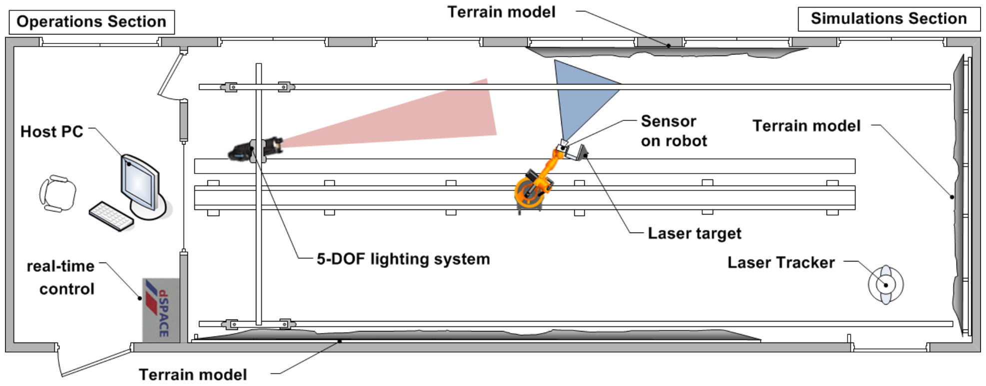
V&V IN TRON

Verification and validation of optical navigation algorithms and sensors in TRON

Hans Krüger, DLR Institue of Space Systems, 23.10.2024

Outline

- TRON building blocks
- Ground truth approach
- Application options
- Data acquisition examples



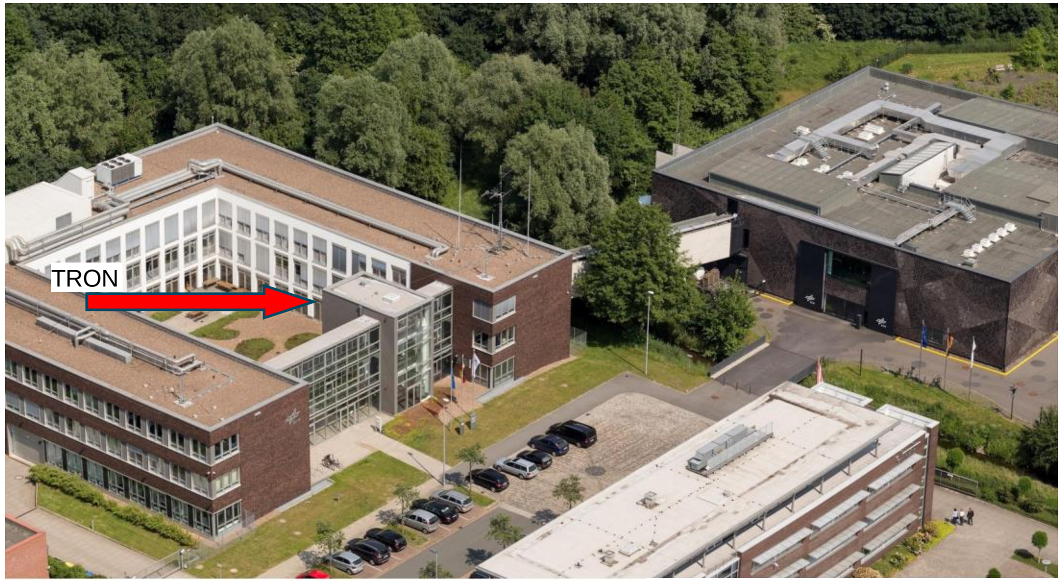
TRON in DLR Bremen

- TRON is located in DLR Bremen

Aerial view of DLR Bremen

TRON in DLR Bremen

- TRON is located in DLR Bremen
- Situated in-house on ground level of the office building



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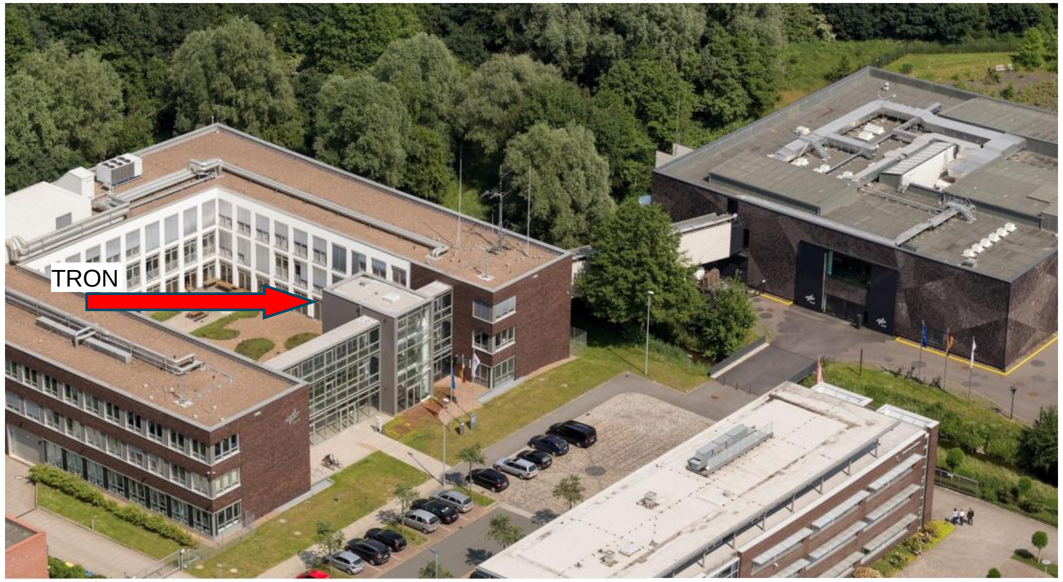

