On-ground testing of Vision-based navigation for non-cooperative rendezvous targets using cameras in the Visible and thermal Infrared range

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Content

- IRPN Activity Overview
- Algorithm Testing
- On-Ground Image Data Generation
- Lessons Learned

Image-based Navigation for Active Debris Removal

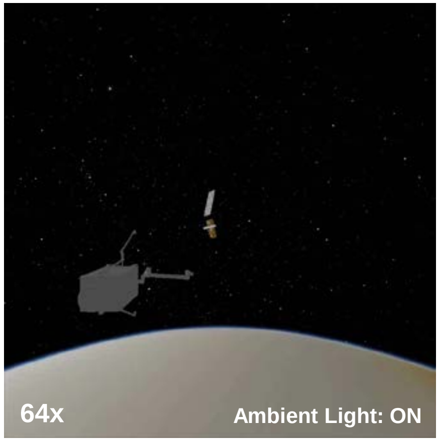
- ESA's *Clean Space* initiative aims at *Active Debris Removal*
  - de-orbiting defunct satellites or pieces of space junk
  - spacecraft rendezvous with an un-cooperative target
- concepts have to be developed for relative navigation between chaser S/C and uncooperative targets → study *Image Recognition and Processing for Navigation* (IRPN)
- image-based algorithms have to be tested with images:

images	representativeness	+	–
in-orbit (real cam)	best	full representative	limited availability of data & ground truth
on-ground (real cam)	varying	easier to obtain, real camera hardware	simulator always limited (trajectories, illumination, …), IR not straightforward
synthetic (rendered)	worst (at limited effort)	any trajectory feasible, low effort for different scenarios	not all effects/details can be simulated (glares, imperfections, …)

→ images taken on-ground with real cameras are important validation basis

Image Recognition and Processing for Navigation (IRPN)

- activity was funded by the European Space Agency
- scenario/constraints:
  - approach to satellite *ENVISAT* from 100m to 2m
  - low Earth orbit (LEO)
  - very quick changes of the illumination conditions (target rotation, revolution around Earth)
- usage of different complementary sensors:
  - visible-spectrum (VIS) cameras
  - thermal infrared (IR) cameras
  - LIDAR

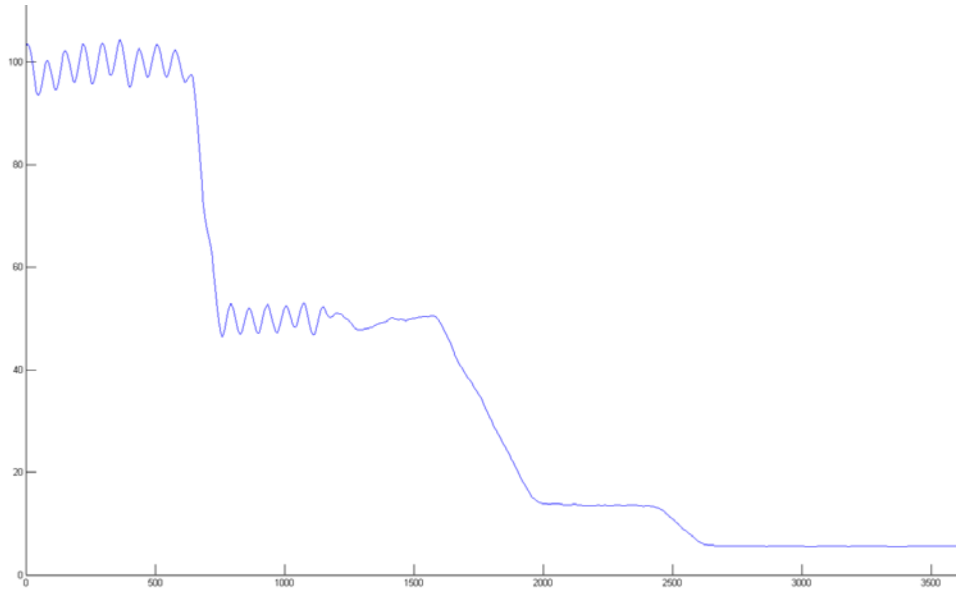


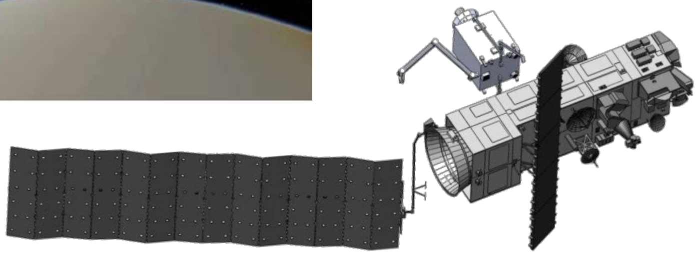
- analysis of sensor data on-board and in real-time using
  - image processing techniques (feature detection, target matching)
  - pose estimation algorithms (relative kinematic state estimation)

→ output: estimated relative kinematic states

Mission Definition (I)

- Direct approach (forced translation) towards COM of target
- Design of approach trajectories according to SoW and NoI
- ➢ Holdpoints at distances of 100 m, 50 m and 2 m, further holdpoint at 11 m
- ➢ At distance of 50 m start of synchronisation with target rotation
  - Approach along rotation axis with almost no relative rotation





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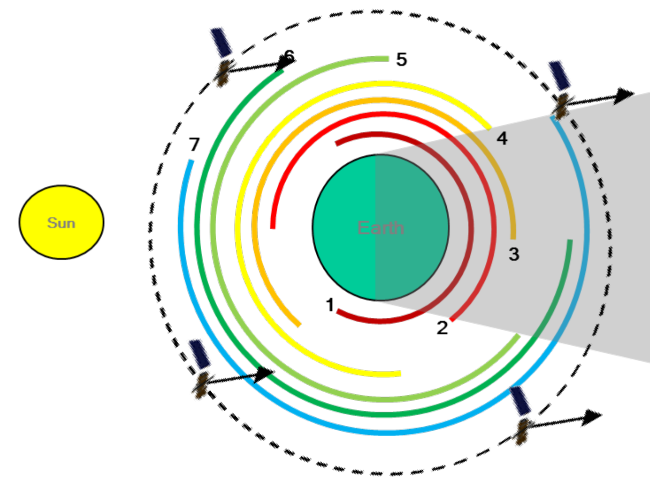
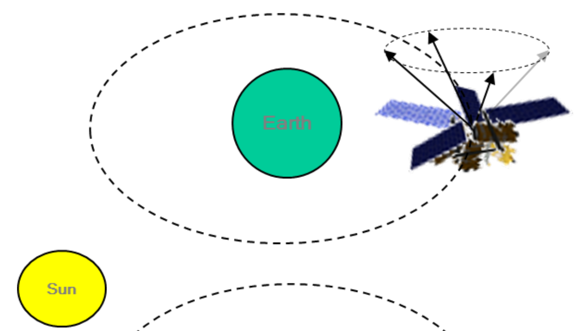
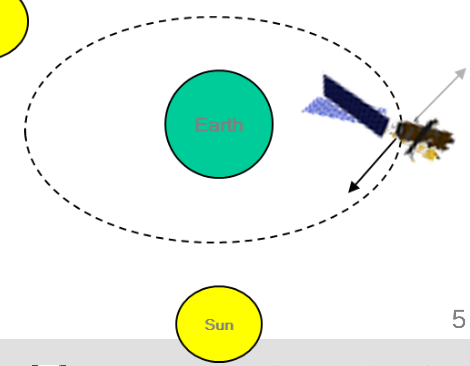
Mission Definition (2)

