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DART Group

Vision-Based Navigation Algorithms for CubeSats Autonomy: From Deep Space to Close Proximity Operations

Paolo Panicucci, Francesco Topputo, Eleonora Andreis[1], Claudia Balossi, Alban Beshaj, Carmine Buonagura, Pietro Califano, Gianfranco Di Domenico, Fabio Ornati, Davide Perico, Felice Piccolo, Andrea Pizzetti, Mattia Pugliatti[2], and Antonio Rizza

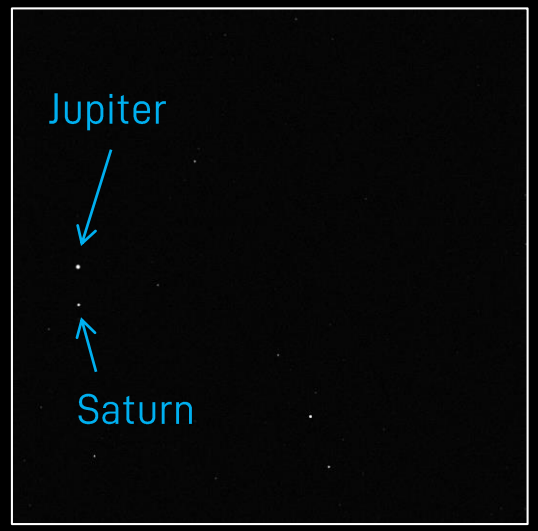
2nd July 2024

[1] Currently at DLR
[2] Currently at University of Colorado Boulder

Autonomous Vision-Based Navigation

FAR-RANGE

Celestial bodies are not resolved in the FOV



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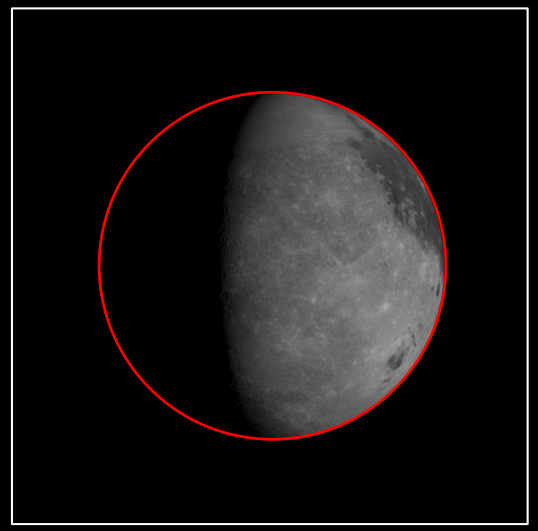
MID-RANGE

Celestial bodies are resolved and global shape is exploited



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CLOSE-RANGE

Celestial bodies are resolved and local features are used

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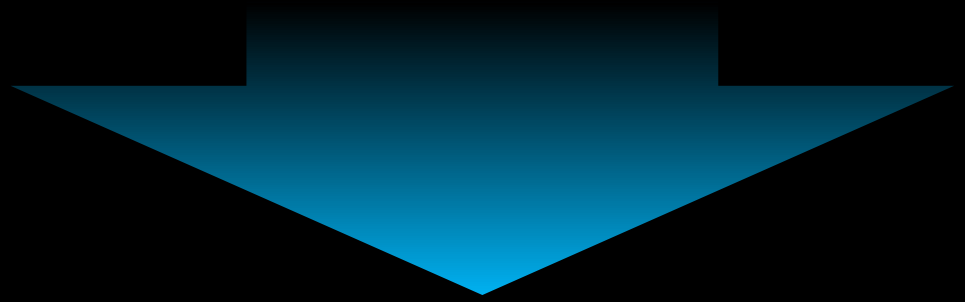
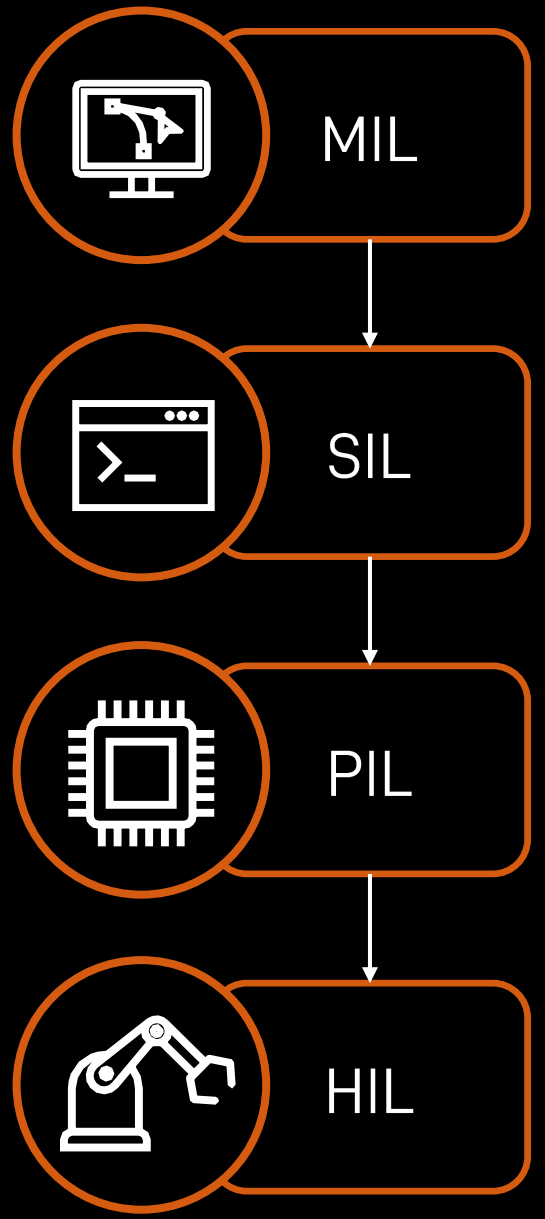
Design & Validation Philosophy

Algorithm design and validation in an SW and HW ecosystem of increasing complexity

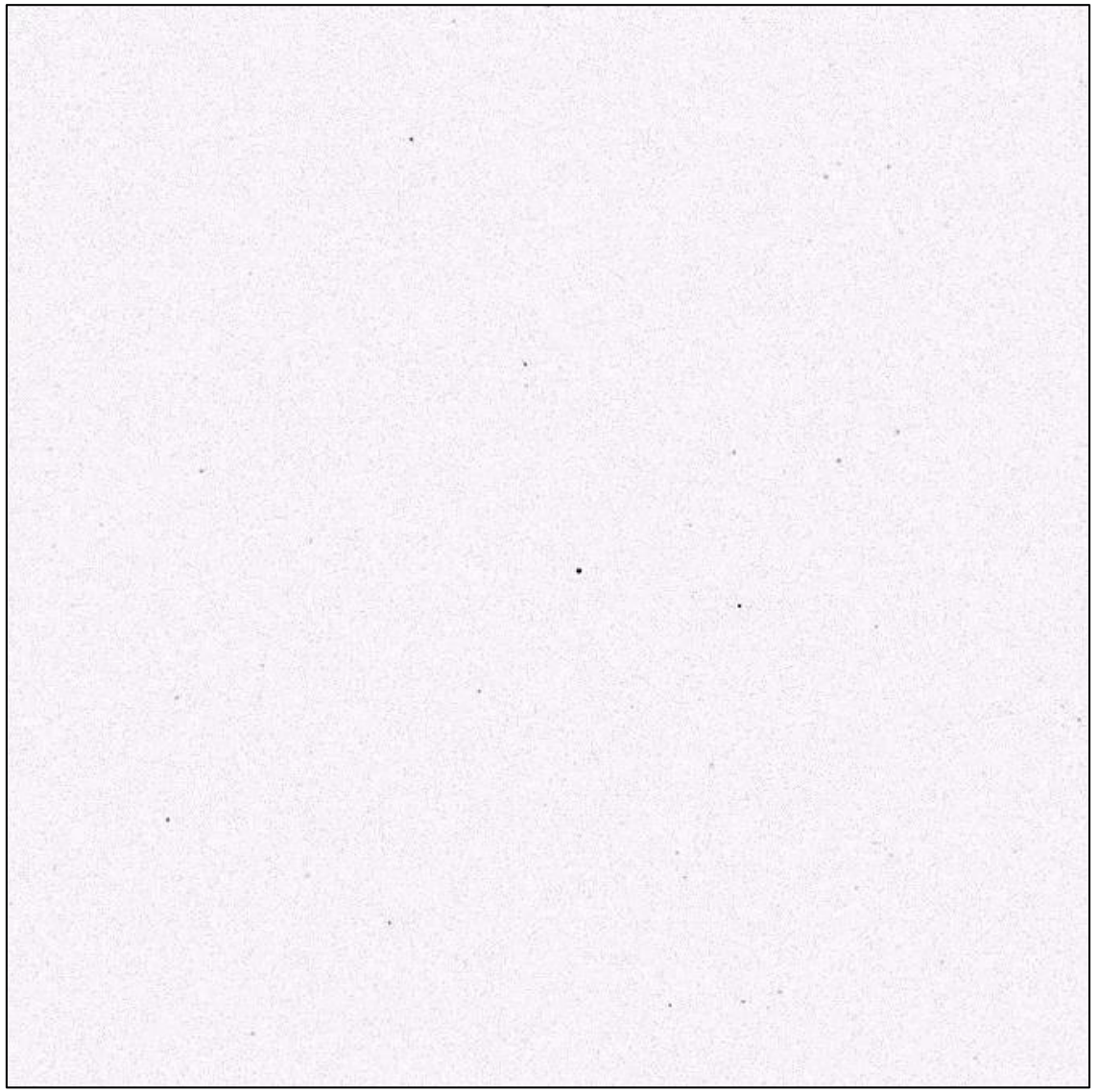


- *Representative rendering tool* for geometry and radiometry
- Assessment of *algorithm latency, allocation and performance* on real processors
- Development of *testing facility* and their calibration