Aerial view of DLR Bremen

DLR Bremen in open street map

TRON overview
Purpose

- TRON is a hardware-in-the-loop test environment
- Provides an operational environment for camera based optical sensors
- Allows testing up to TRL 7
- Current setup for lunar landing missions
- Other sensors are welcome
- In the follwowing we introduce the building blocks

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How it started

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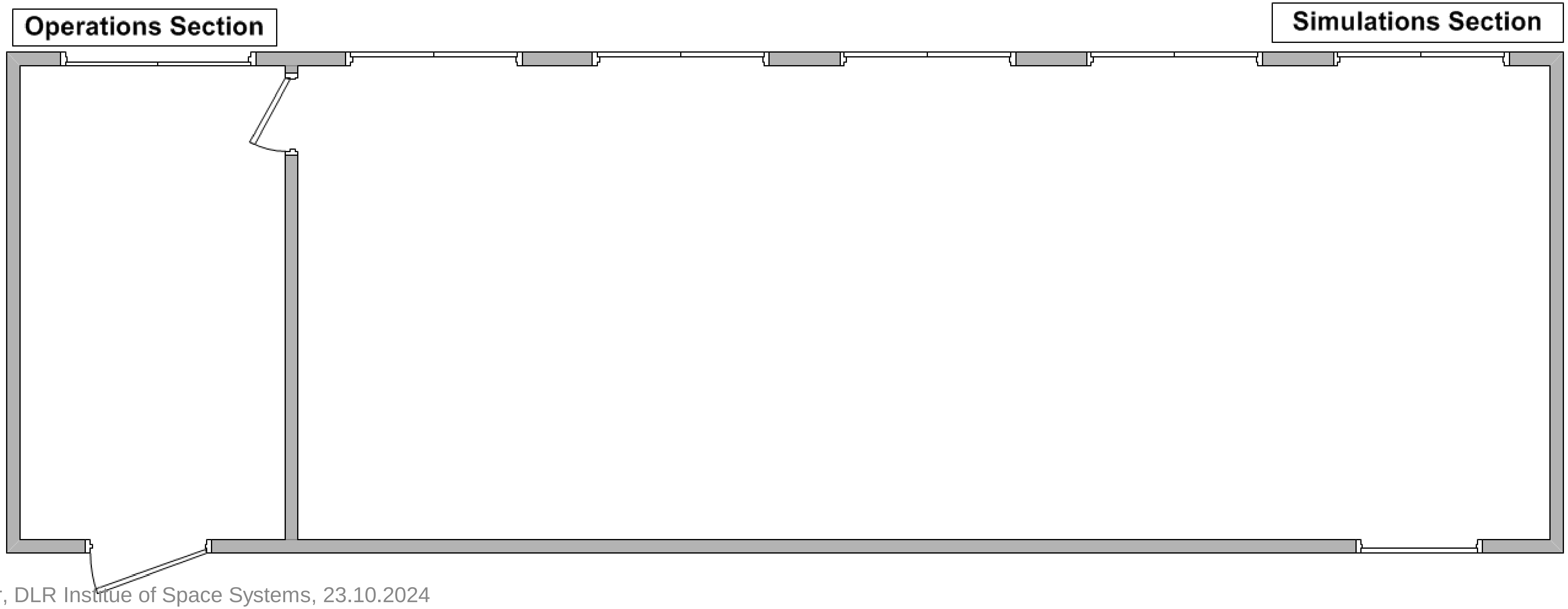
How it's going