- 14 scenarios created for generating image data with different lighting conditions
  - ➢ 7 sets with starting points distributed around the earth orbit in August 2014; initial target attitude is fixed in inertial coordinates; 10 PM MLST (asc. node)
  - ➢ 1 set starting in May 2020; initial target attitude is fixed; 6 PM MLST (ascending node)
  - ➢ 3 further sets with rotated initial target attitude; initial target attitude is fixed, May 2020
  - ➢ 2 sets with initial target attitude in opposite direction; initial target attitude is fixed, May 2020
  - ➢ 1 further trajectory set with tumbling target; no active stabilization is used, May 2020
- For each scenario generation of 60 Monte Carlo run trajectories
- Before final sensor data generation for MIL/PIL tests:
  - Review of scenarios in terms of illumination
  - Selection of reasonable scenario subset







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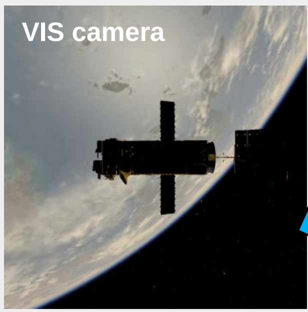
Structure of the IRPN System

sensors



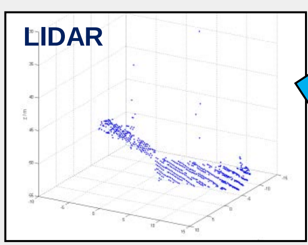


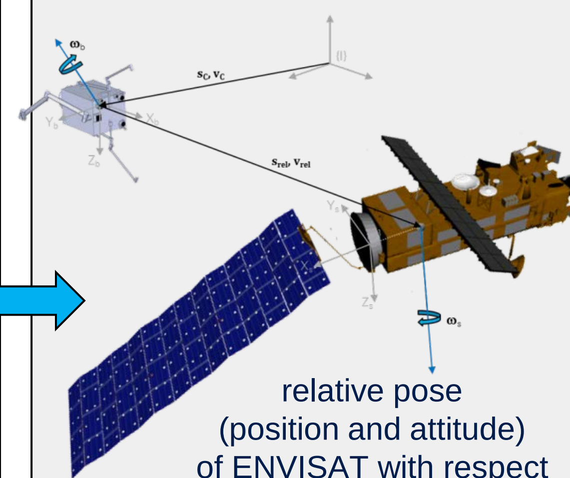
image recognition and processing (IRP) algorithms to be developed

- IRP algorithms for visible spectrum (VIS) camera
- IRP algorithms for infrared spectrum (IR) camera
- IRP algorithms for LIDAR

navigation function to be developed

- Navigation Function

objective



relative pose (position and attitude) of ENVISAT with respect to the chaser

→ define requirements to run algorithms on dedicated hardware

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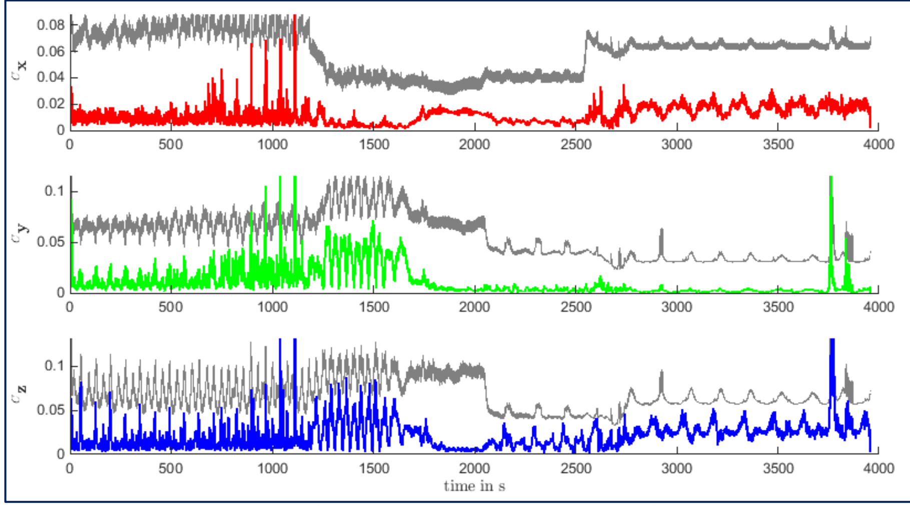


Typical mean relative position error [m]

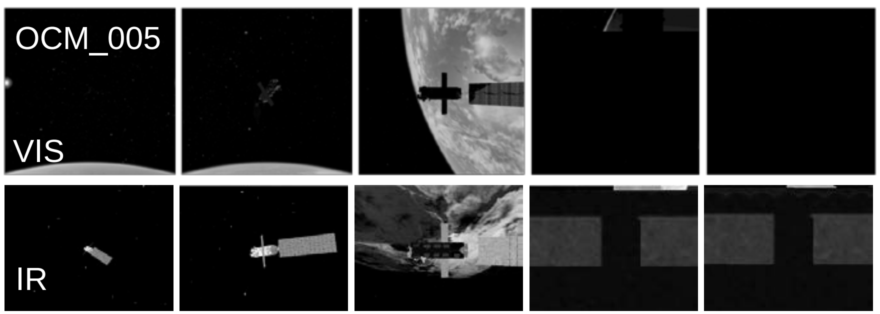
Test on Different Testbeds

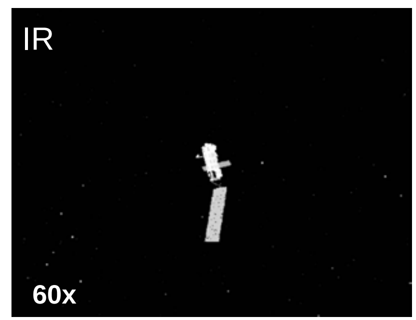
- representative reference trajectories
- model-in-the-loop (**MIL**), MATLAB Simulink
  - fast algorithm evaluation (faster than real time)
  - extensive Monte-Carlo tests
  - synthetic images/LIDAR measurements
  - derivation of SIL model for automatic code generation for target hardware
- processor-in-the-loop (**PIL**), dSPACE
  - evaluation of real-time capabilities (timing and scheduling tests)
  - realistic data exchange between processors
  - distribution of algorithms to several processors
  - synthetic images/LIDAR measurements

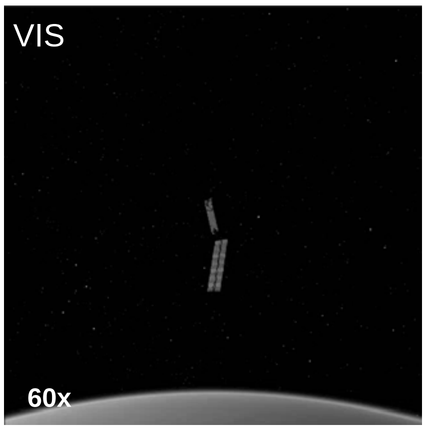
- hardware-in-the-loop (**HIL**), laboratory spacecraft simulator MiPOS
  - image data recorded by real camera hardware
  - evaluation of algorithm performance concerning effects missing in artificial image generation (e.g. glares, imperfections)