Deep-Space Rendering Engine

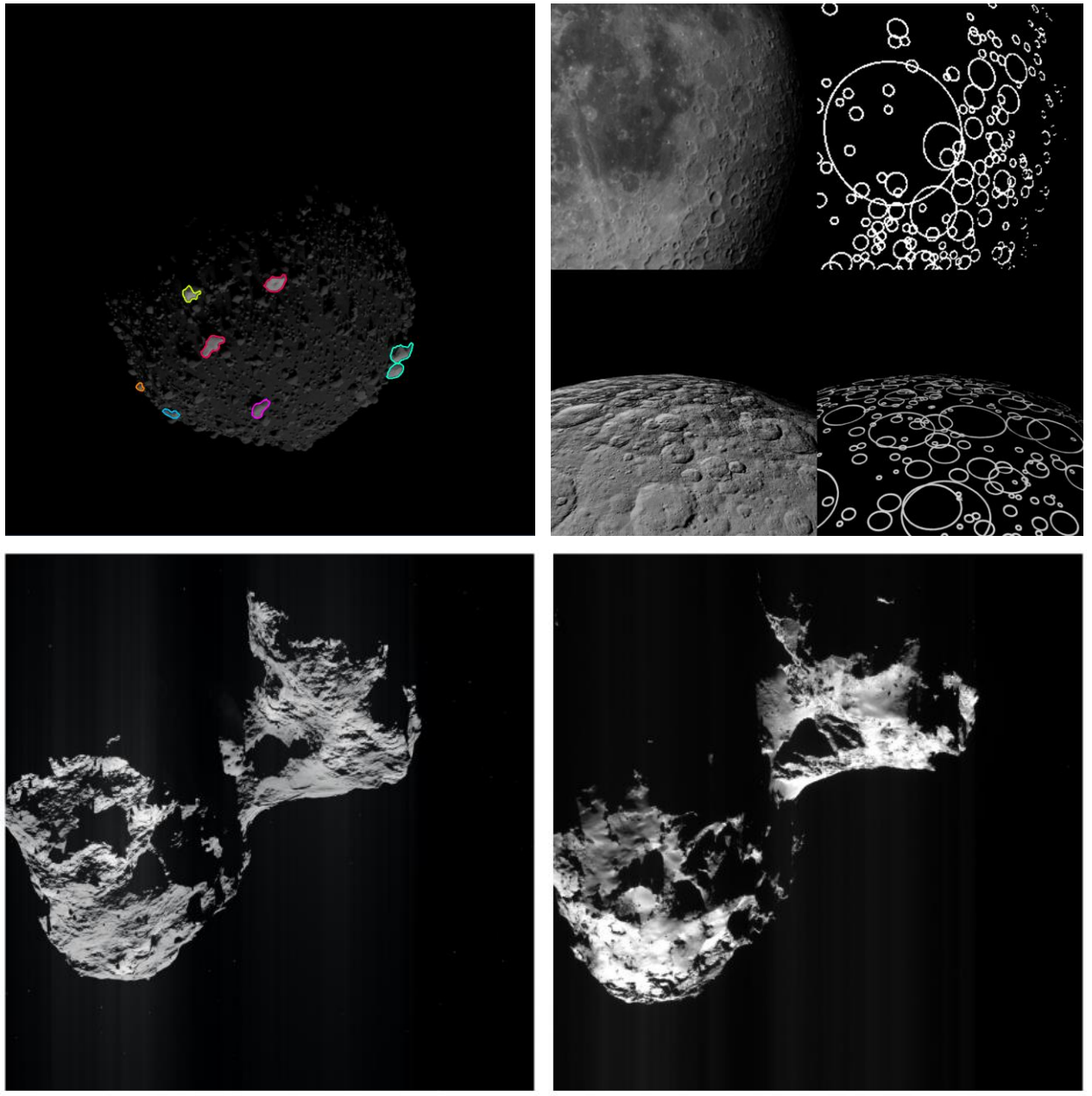
- *Stellar and non-stellar celestial objects* can be simulated
- *High-fidelity camera model* includes optical efficiency, distortions, PSF, and A/D conversion
- *Representative noises*, such as read-out and dark current, can be efficiently modeled
- Developed to be *radiometric consistency*
- *Running in real-time* at 60 Hz



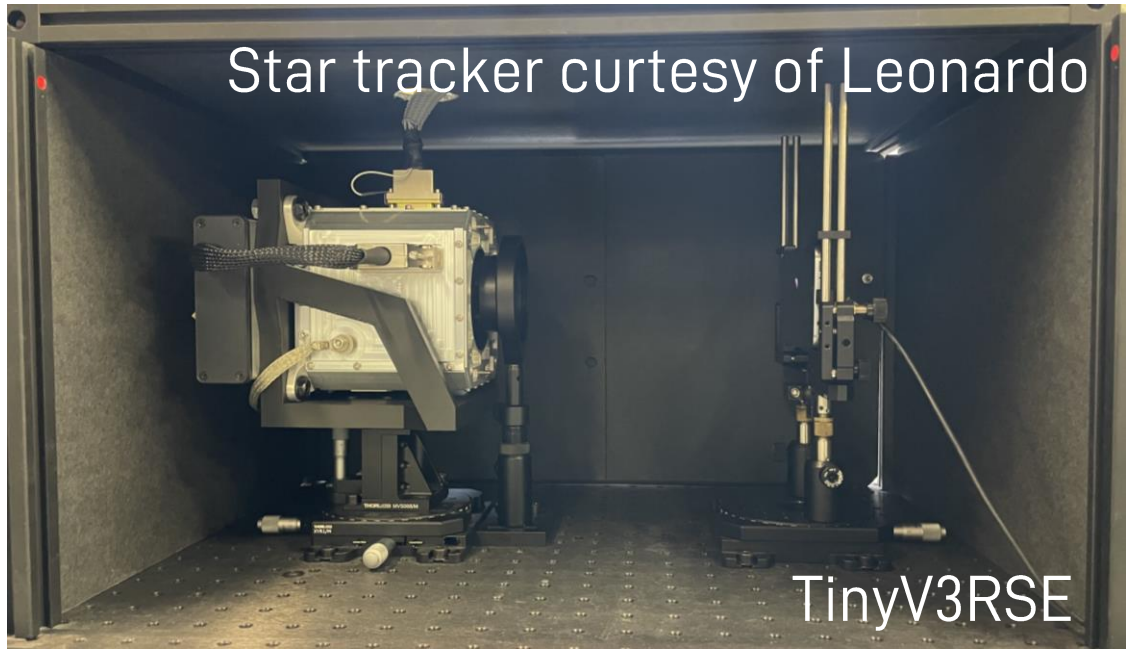
CORTO

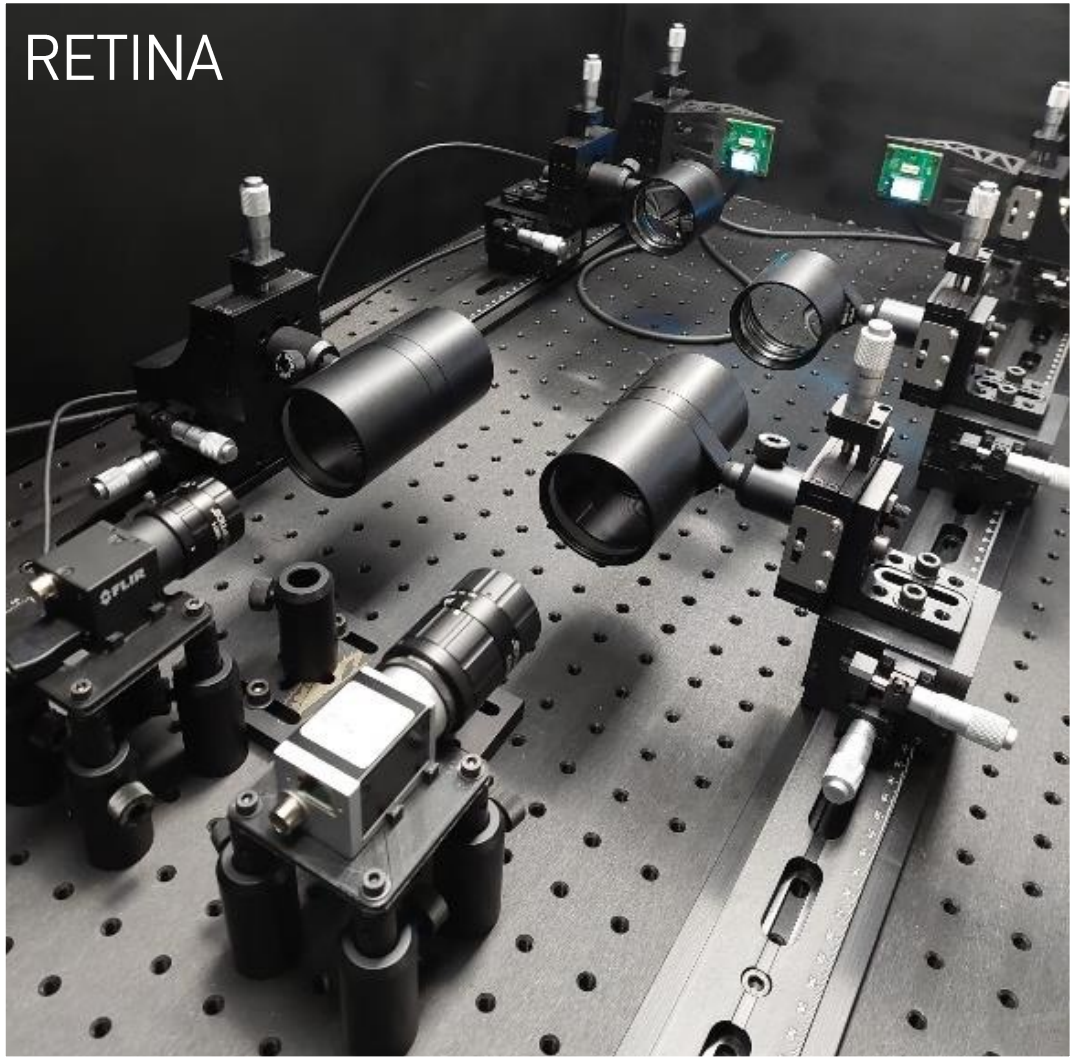
Celestial Objects Rendering Tool

- Exploits Blender as rendering software
- In-house developed model to ensure *radiometric consistency*
- *Procedural generation* of surface features: roughness, boulders, and craters
- *Noise model can be applied* to rendered images (e.g., read-out, dark current, motion blur, defocus)
- *Available open-source at: https://github.com/MattiaPugliatti/corto*