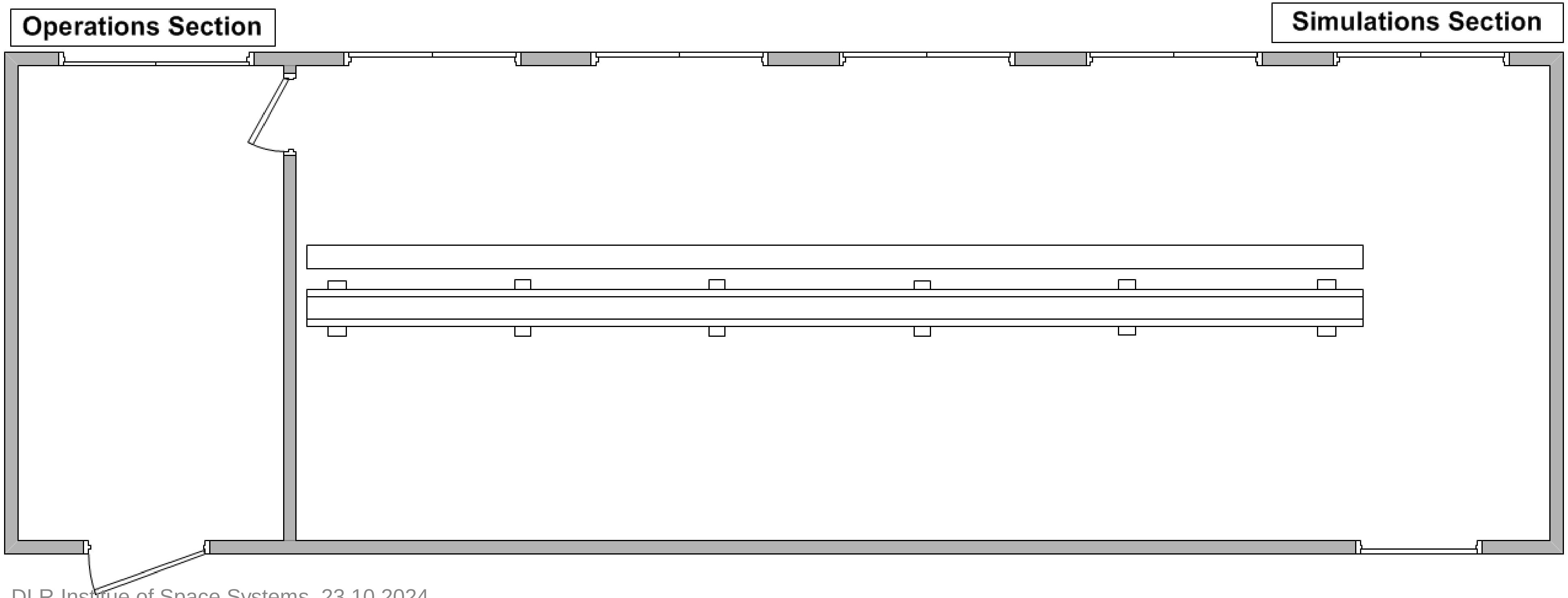
TRON overview
Building blocks

- Lab size:
  - Length: 13.50 m
  - Width: 5.10 m
  - Height: 3.00 m



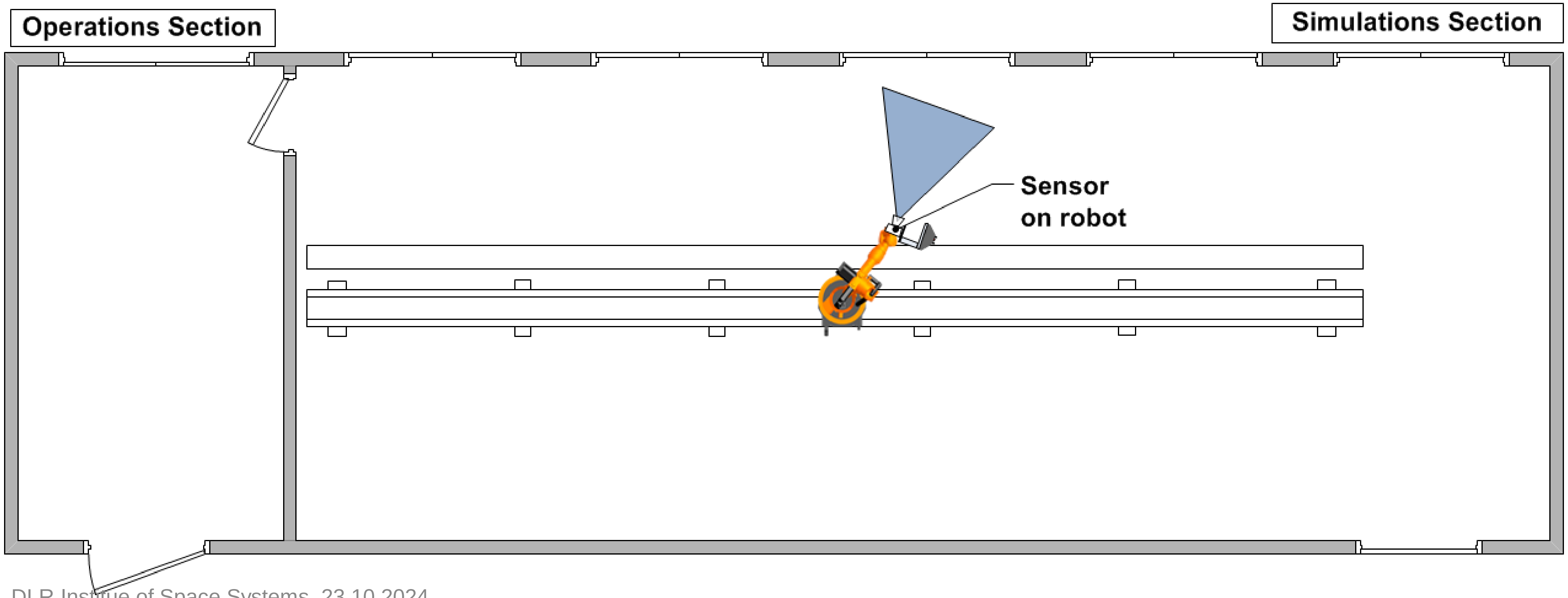
TRON overview
Building blocks

- 11.7 m rail



TRON overview
Building blocks