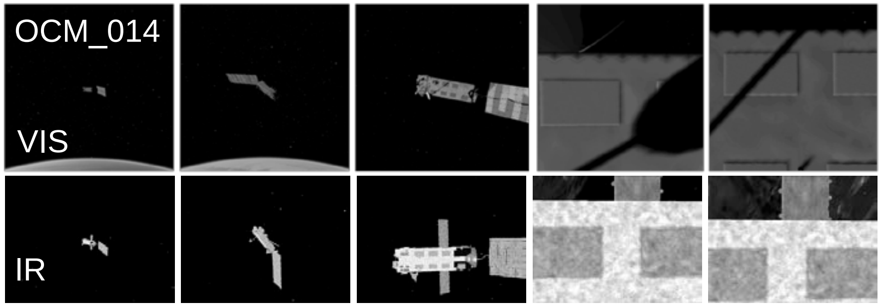
Synthetic Images (for MIL and PIL)

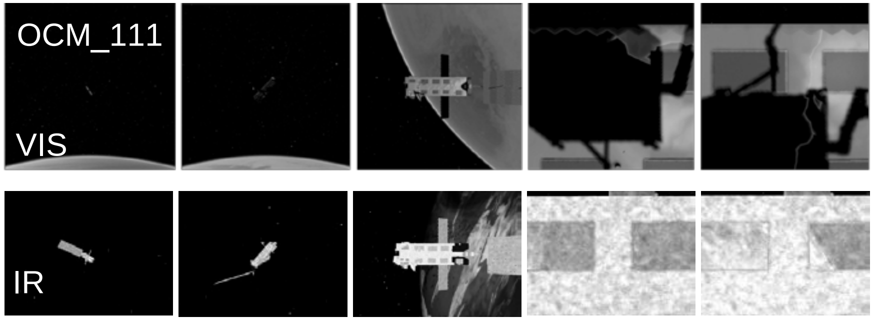
- synthetic IR/VIS image and LIDAR data
- Monte-Carlo runs of several scenarios
- different lighting conditions and orbital start points for scenarios











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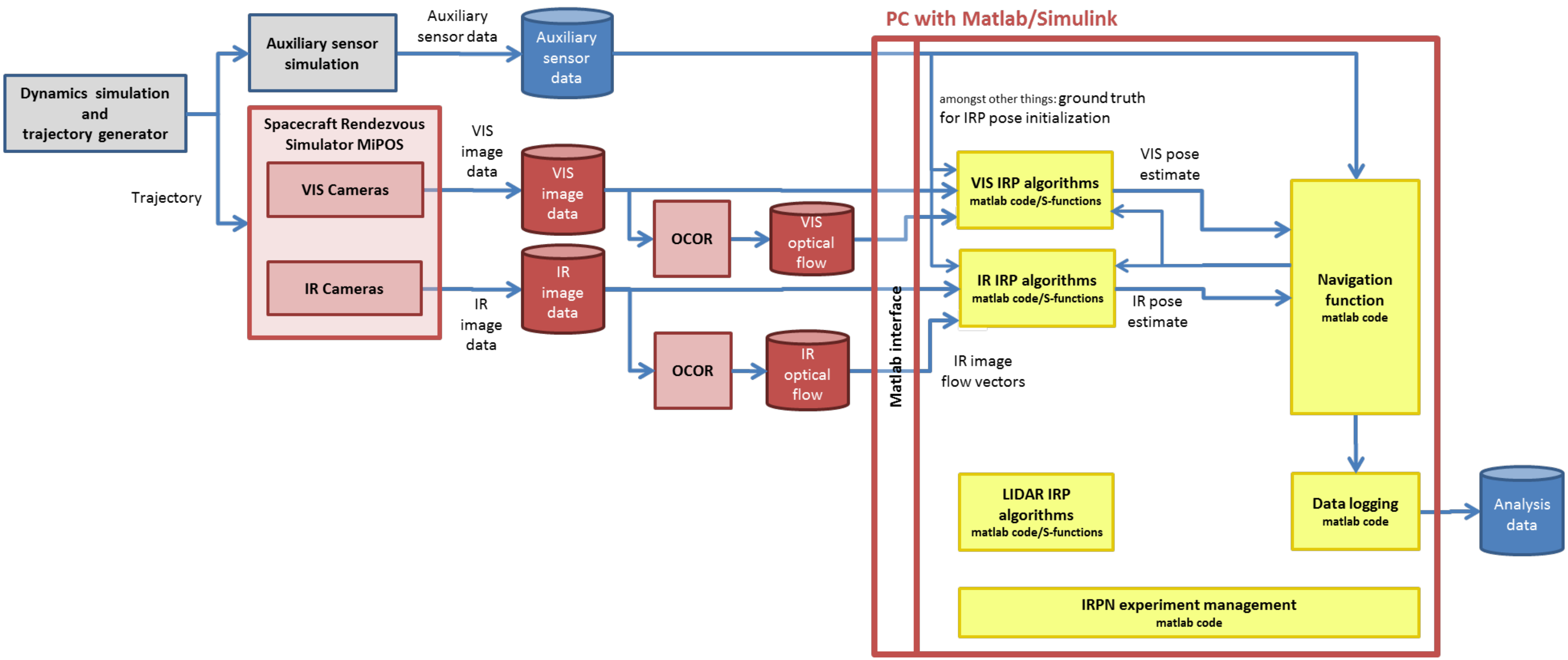
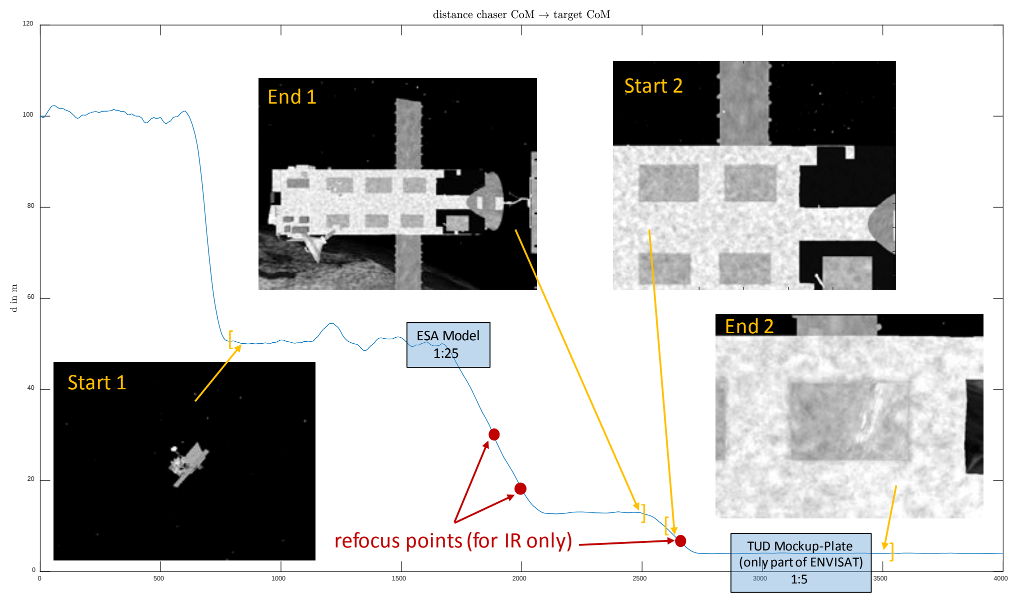
HIL System Overview