Optical Facilities

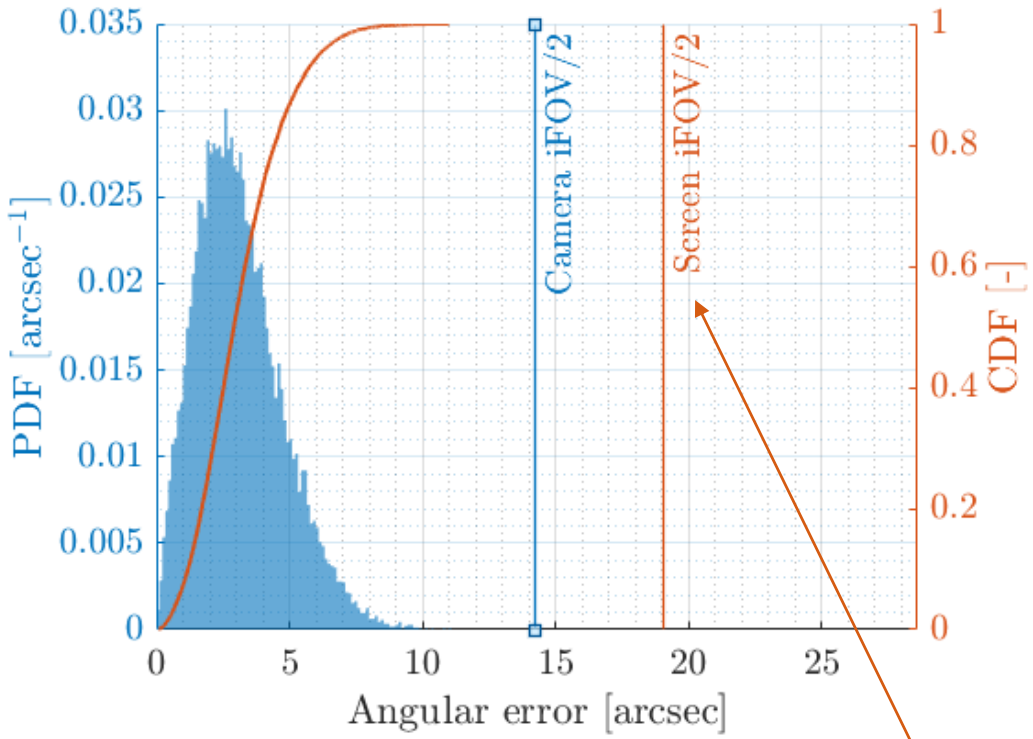


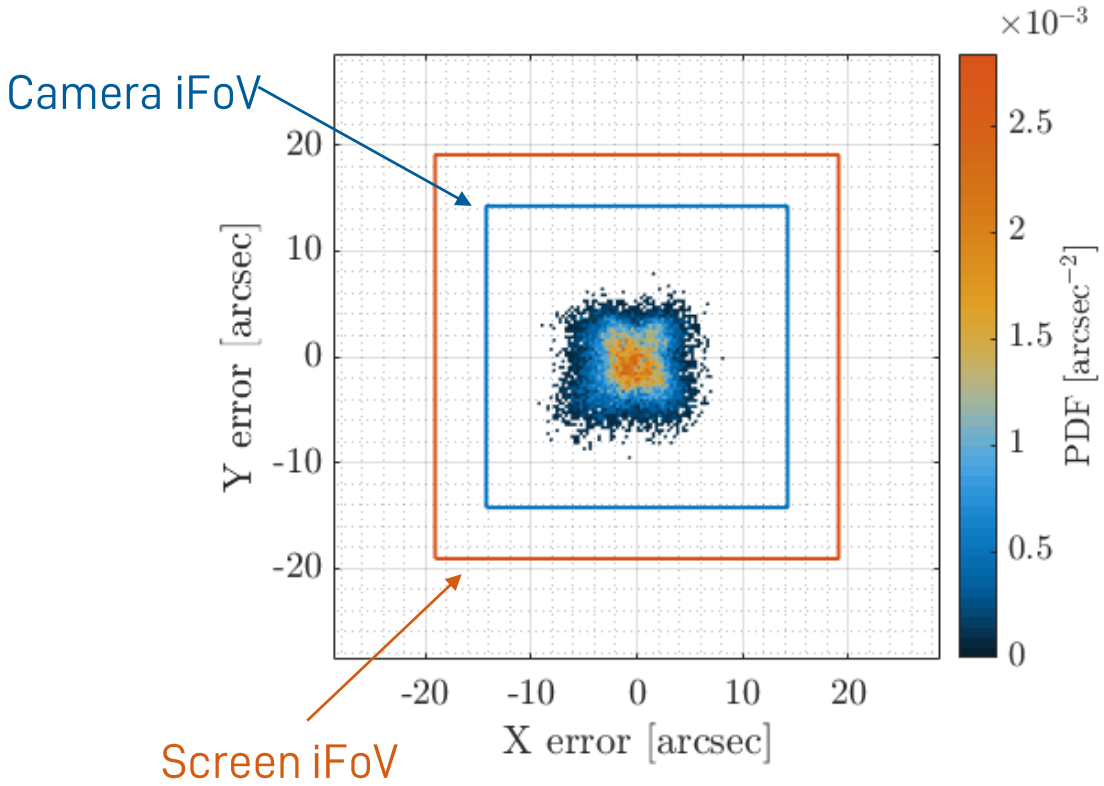


- Camera stimulation via *high-resolution and radiometrically controlled screens*
- Single and multi camera possible for *mono and stereo vision*

Geometrical Calibration

Geometrical calibration procedure to counteract *geometrical distortions* and *misalignment errors*



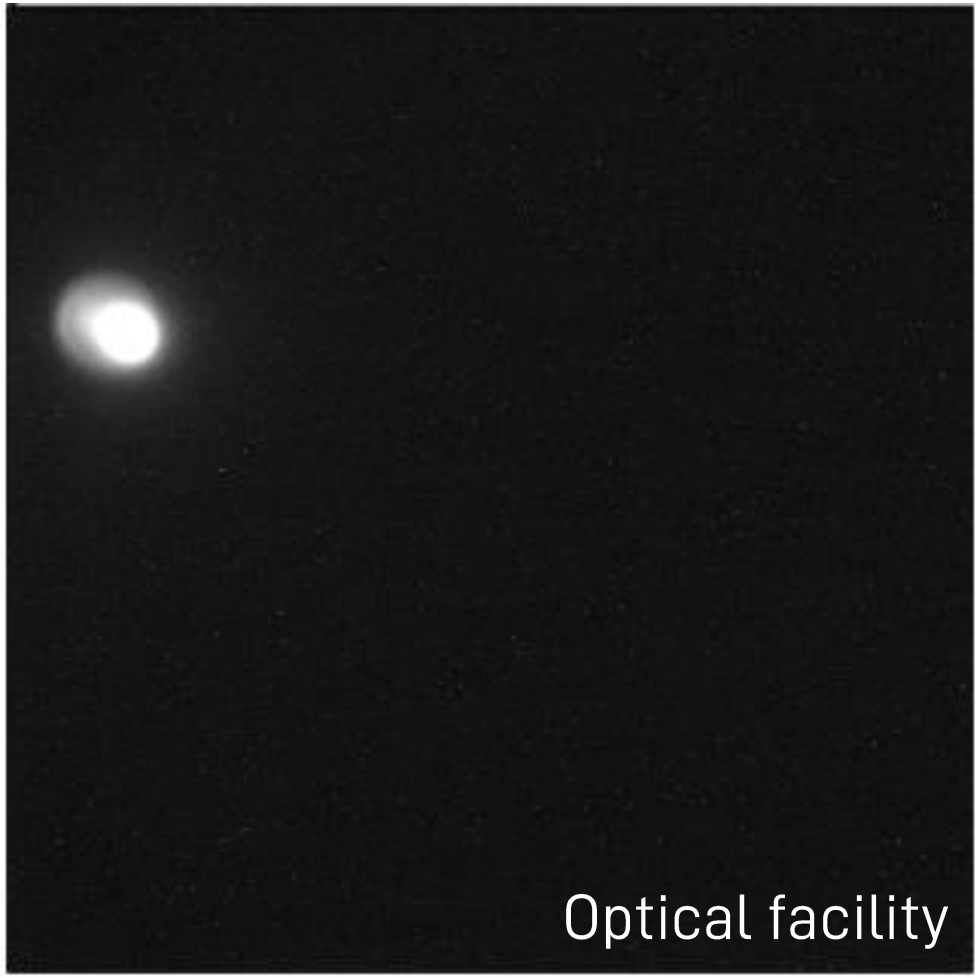


Angular size of one screen pixel as seen from the camera

Geometrical and Radiometrical Calibration

Accurate calibration procedure to ensure *radiometrically consistency* at camera pupil