- 11.7 m rail, with 6 DOF robot for sensor actuation, 16 kg + 24 kg payload



TRON overview
Building blocks

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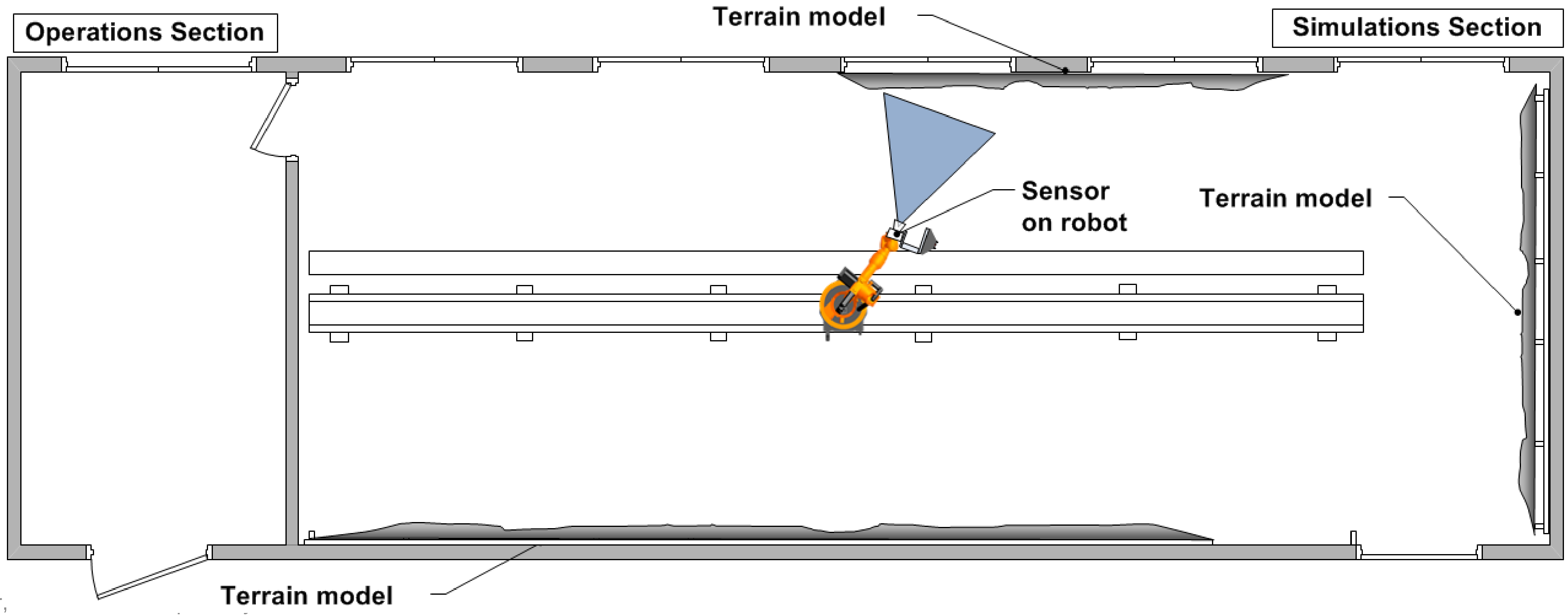
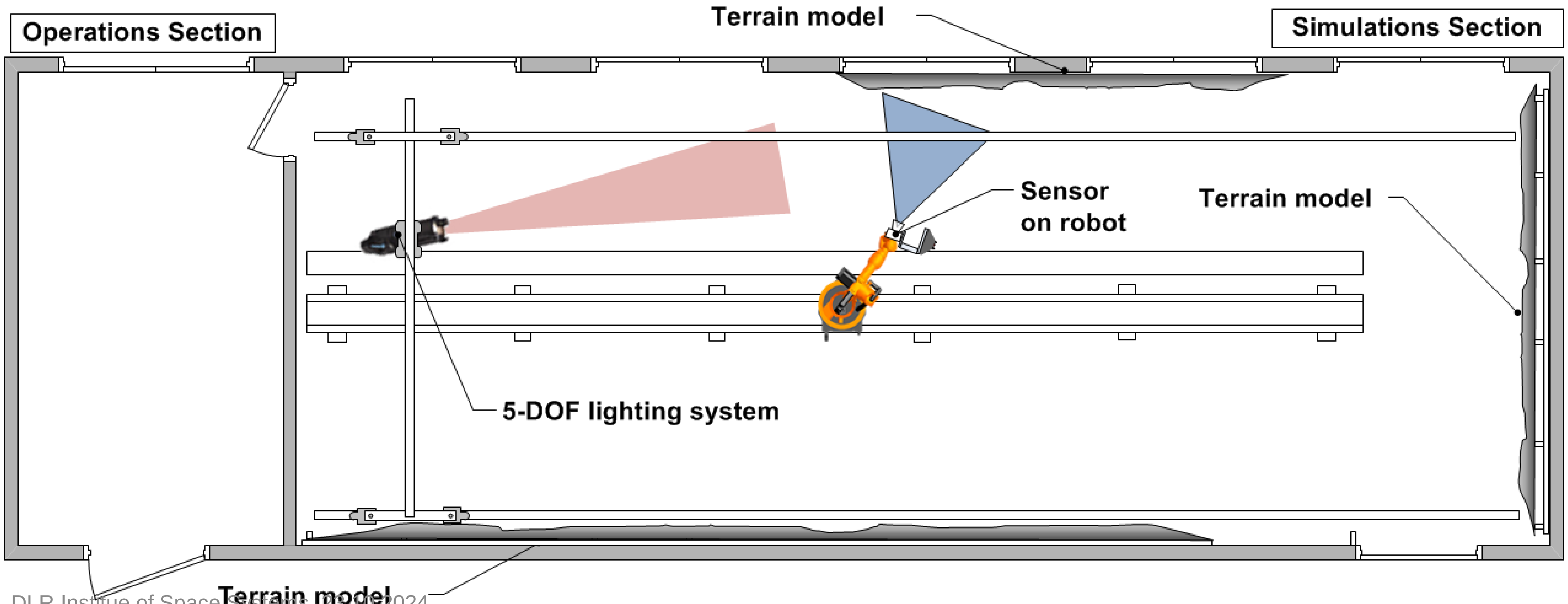
- 3 terrain models of lunar environment