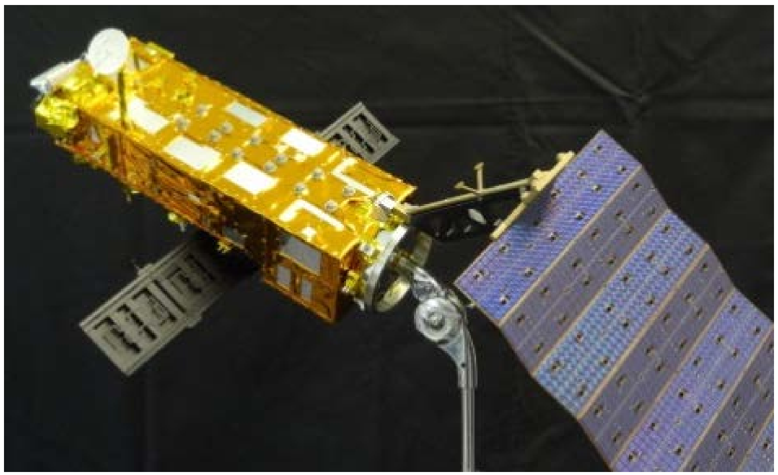


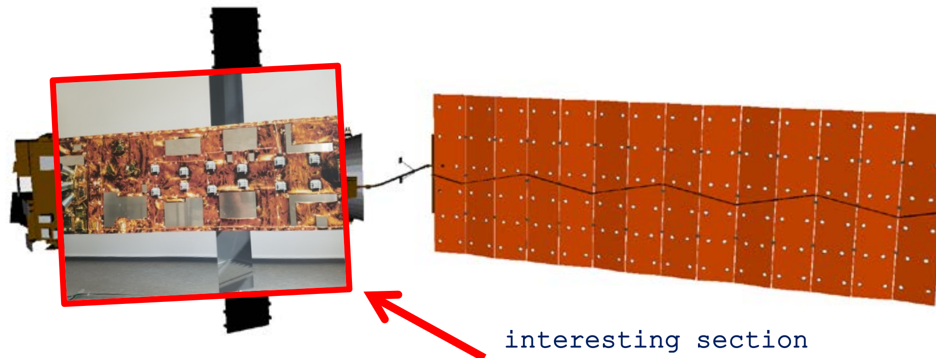
HIL Basic Test Concept (I)



- VIS and IR images generated at the same time (direct comparison of results)
- Interesting range for HIL Tests: 50m to 2m (limited capabilities in the distance from 100m to 50m without LIDAR)
- ESA mock-up 1:25 for range 50m to 11m (2x refocus/recalibration for IR)
- Simplified model 1:5 for range 5m to 2m (1x refocus/recalibration for IR)

HIL Basic Test Concept (II)



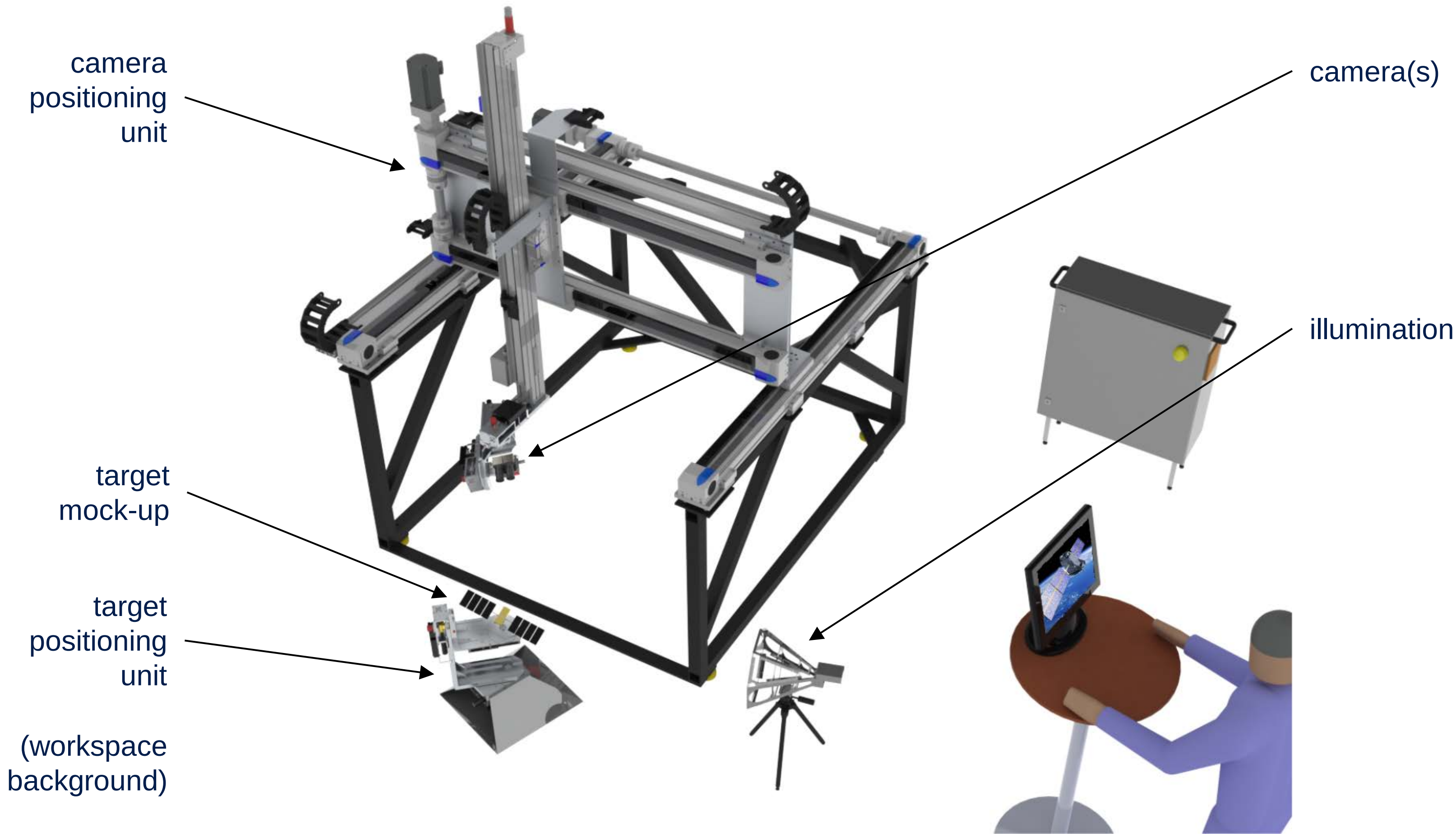


- Two different set-ups (scale 1:25 and 1:5)
- ENVISAT mock-up position fixed, 3 DOF (limited) rotation for 1:25 mock-up
- Camera pose according to relative pose (depending on scenarios)
- Calibration necessary (for VIS & IR), IR during approach
- Step-by-step movement and image capturing