Open Sky Test, Curtesy of Leonardo

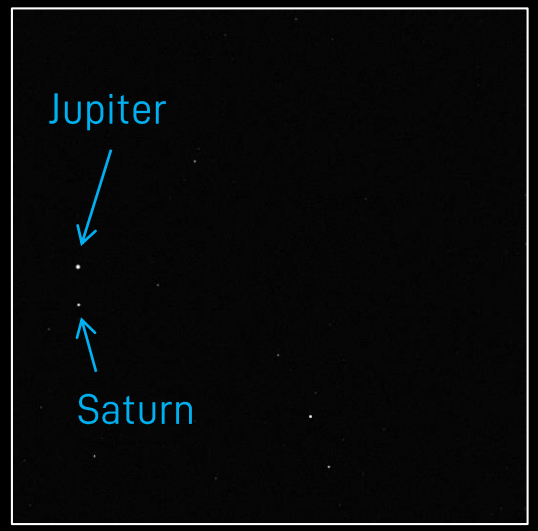


Optical facility

Far Range Vision-Based Navigation

FAR-RANGE

Celestial bodies are not resolved in the FOV



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MID-RANGE

Celestial bodies are resolved and global shape is exploited

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CLOSE-RANGE

Celestial bodies are resolved and local features are used

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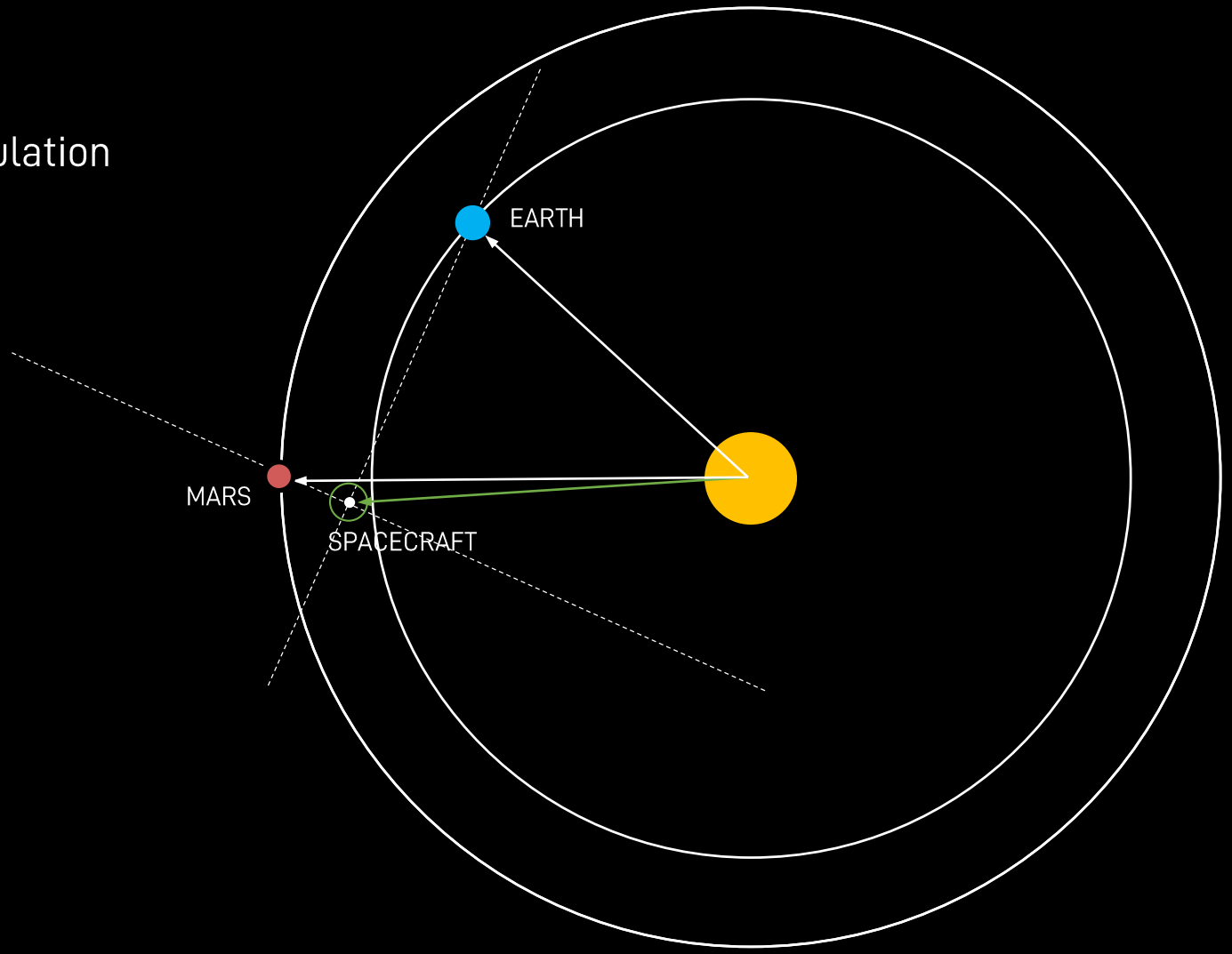
Far Range Vision-Based Navigation

Celestial triangulation



S/C – Planets LoS (extracted from the image)