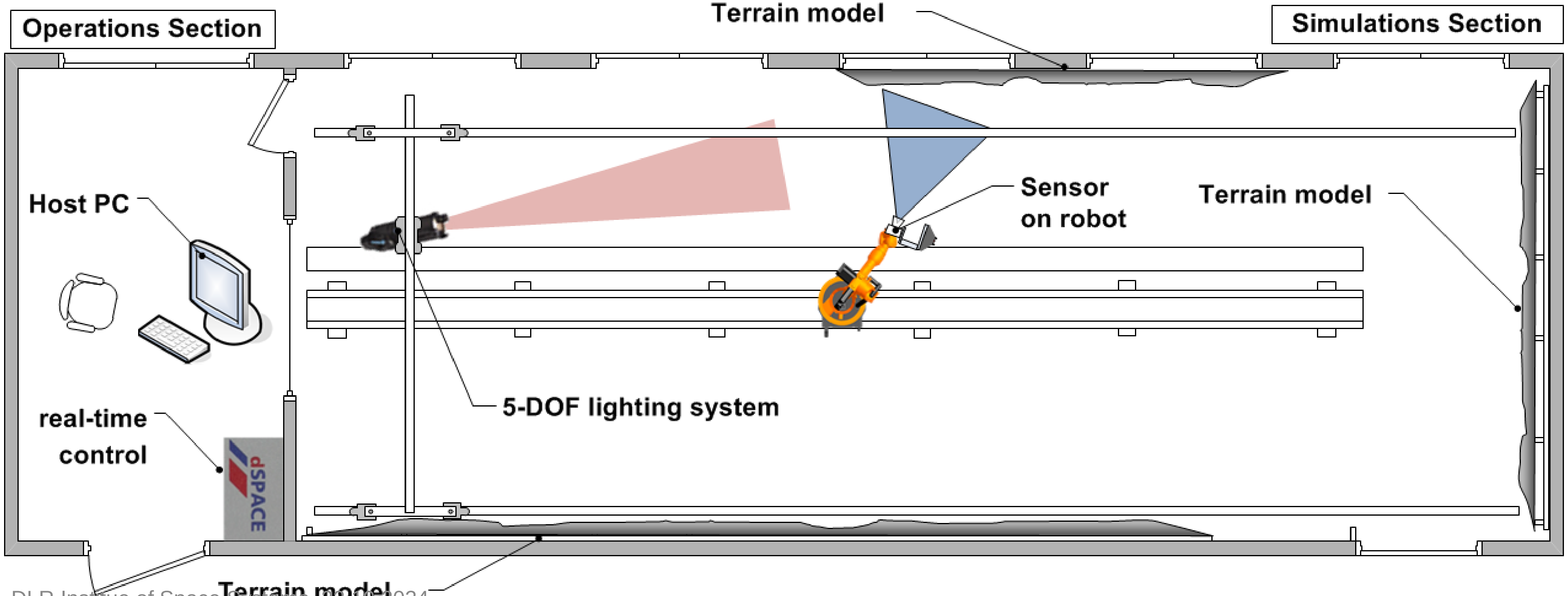
TRON overview
Building blocks

- 11.7 m rail, with 6 DOF robot for sensor actuation
- 3 terrain models of lunar environment
- 5-DOF lighting system & ambient light prevention



