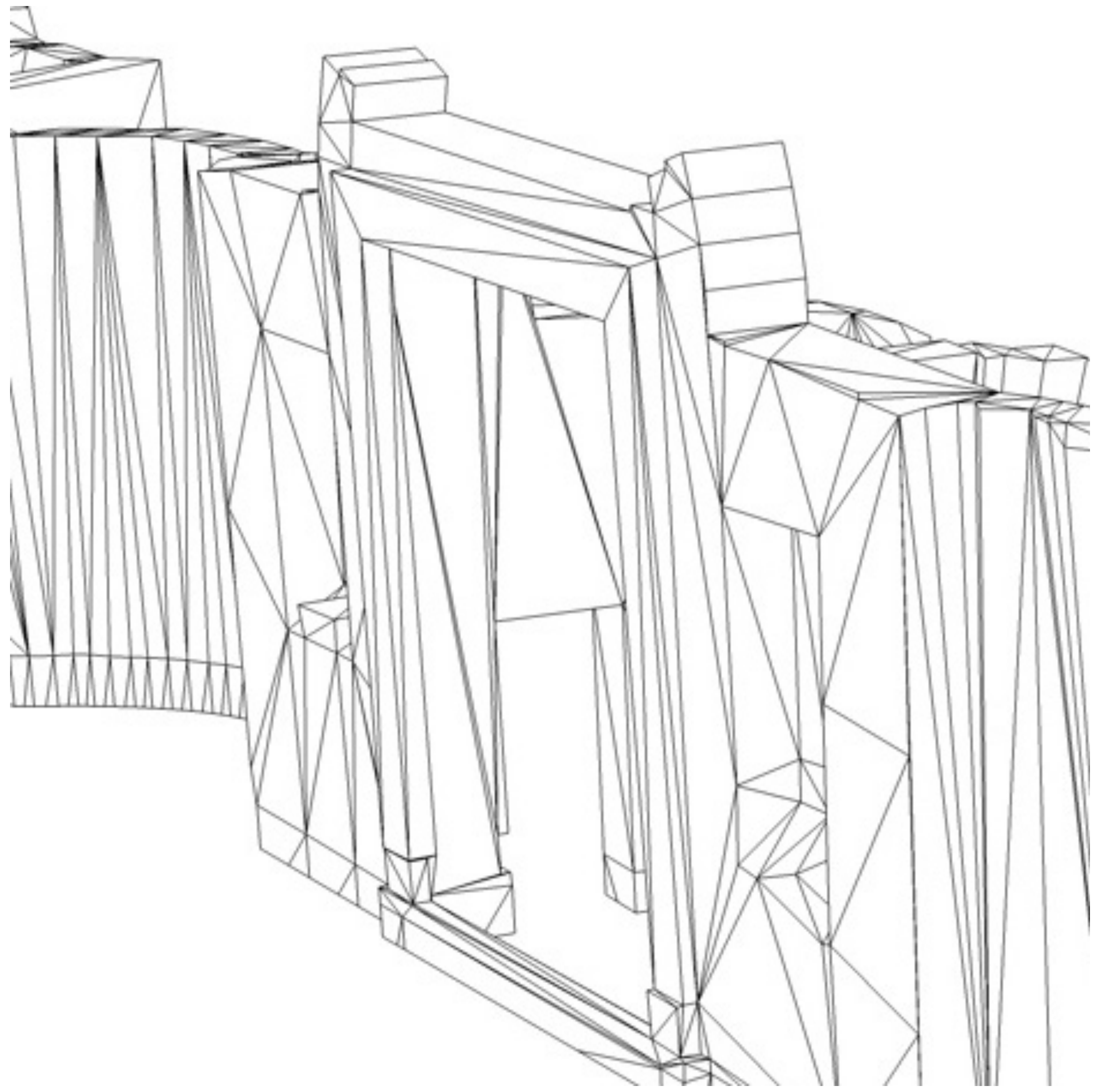
Traditional photogrammetry model

DIFFERENT 3D RESOLUTION

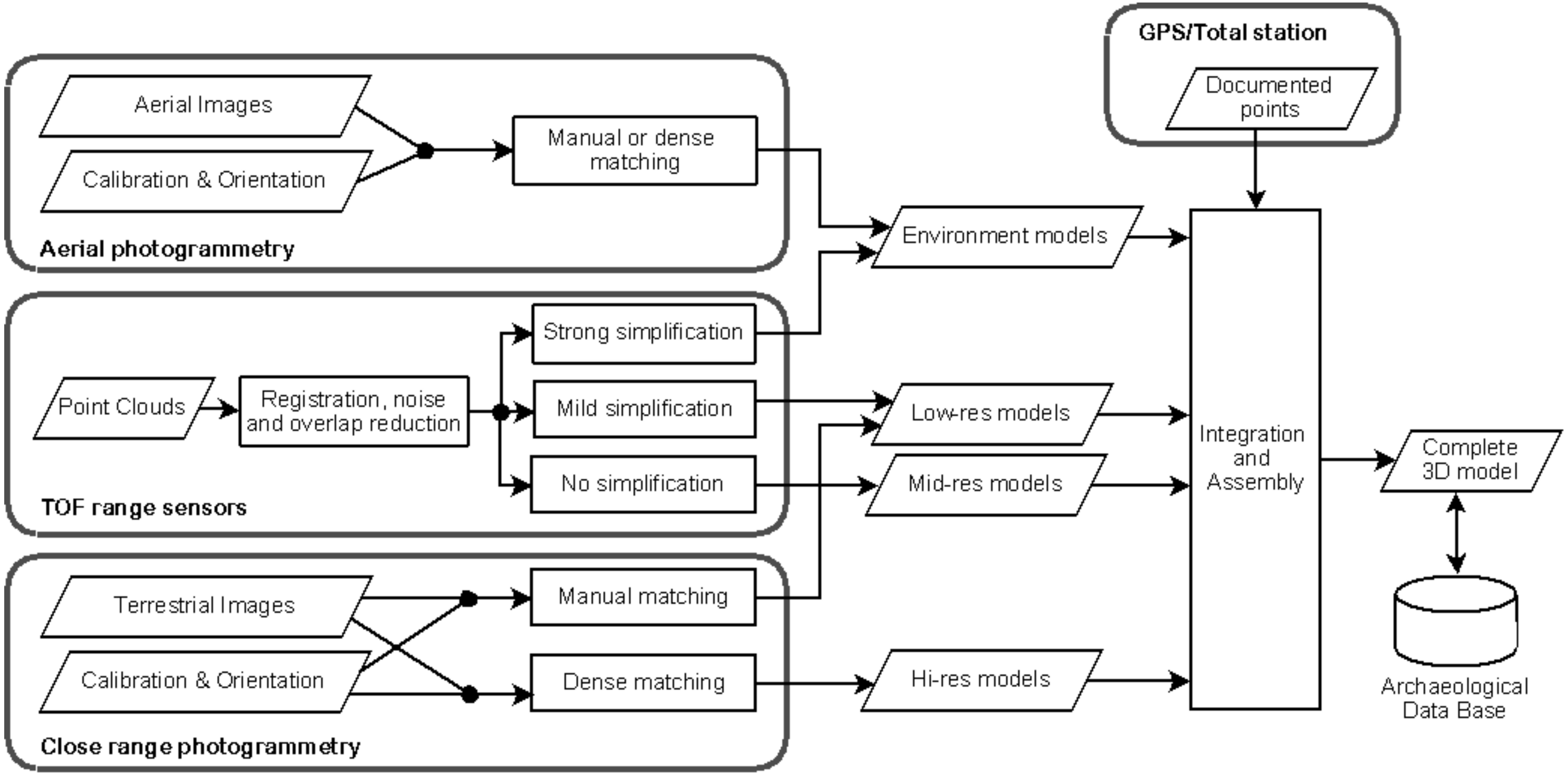
Laser scan + image texturing model