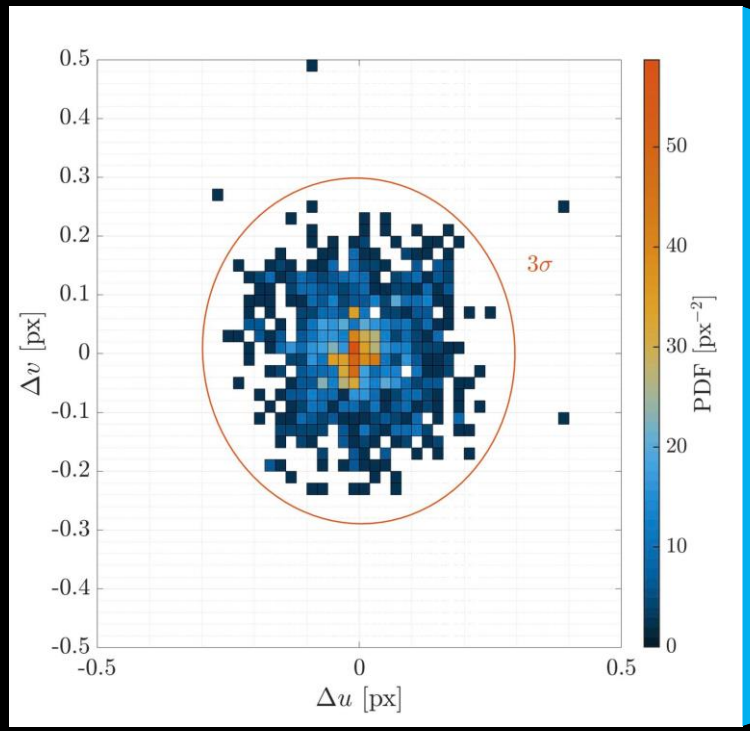
+

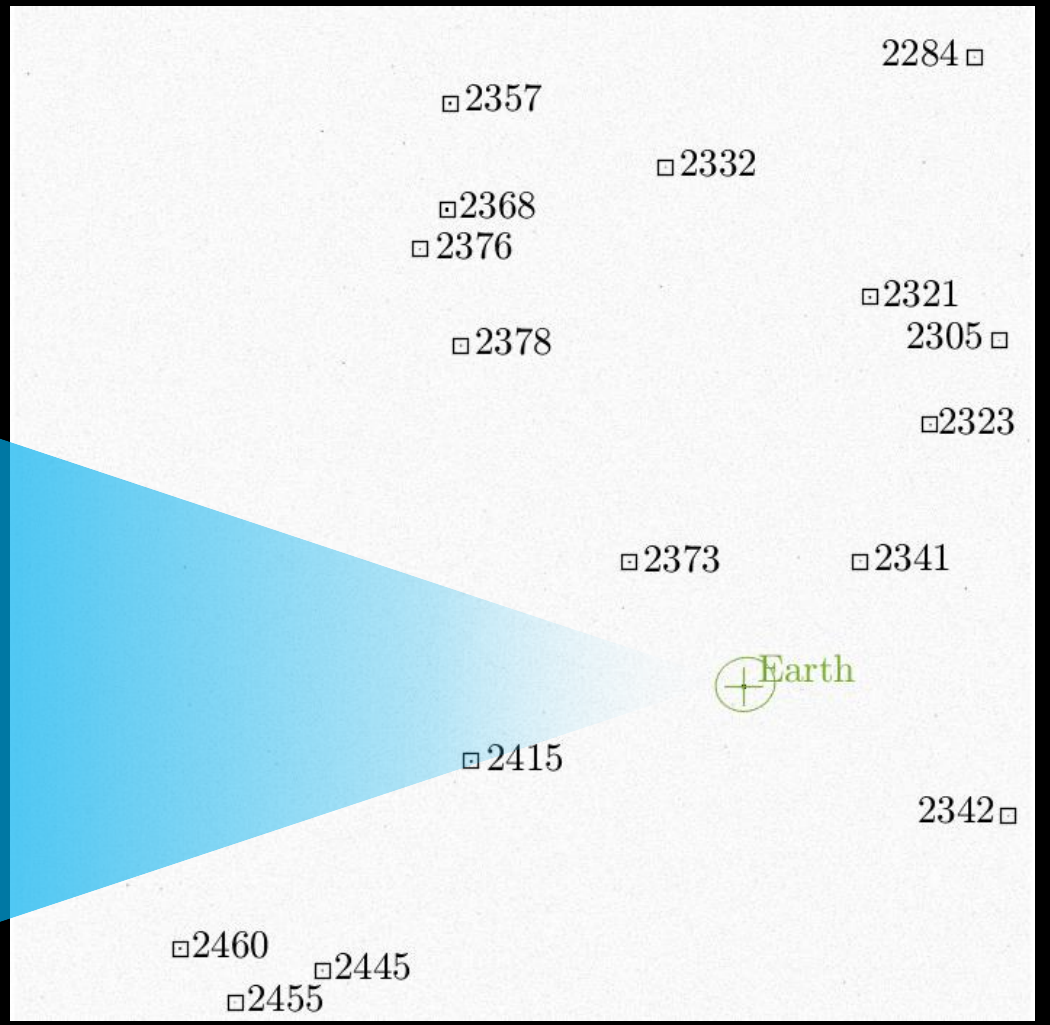
Planets ephemeris

Spacecraft position with respect to the Sun

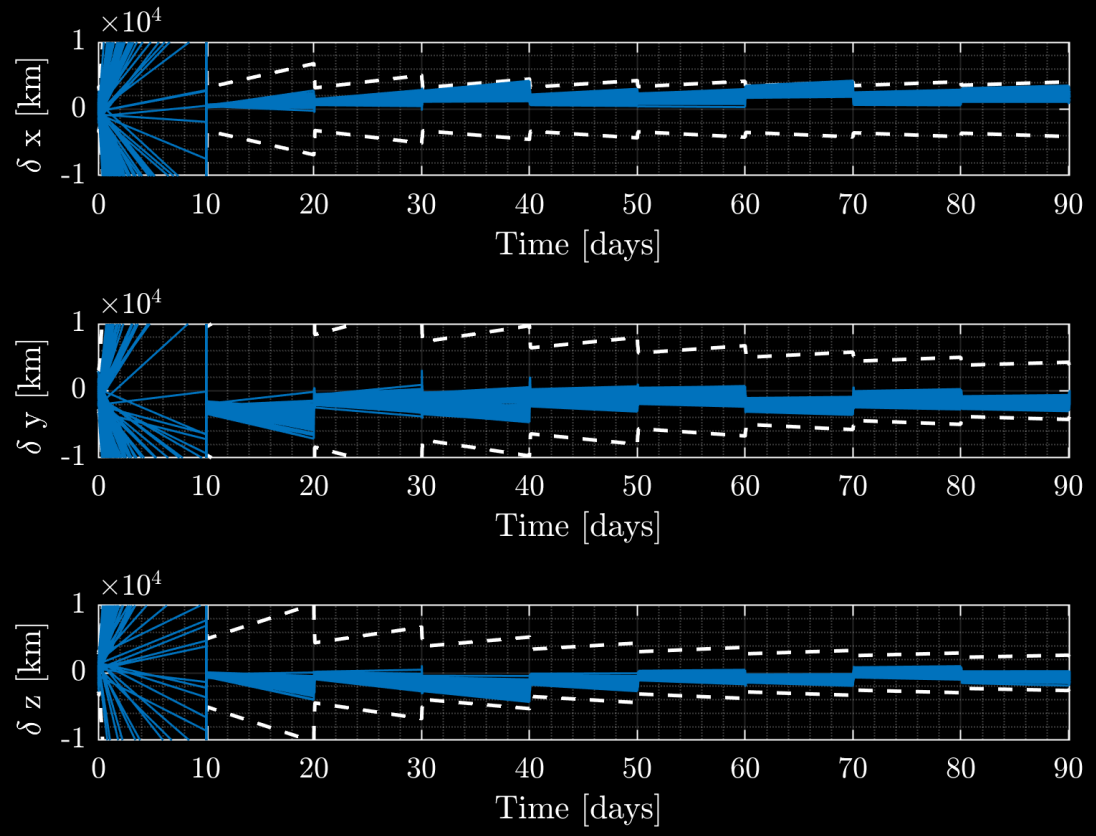
Far Range Vision-Based Navigation

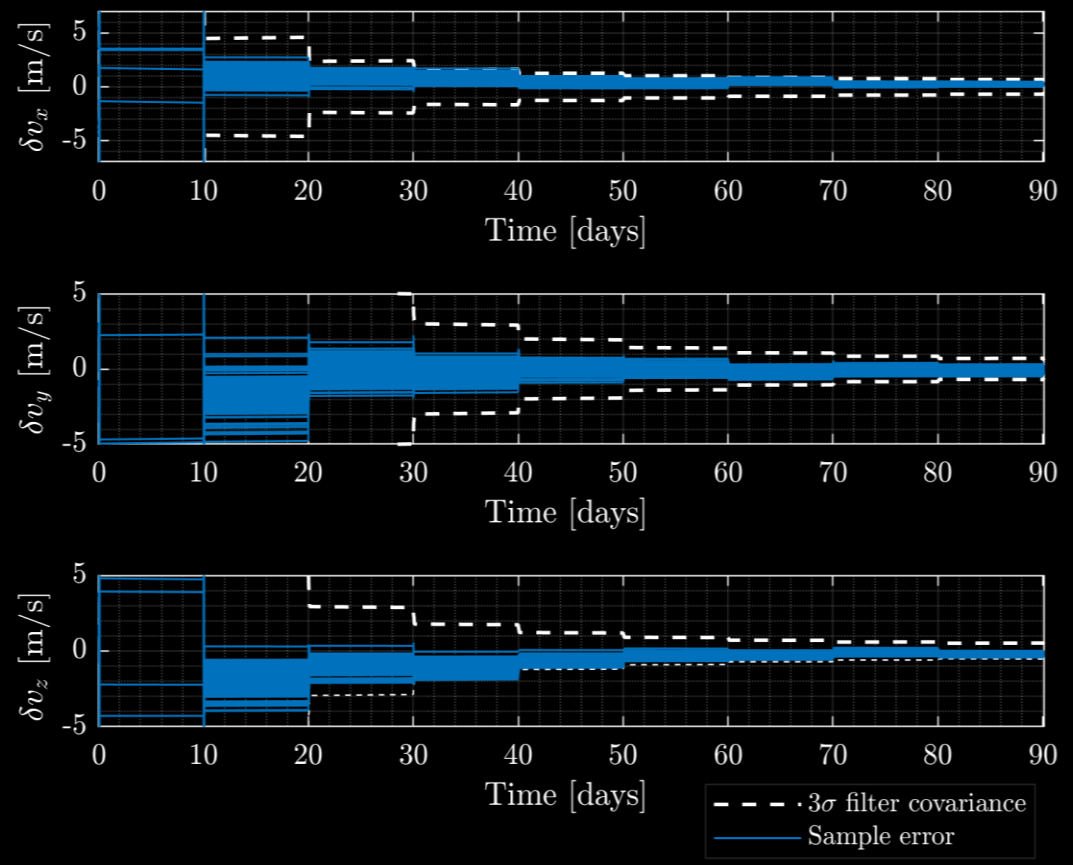
- *Attitude determination* from images with accuracy of 15 arcsec (1-sigma)
- *Determination of the planets* (3-σ < 0.5 pixels) based on geometrical and statistical considerations





Filter Performances





HIL Position errors (3-σ < 5320 km)

SIL Position errors (3-σ < 1025 km)

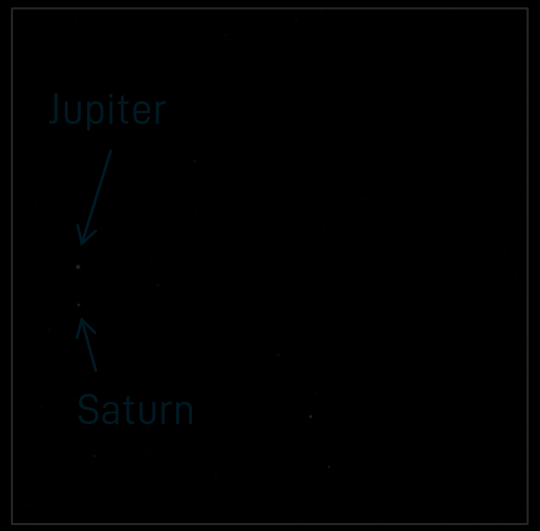
HIL Velocity errors (3-σ < 0.97 m/s)

SIL Velocity errors (3-σ < 0.42 m/s)

Mid-Range Vision-Based Navigation

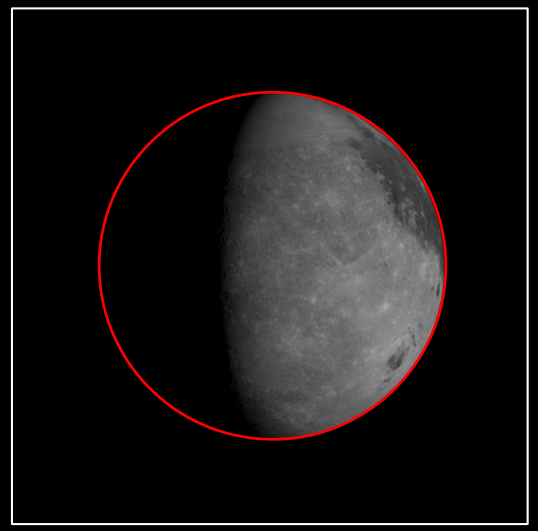
FAR-RANGE

Celestial bodies are not resolved in the FOV



MID-RANGE

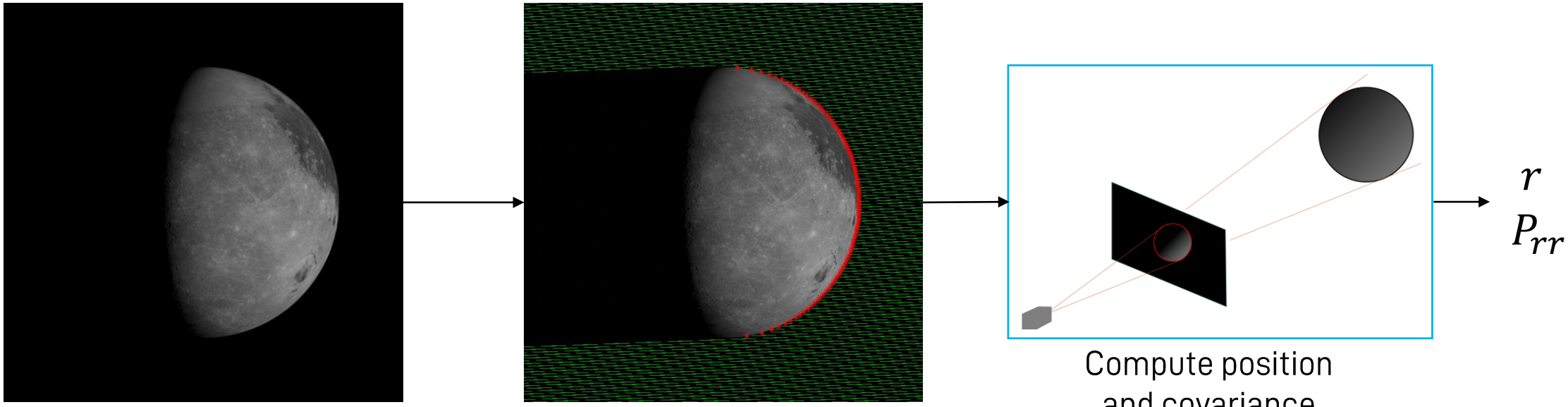
Celestial bodies are resolved and global shape is exploited