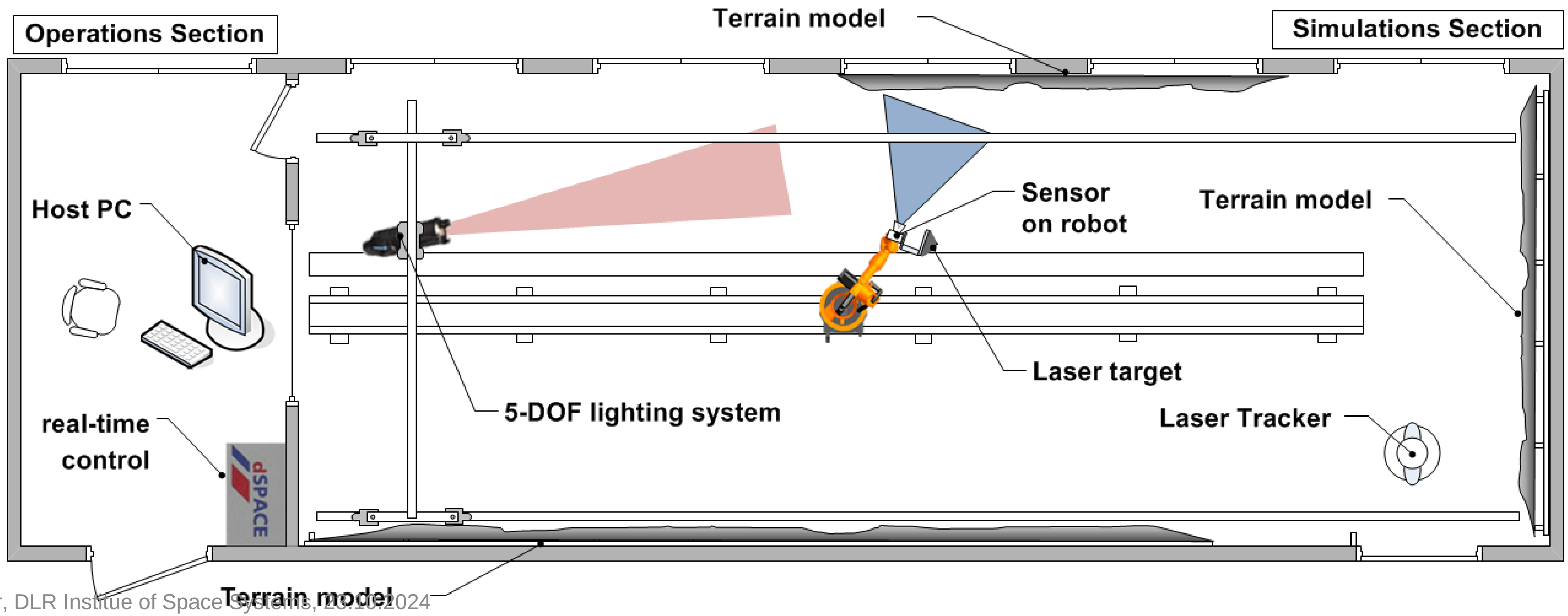
TRON overview
Building blocks

- Control via operations section in a separate room



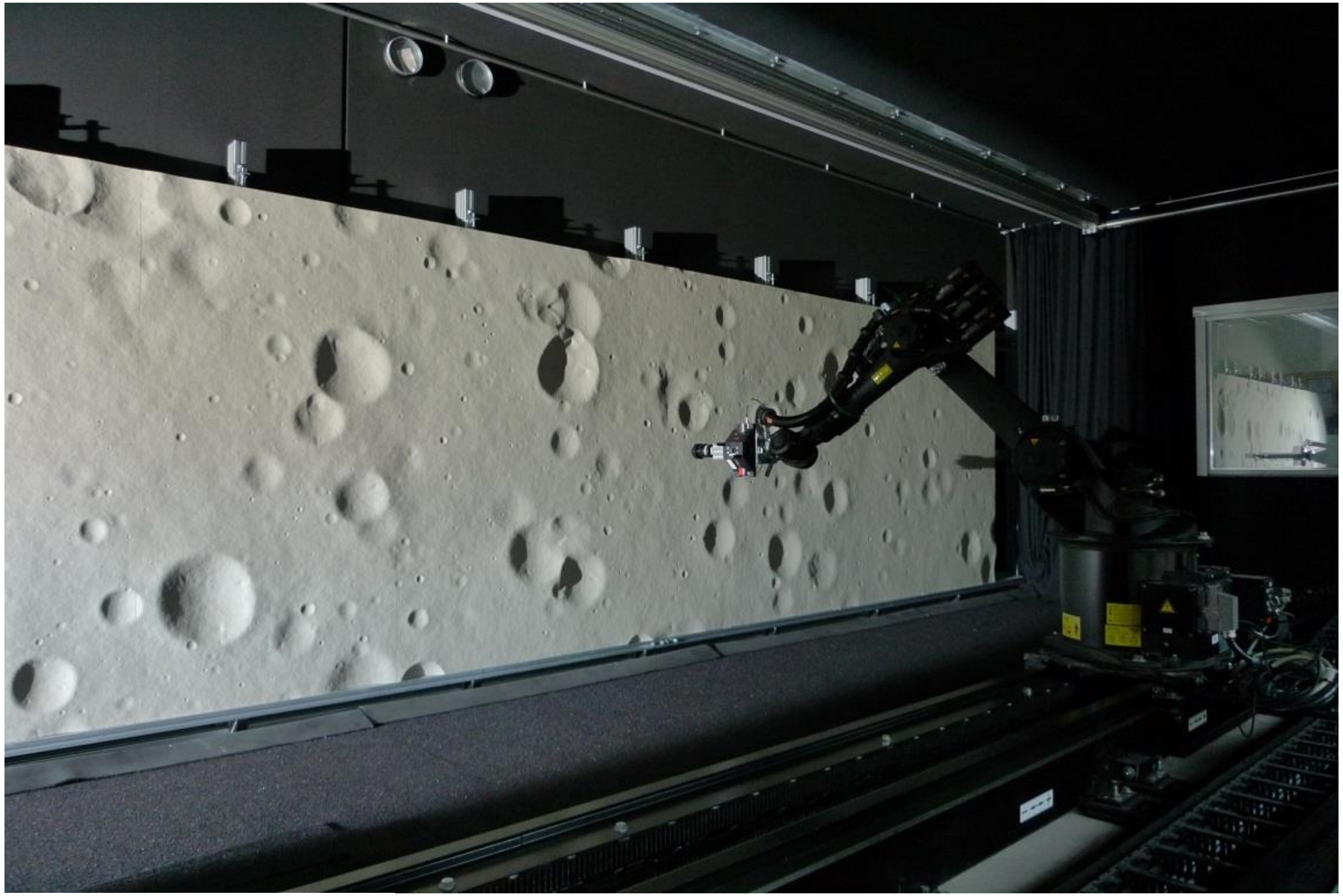
TRON overview
Building blocks

- Control via operations section in a separate room
- Laser metrology equipment for ground truth