Traditional photogrammetry model



POMPEI FORUM: CO-OPERATIVE 3D IMAGING

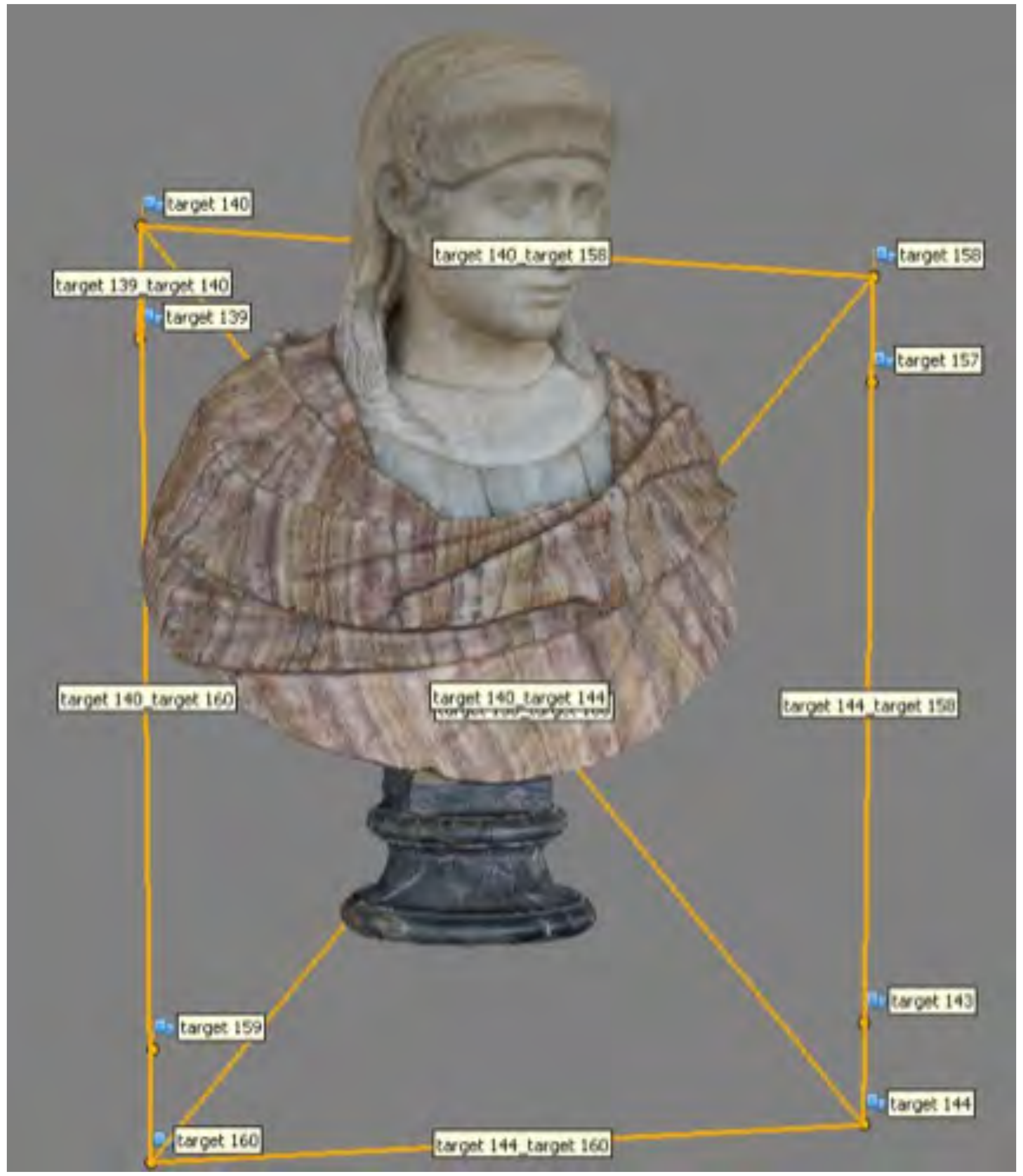


G. Guidi, F. Remondino, M. Russo, F. Menna, A. Rizzi, and S. Ercoli, **A multi-resolution methodology for the 3D modeling of large and complex archae**
Archit. Comput., vol. 7, no. 1, pp. 39–56, 2009.