CLOSE-RANGE

Celestial bodies are resolved and local features are used

Mid-Range Vision-Based Navigation



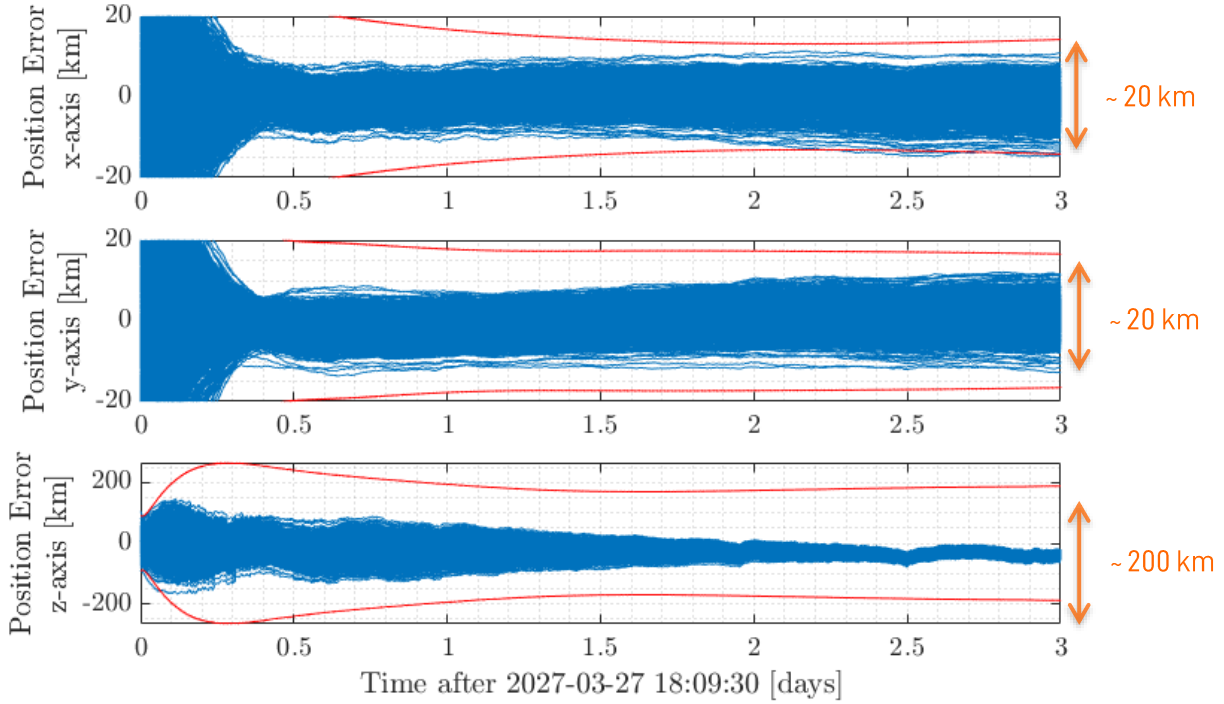
- *Limbs determined at subpixelic precision* (~ 0.2 pixels) and outliers are rejected to ensure robustness

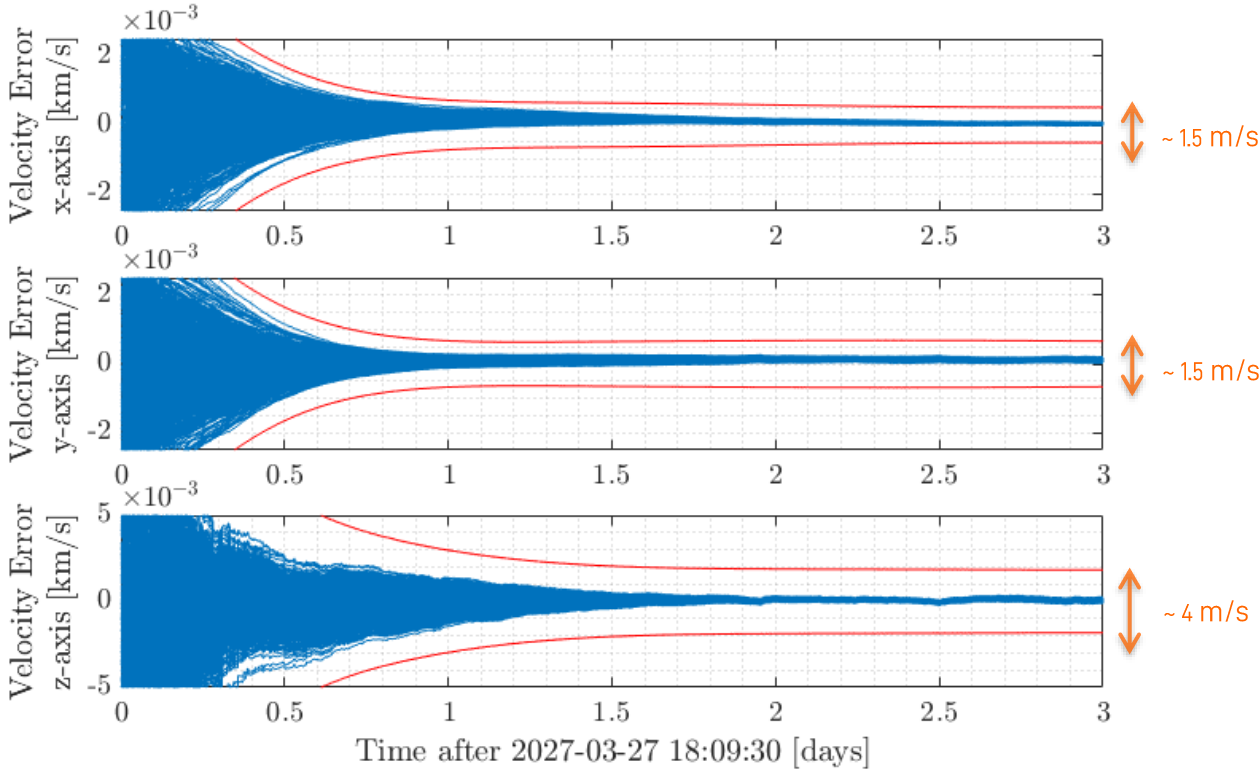
- *Accurate image-based position determination*
  - 3-σ <10 km for image plane
  - 3-σ <300 km for camera boresight

Mid-Range Vision-Based Navigation

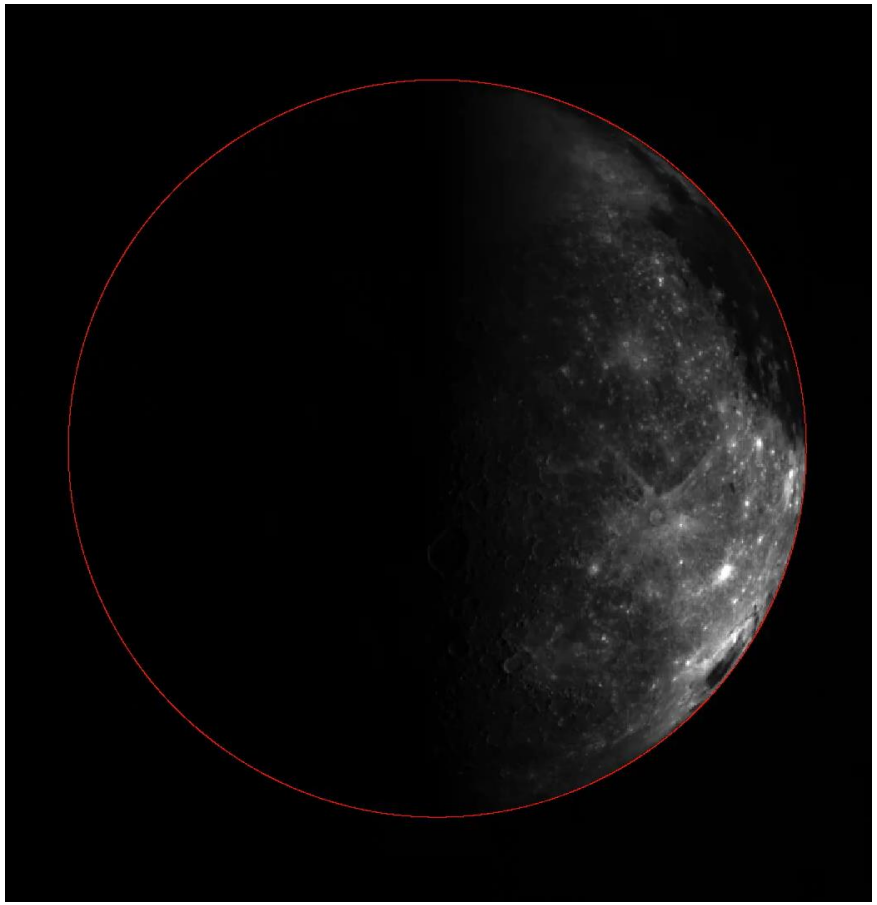
- *Limb-based navigation filter provide accurate and precise estimations* of less than:
  - 3-σ < 20 km (0.05% true range) and 3-σ < 1.5 m/s on the camera plane axes
  - 3-σ < 200 km (0.5% true range) and 3-σ < 4 m/s on the camera boresight

- Uncertainties on attitude knowledge, camera calibration, camera distortion, spacecraft state errors



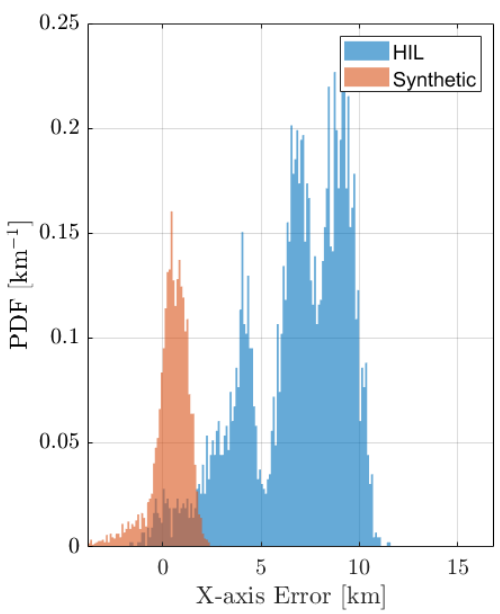


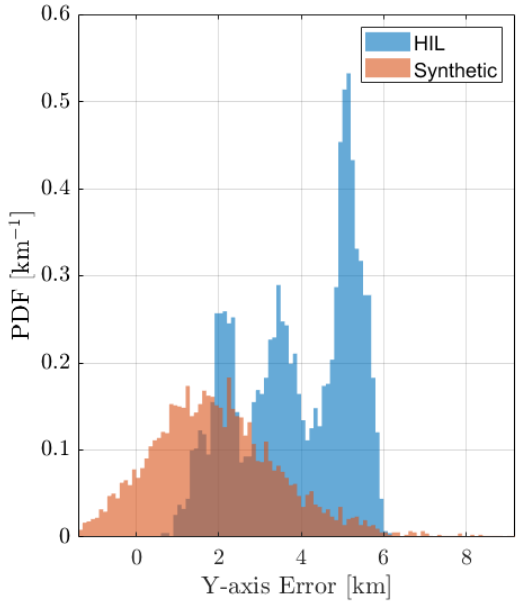
Mid-Range Vision-Based Navigation

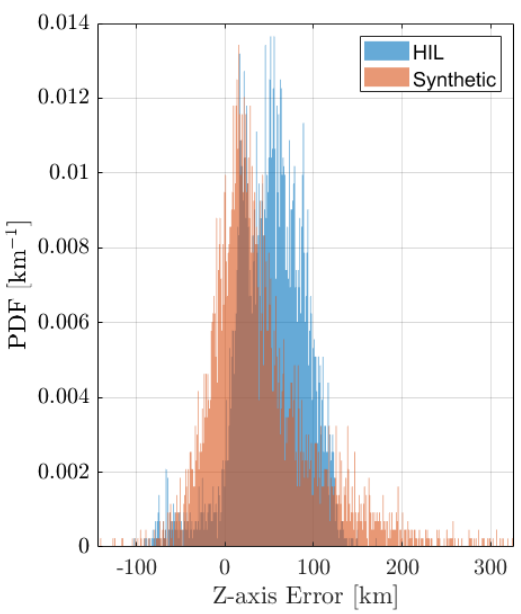


- The VBN algorithm *run in less than 0.4 sec* (w/ margin) on a ZedBoard Zynq-7000 (advised by ESA as CubeSat processor)