TRON building blocks
Terrain models: Moon 1

- Size: 10 m x 2 m
- Z-dynamic: 62 mm
- Resolution: 1 mm
- Scale: user defined
- DEM: PANGU



Terrain model Moon 1 in TRON

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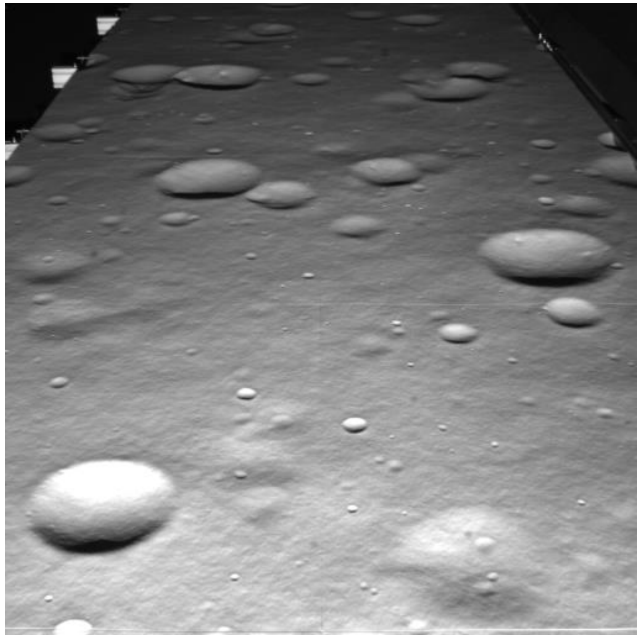