HIL Basic Test Concept (III)

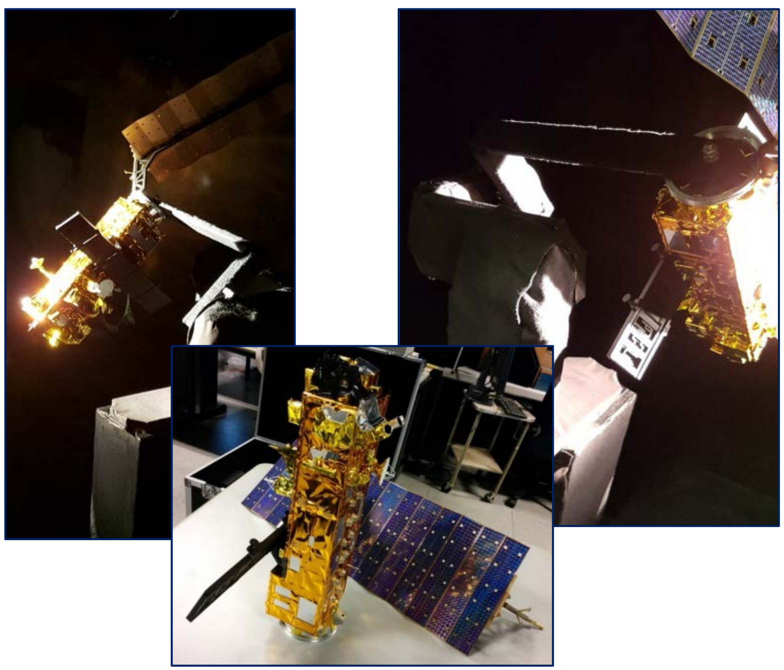
- IR images: principle testing of algorithm capabilities (without representative spatial gradients/temporal variations of temperature)
- Range from 11m to 5m is not covered:
  - Model scale is not available
  - Whole body is in FOV → model is very complex
  - Non critical distance (best MIL and PIL results)

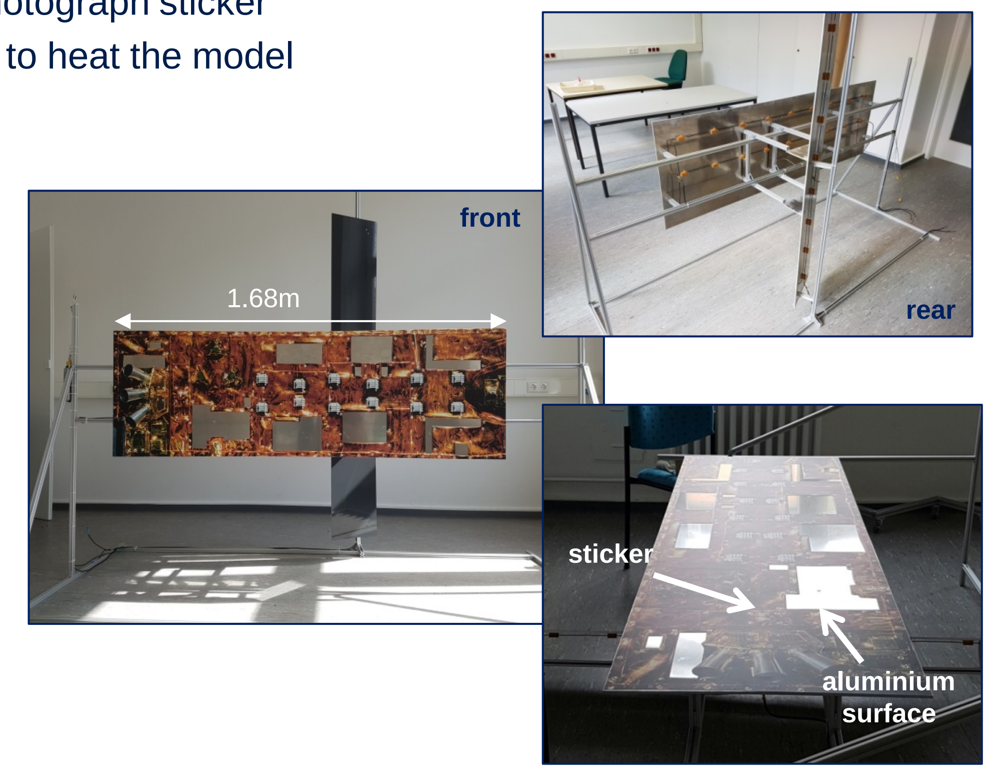
Key Elements of HIL Image Data Generation



ENVISAT Mock-ups

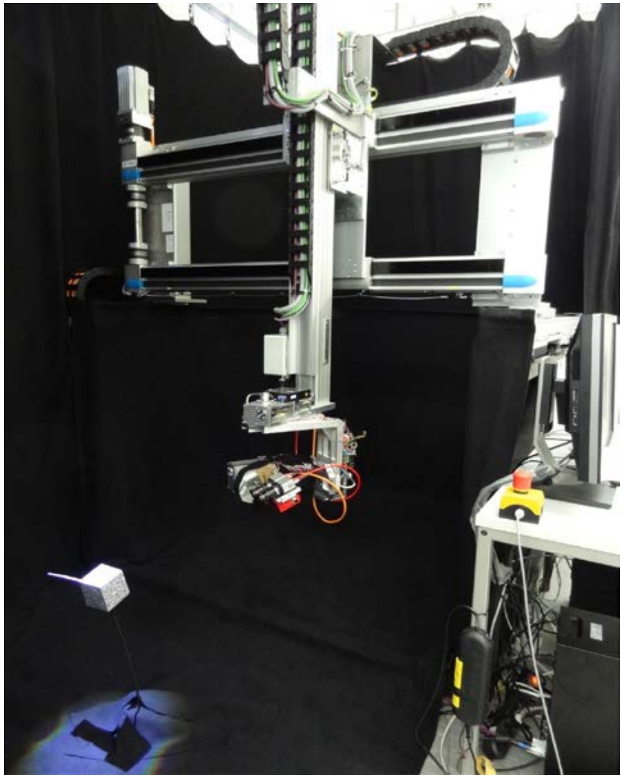
- mid-range, scale 1:25: complete satellite, high detailed, covered with MLI foil
- close-range, scale 1:5: FOV optimized (only Payload Module and ASAR antenna)
  - aluminium plates covered with photograph sticker
  - resistors on the rear can be used to heat the model





Spacecraft Rendezvous Simulator MiPOS

- portal robot with spherical joints for camera system
  - 3 translational DOF
  - 3 rotational DOF
  - workspace:1.5 m x 0.8 m x 0.8 m (L×W×H)
- target unit with spherical joint for target mock-up
  - 3 rotational DOF
  - two ENVISAT mock-ups (scale 1:25 and 1:5)
- black curtains for dark background
- off-the-shelf stereo cameras:
  - visual spectrum: 2x AV Manta G-419B
  - thermal infrared spectrum: 2x Xenics Gobi-640
- illumination (+ heating):
  - halogen floodlight (500 W)
  - dual head high performance halogen spotlight (2x150 W, UV filter)