Una passeggiata nel Foro

IU-UFFIZI PROJECT: DISTANCE BASED SCALING OF PHOTOGRAMMETRIC MODELS

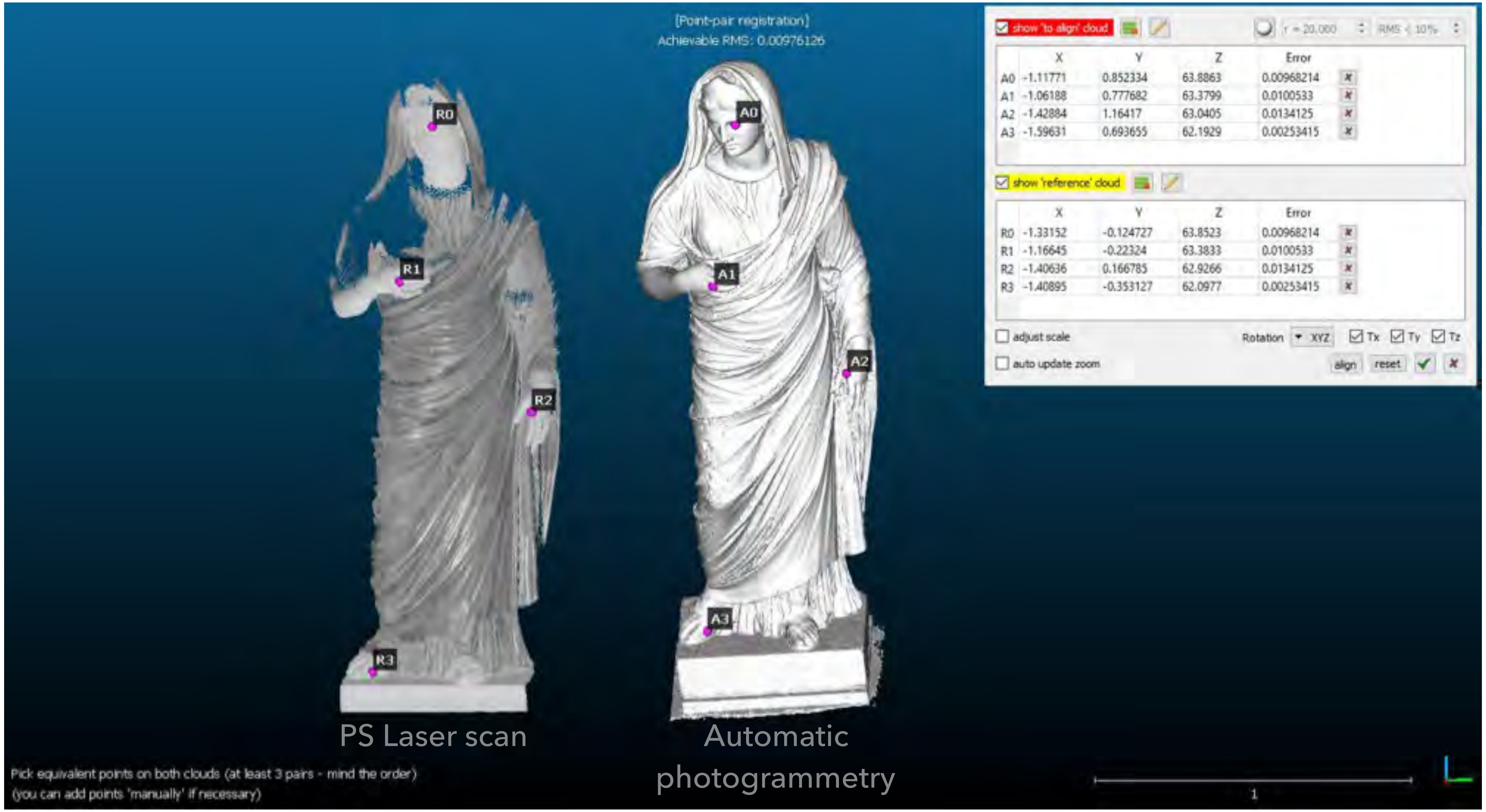
Physical targets are placed in space around the sculpture to be digitized and measured manually with a tape meter



The same markers are then detected in the virtual environment and actual distances are imposed to the digital model

TIME CONSUMING!