- *Robust to calibration errors* with limited decrease in accuracy



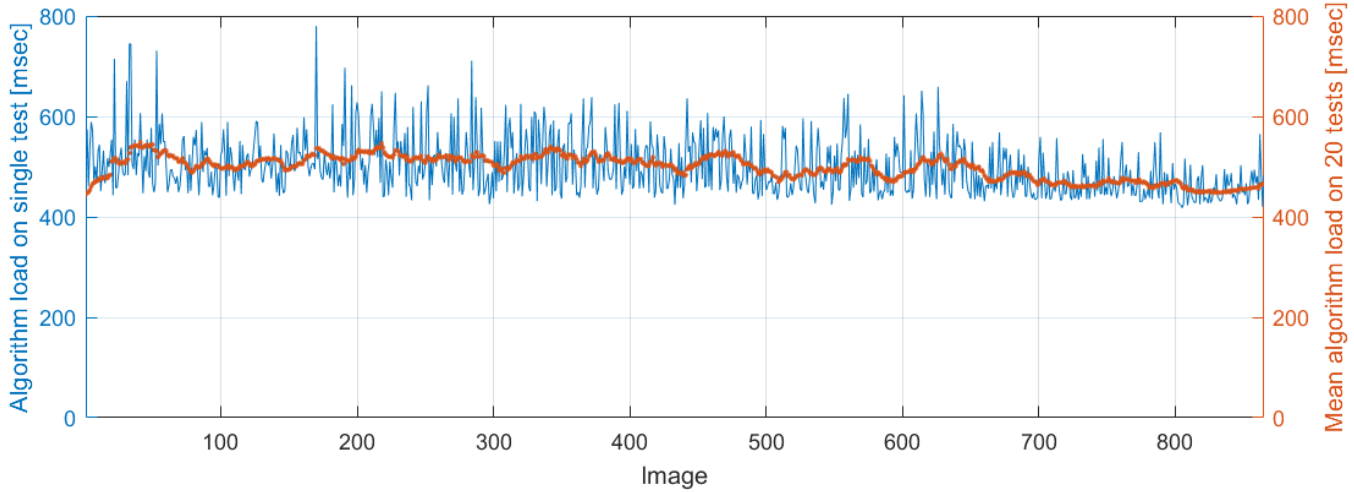


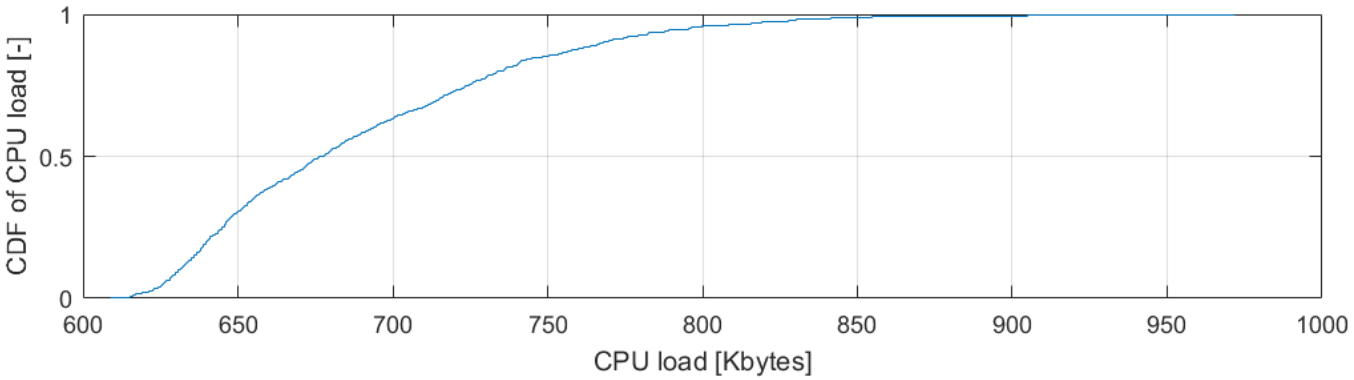


Mid-Range Vision-Based Navigation

Algorithm also *customized and implemented on a high TRL Leonardo star tracker (AA-STR MKII)* in the context on an ASI-funded GSTP ESA project:

- *Integrated in the star tracker flight software* with a dedicated mode
- *Run on hard-real time on the STR processing unit* (SAMV71RH Rad-Hard 32-bit Arm® Cortex®-M7 Microcontroller)
- Currently performing optical stimulation with optical facility at Polimi

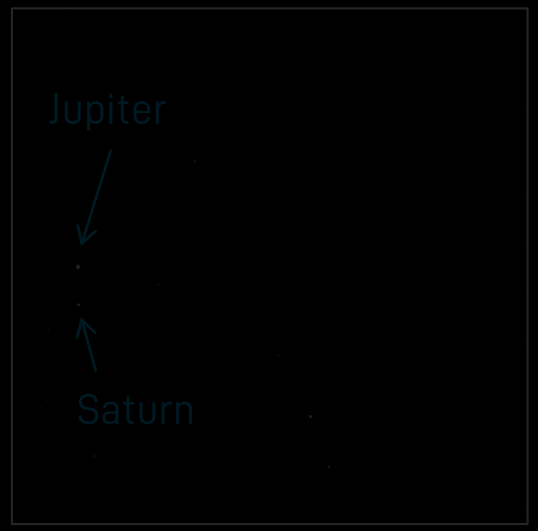




Close Range Operations

FAR-RANGE

Celestial bodies are not resolved in the FOV



MID-RANGE

Celestial bodies are resolved and global shape is exploited

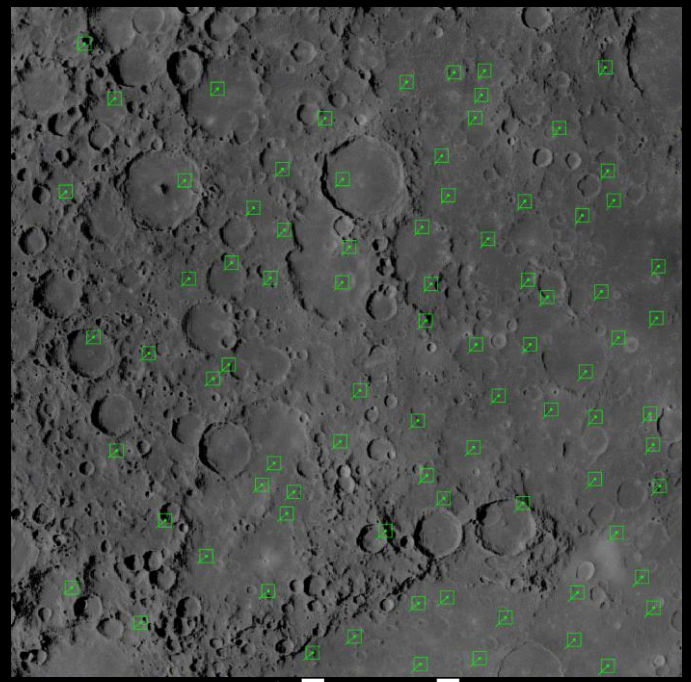
CLOSE-RANGE

Celestial bodies are resolved and local features are used

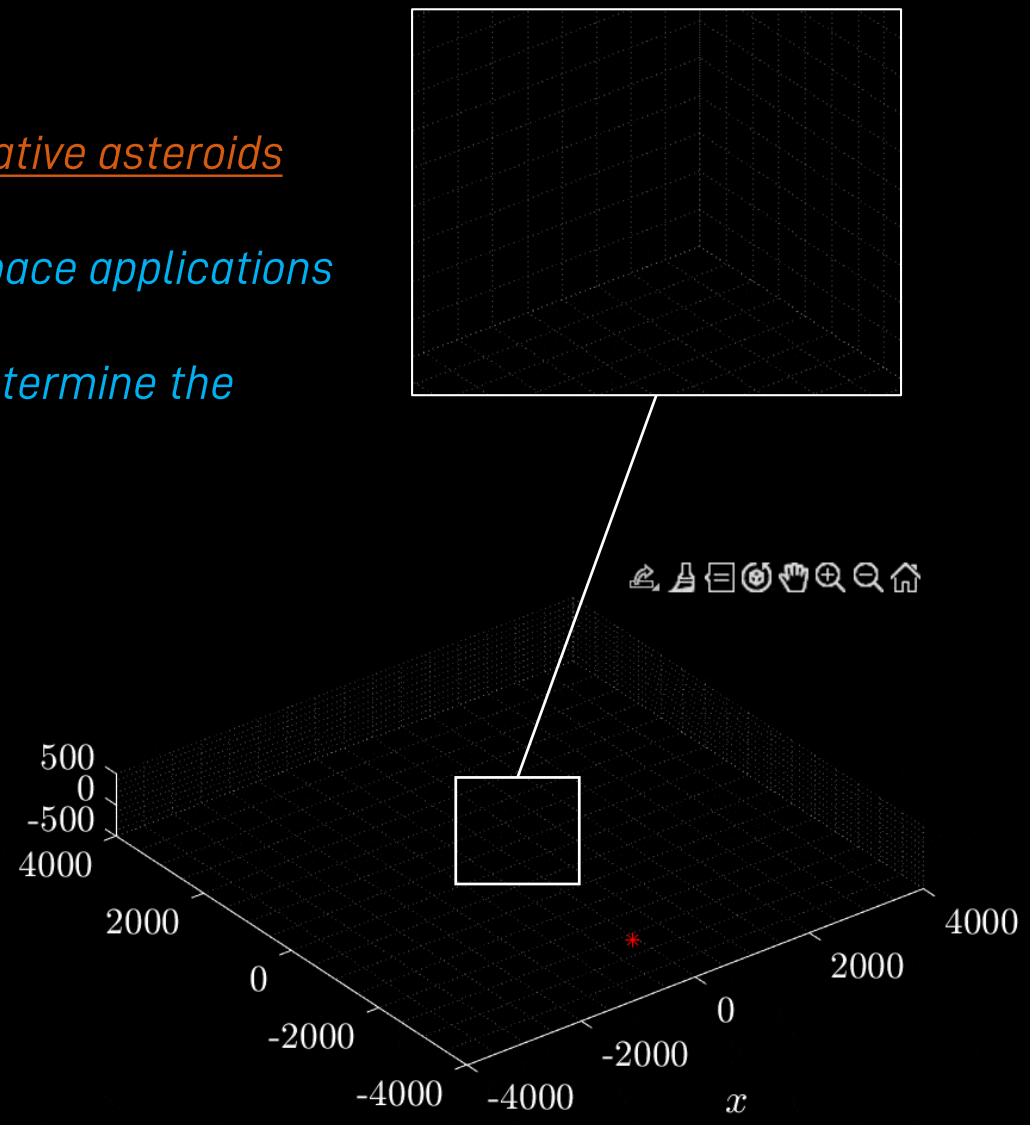
Close-Range Navigation

The goal is to *autonomously characterize an unknown and uncooperative asteroids*