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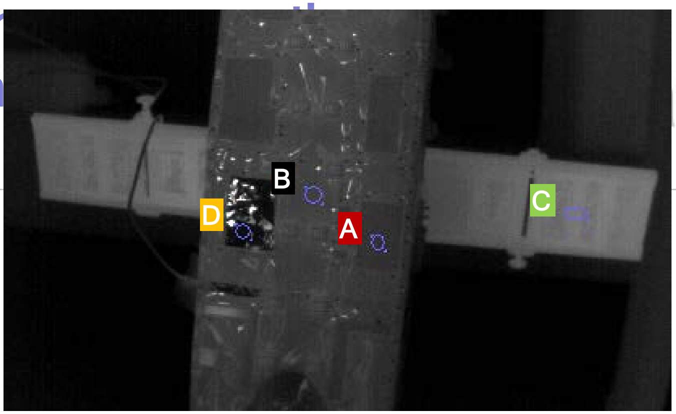
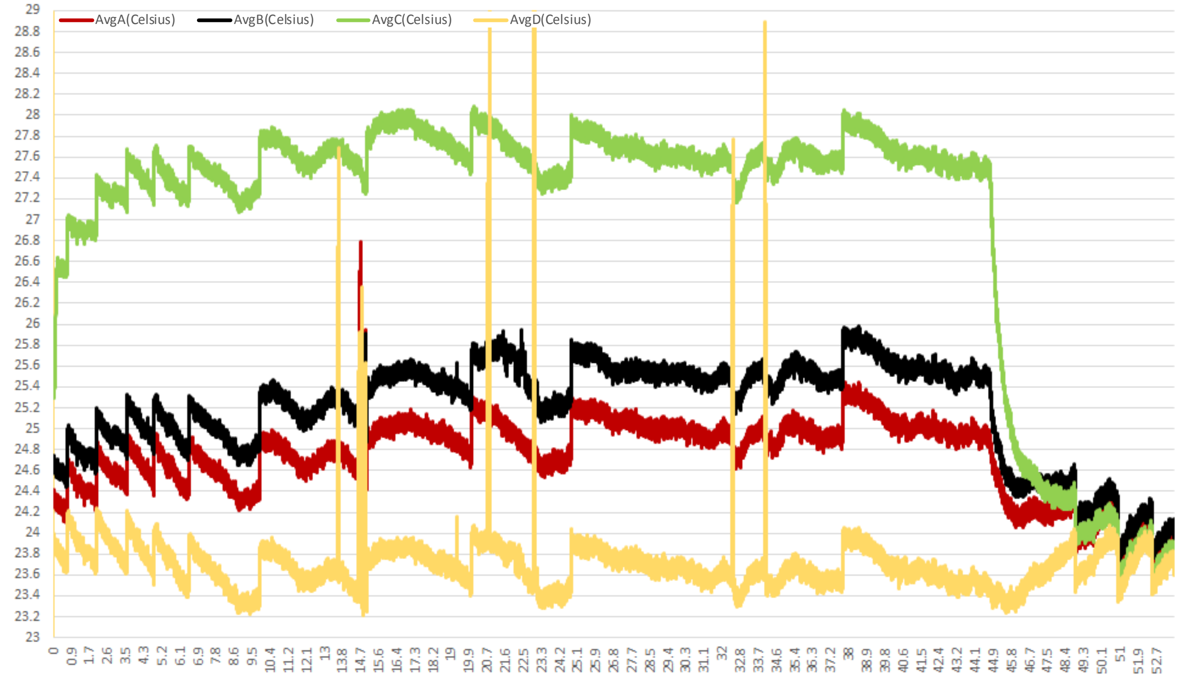


IR Images for 1:25 Mock-up

- Heating of the mock-up using Halogen spotlight
- MLI shows actual surface temperature, radiators (aluminium foil) reflect background
- Temperature difference between MLI and radiators: $\Delta T \approx 2°C$

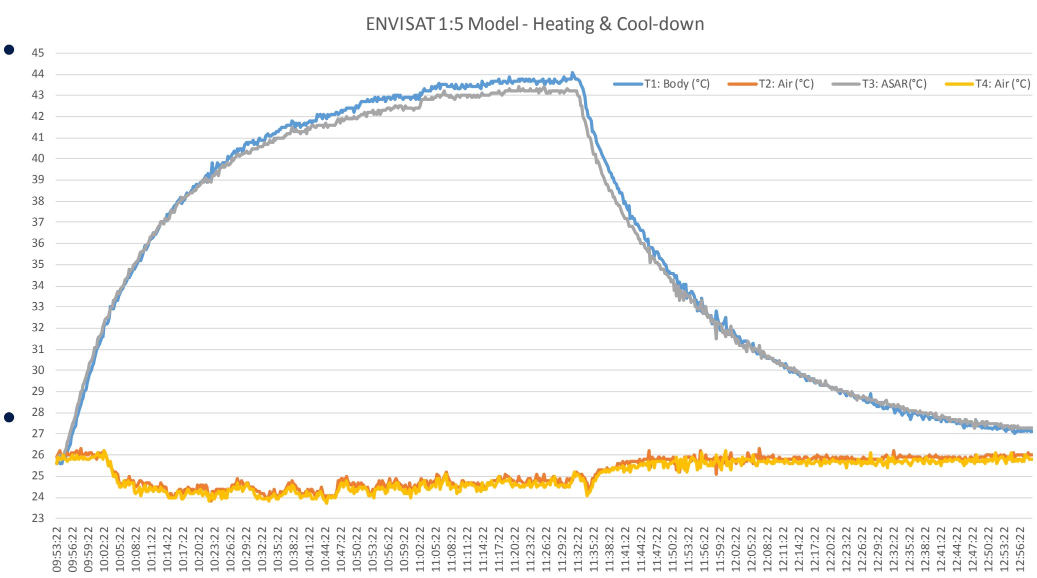


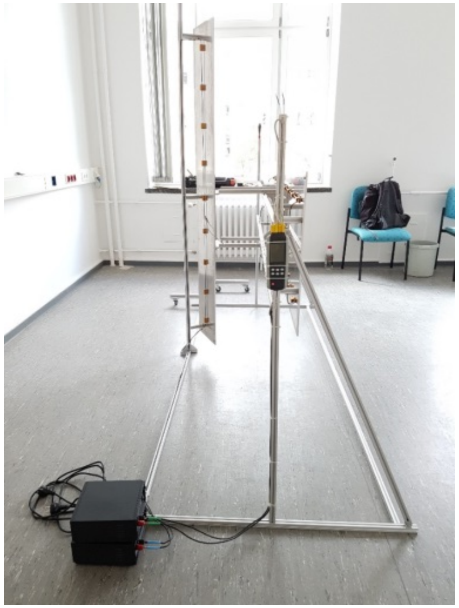
IR Images for 1:5 Model (1)

Resistors on the rear heat the aluminium plates and the photograph sticker

- Sticker "emits its temperature"
- Aluminium behaves like a mirror → background (behind camera) is reflected

➔ Temperature difference between MLI and radiators: ΔT ≈ 20°C after 1.5 h of heating





IR Images of Background (Mid-range)

Using spotlights for heating increases temperature of target mock-up only by 2°C.