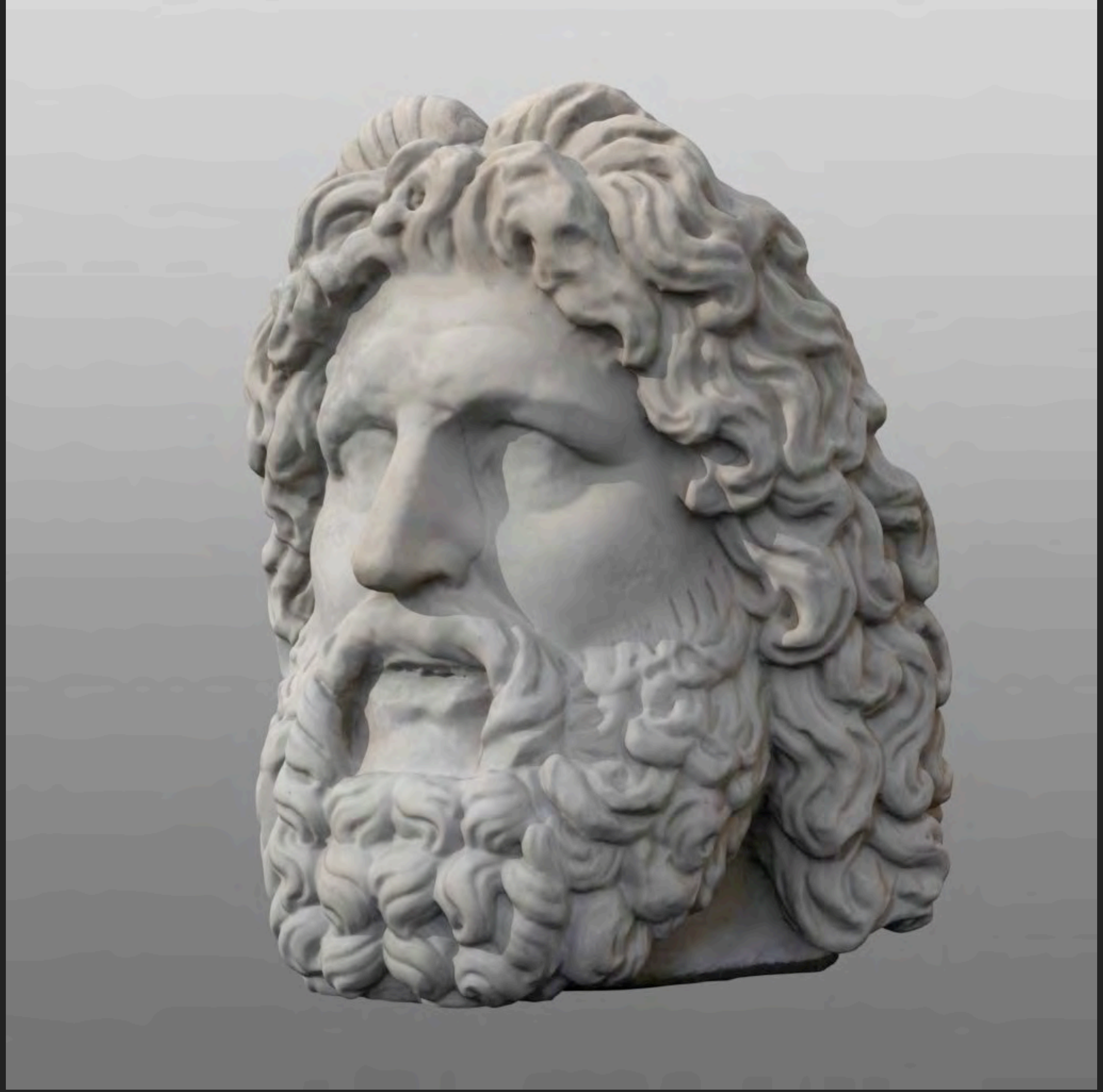
QUICK SCALING



G. Guidi, U.S. Malik, B.D. Frischer, C. Barandoni, 2017, **The Indiana University-Uffizi project - Metrological challenges and workflow for massive 3D sculptures**, *IEEE Proceedings of VSMM 2017*, in print.

CONCLUSIONS

- 3D image fusion for generating a complete 3D model of a real scenario, follows a top-down approach, from the general view (level 0) to the details (levels 1, 2,… n)
- The registration of each element at the level k to its reference at level k-1 is generally a critical issue
- In the “atomization” of sensors that is nowadays constantly growing thanks to the IoT, 3D sensor fusion strategies has to be further developed for properly interpret sensor’s output
- Small Intelligent 3D imaging sensors are now available for pursue this goal



Gabriele Guidi, PhD
Politecnico Milano, Italy
IEEE Senior member

g.guidi@ieee.org

Twitter: @Nexus6it

THANK YOU FOR YOUR ATTENTION