- Features are tracked with an *optical flow algorithm tailored for space applications*
- Feature are given to an *in-house-developed SLAM algorithm to determine the asteroid shape and the spacecraft orbit*



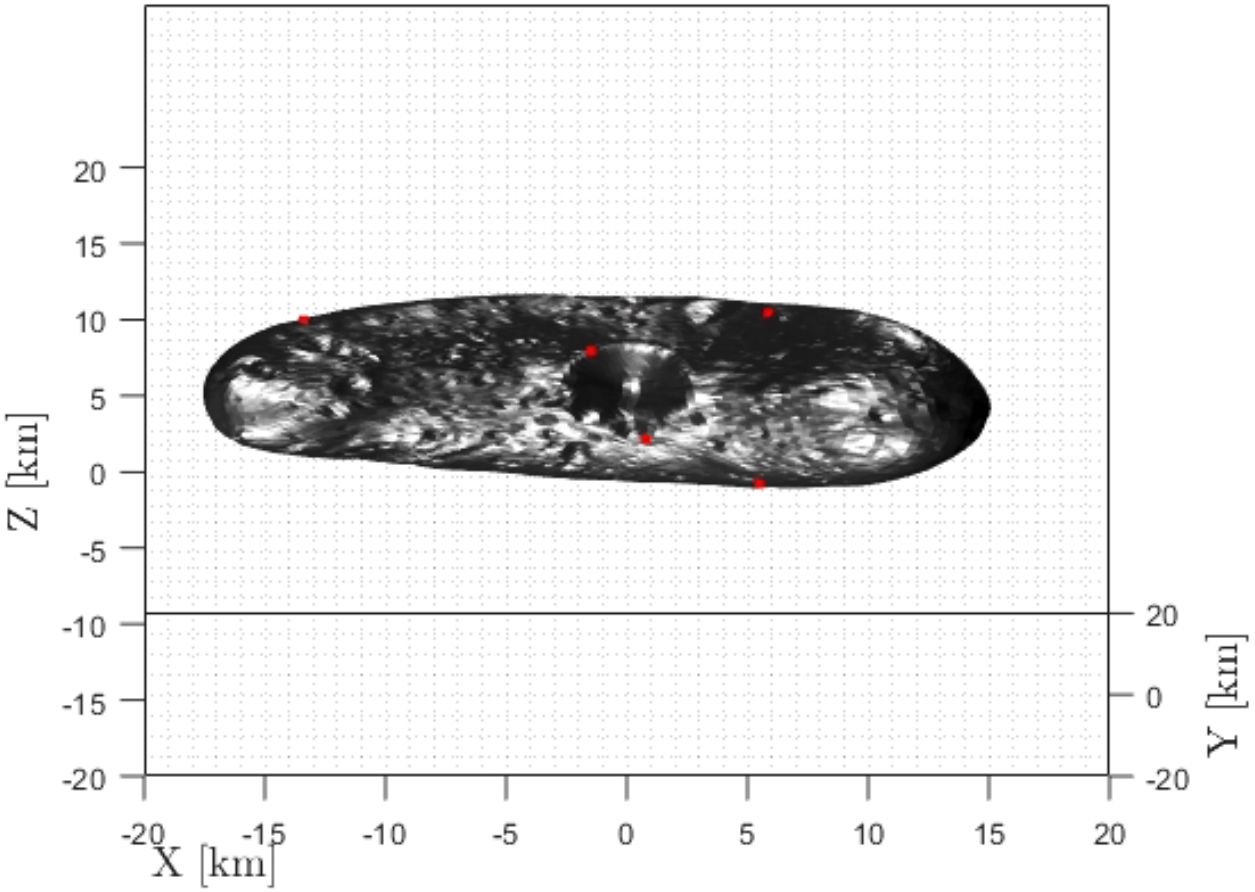
Tracked features



Close-Range Guidance

The goal is to autonomously plan the trajectory without any a priori knowledge or first guess

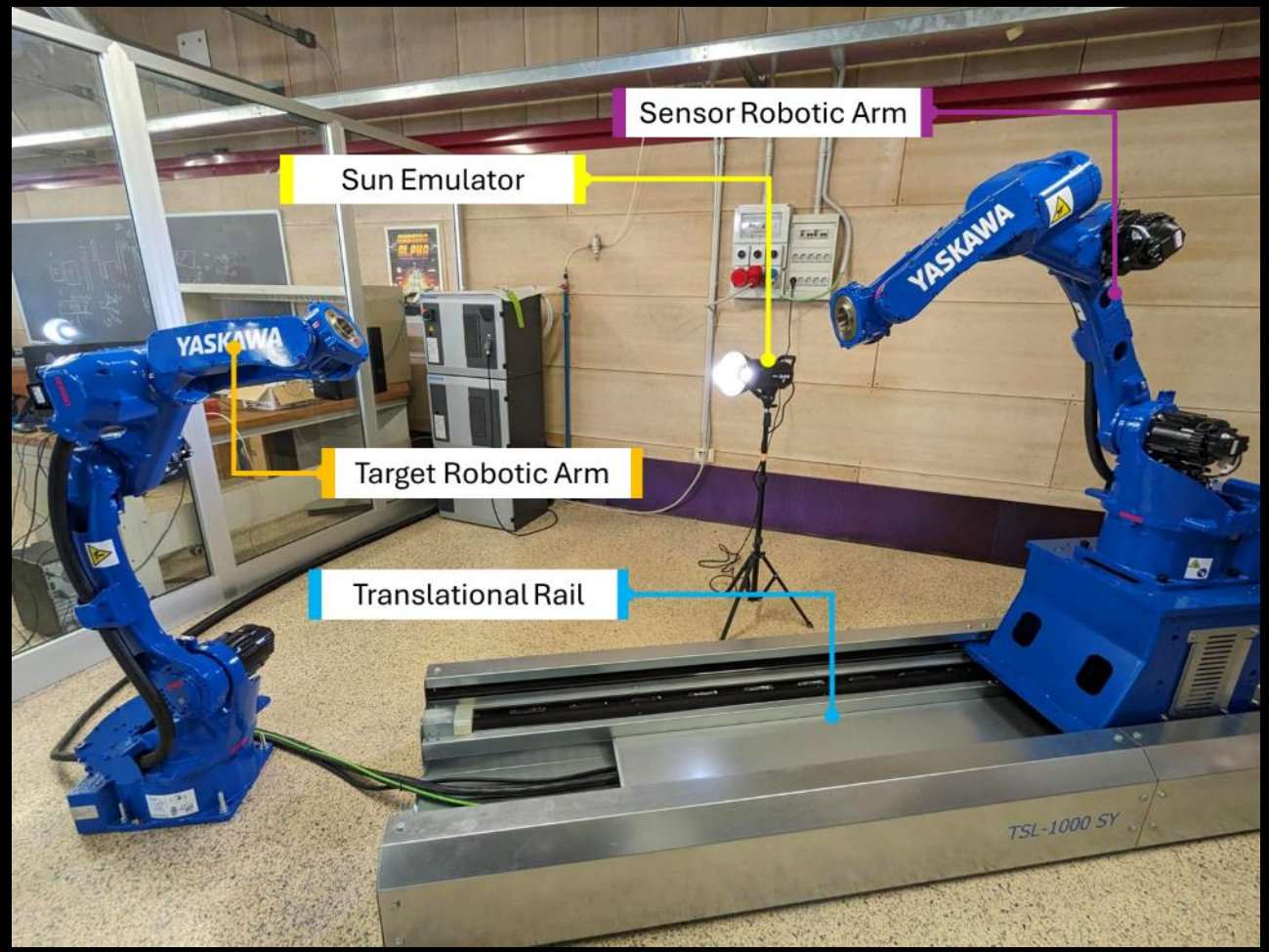
- The algorithms only knowns that *it must target the observation of determined features on the surface*
- Deterministic *path planning with operational and safety constraints*
- *Trajectory refinement* accounting for navigation, control and dynamics uncertainties



Close-Range Robotic Facility

Robotic versatile set-up for all operational scenarios (e.g., landing and close proximity):

- *Two Yaskawa robots and a translational ray* in a synchronous configuration
- A *collimated lamp* to emulate the Sun
- *Enclosing dark room* to avoid light pollution
- *Automatic mapping of the trajectory to the robot movements* in the facility
- Accurate calibration to ensure *below mm-precision truth estimation*



Close-Range Robotic Facility

Future Perspective and Conclusions

- The space sector is rapidly demanding for challenging applications (e.g., in-orbit servicing, asteroid mining) and *CubeSat will play a pivotal role thanks to their low-cost and modularity*
- *Autonomy is and will be a game changer* in complex and risky scenarios
- Detailed algorithm design is mandatory, but *it must be complemented by representative testing* on ground to increase the TRL and ensure robustness

DART has developed an ecosystem of tools and facilities to *support current and future needs in enhancing space systems with autonomous capabilities* accounting for CubeSat's limitations

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Thank you for your attention!

Paolo Panicucci

paolo.panicucci@polimi.it

dart.polimi.it