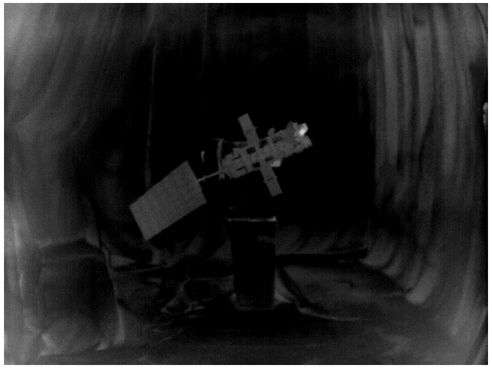
- Background is still visible
- Target unit heats up by integrated sensors and actors

➔ Cooling of environment (water spray) is necessary to generate usable images

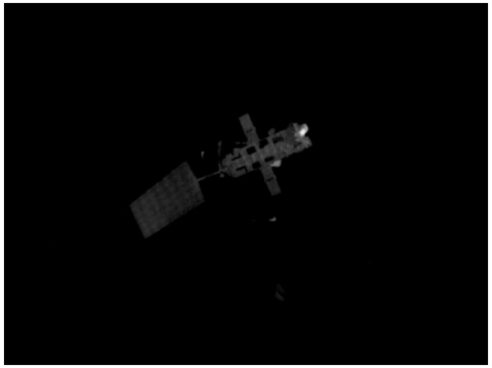
- Applying a vignette and adjusting the black level would even more improve the images

Uncooled target unit and background

Water-cooled target unit and background



Water-cooled environment, application of vignette and adjustment of black level



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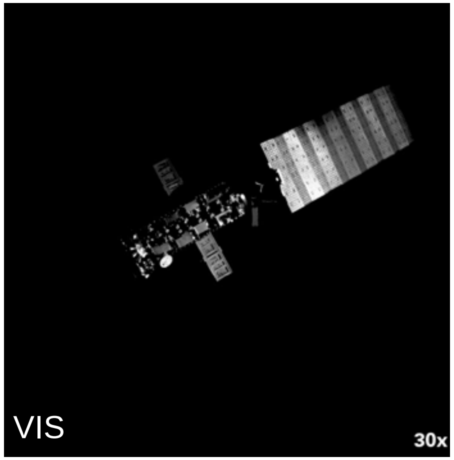
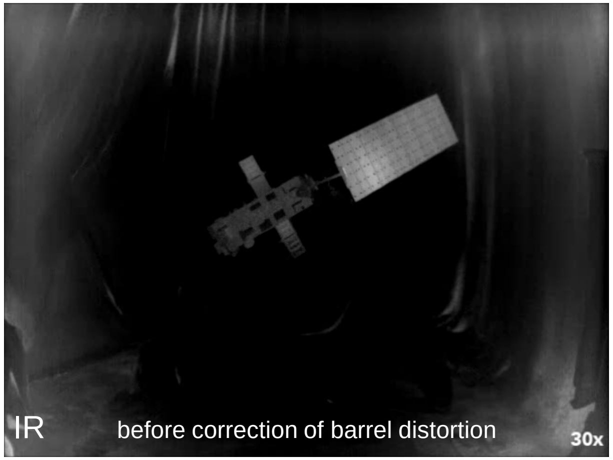
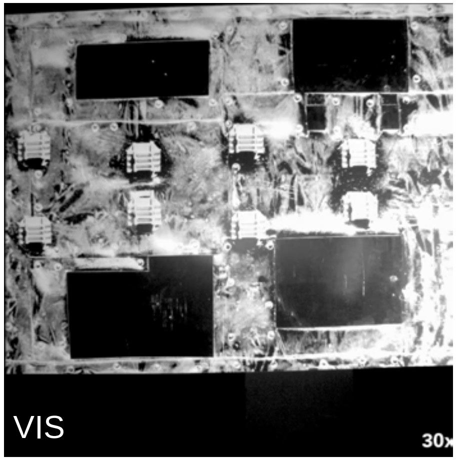
On-ground Images (Real Cameras, for HIL)

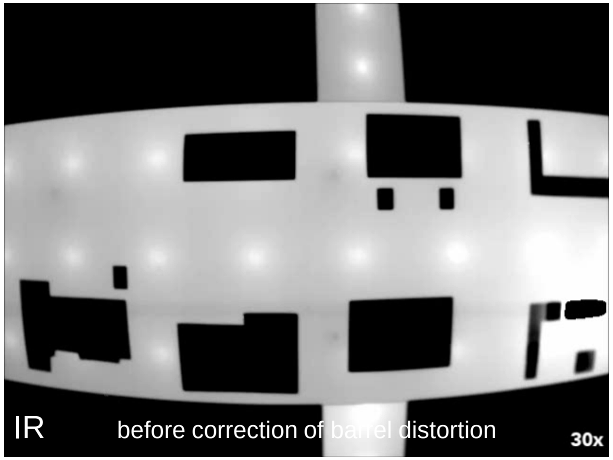
scale 1:25





scale 1:5





Lessons Learned – Size of the Lab/Simulator

- laboratory & simulator need to be big enough (and capable) to simulate relative motion of all elements (incl. illumination by sun and earth!)
- downscaling causes undesired effects:
  - extreme high detailed small-scale mock-up needed
  - depth of field can not be scaled:
    - no representative image blurring
    - time-consuming refocusing or scale change necessary
- seamless assembling of trajectory patches (variable focus/scale) is complicated
- size of cameras not scalable: their reflections appear up-scaled
- used LIDAR sensor not suitable for down-scaling
- background with small distance to the target will be heated/illuminated by lighting

Lessons Learned – Thermal Effects

Using thermal infrared cameras leads to special requirements for representative image generation:

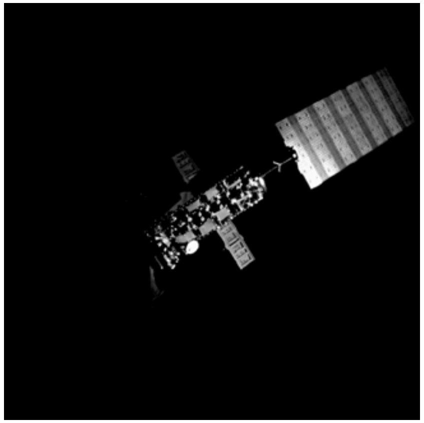
- thermal characteristics of the target must be known
- thermal behaviour of the mock-ups need to be simulated (active thermal control may be necessary)
- real high temperature differences in space are difficult to simulate (extensive heating and cooling is needed)
- thermal effects do not scale with size: down-scaled experiments without active thermal control would have to be run faster
- convection in laboratory is smoothing the surface temperatures (less contrast)

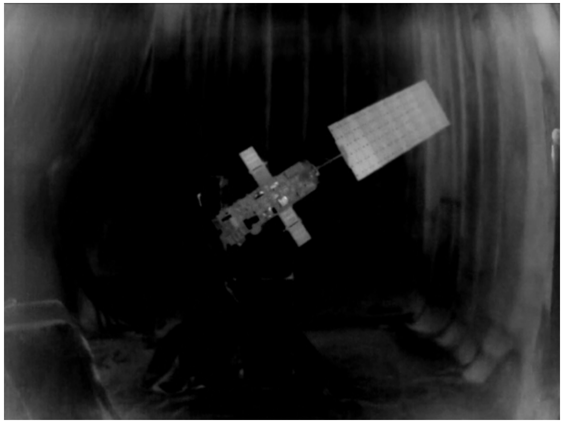
→ for IRPN simulated thermal effects have shown only limited representativeness (heating by spotlight/resistors)

Lessons Learned – Background

Background in the laboratory should be invisible for cameras:

- distance from target to background big enough (to avoid undesired illumination/heating)
- visible spectrum: black molleton curtains are suitable
- thermal infrared spectrum:
  - space background is cold → cooling lab background or heating mock-up
  - background should have high thermal capacity and/or high thermal conductivity (e.g. solid walls).
  - background should be made of smooth material without wrinkles or corners

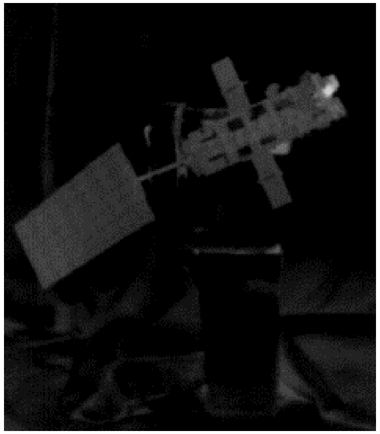




Lessons Learned – Mock-up Mounting

Mounting/wrist joint should be invisible for cameras:

- target unit can heat up during the experiments
- the target unit should be actively cooled down (depending on mock-up/background temperature)
- especially motors and sensors need to be cooled (or thermally covered)



Lessons Learned – Realism

- in general it is very expensive to generate highly realistic images in a laboratory spacecraft simulator; relevant are:
  - true relative motion of satellites and sun
  - relative position of Earth and the Earth albedo
  - illumination spectrum corresponding to sun light spectrum in the Earth orbit
  - real (or comparable) target mock-up surface materials
  - visual and thermal characteristics of target
- representativeness of images from algorithms point of view varies and depends on algorithm → should be further investigated (reduction of effort for non-relevant effects)
- background/background objects like Earth cannot be simulated in the correct scaled distance → range measuring sensors (e.g. stereo cameras) can *not* be deceived
- algorithms' behaviour with real camera image data can be drastically different to the behaviour with synthetic image data (even for high realism) → test algorithms with real camera images as early as possible

On-ground testing of Vision-based navigation for non-cooperative rendezvous targets using cameras in the Visible and thermal Infrared range

esa

Edges in the VIS Image Data (1)

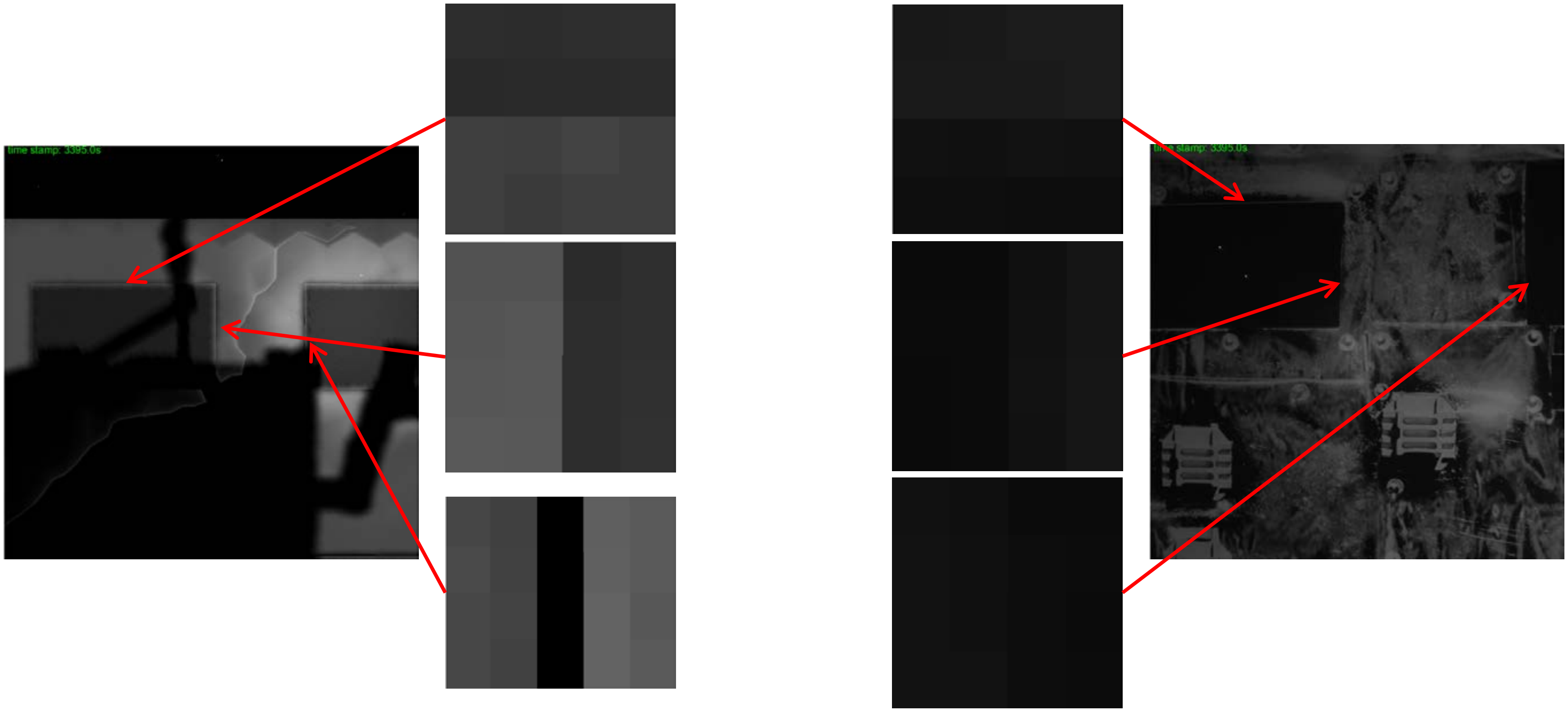
- The edges in the HIL image are less clear than in the PIL image data

PIL:

HIL:

Edges in the VIS Image Data (2)

- The edges in the HIL image are less clear than in the PIL image data



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Conclusions

- image processing algorithms and a navigation function have been developed for estimation of relative pose to a target satellite (in IRPN exemplary ENVISAT; distance <100m)
- beside synthetic image data, on-ground image data has been generated in a laboratory environment using visible-spectrum and thermal infrared camera hardware and different mock-ups
- there are a lot of limitations for generating realistic on-ground image data (especially for thermal infrared spectrum) – several important lessons learned have been presented
- the results generated with the given limitations are promising → justifies increased effort for more realistic/representative on-ground (IR) images (even better are in-orbit images + good ground-truth)
- testing with images from real cameras is essential (synthetic images only are not sufficient)