Example image of Moon 1

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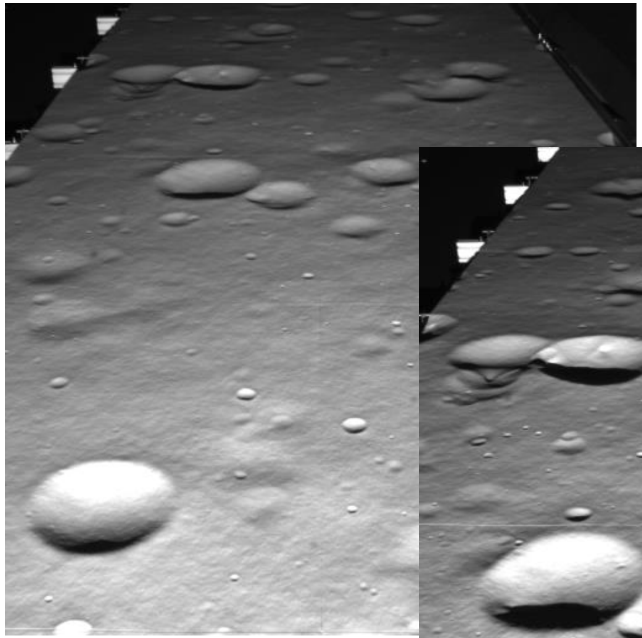

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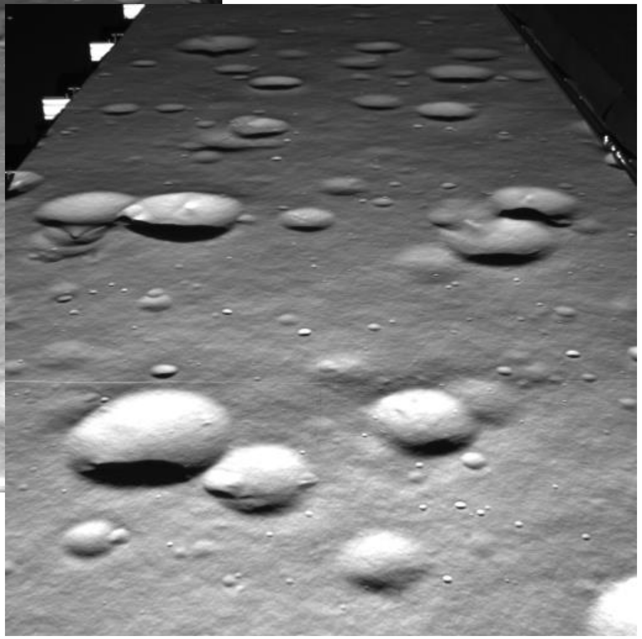

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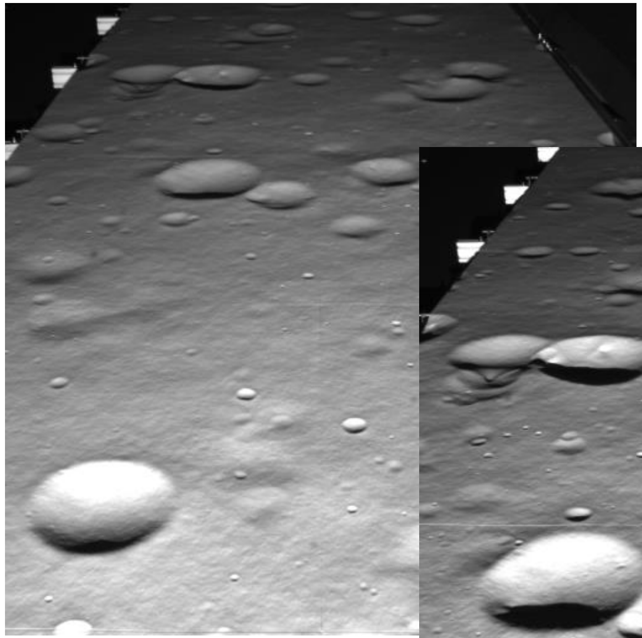

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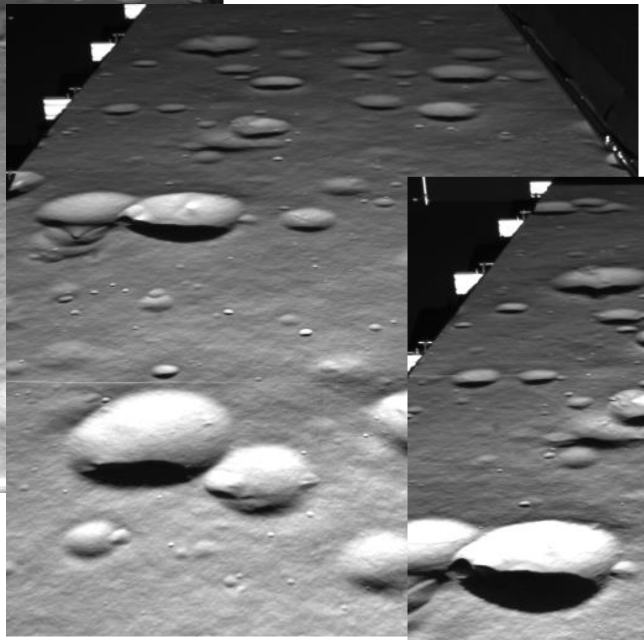

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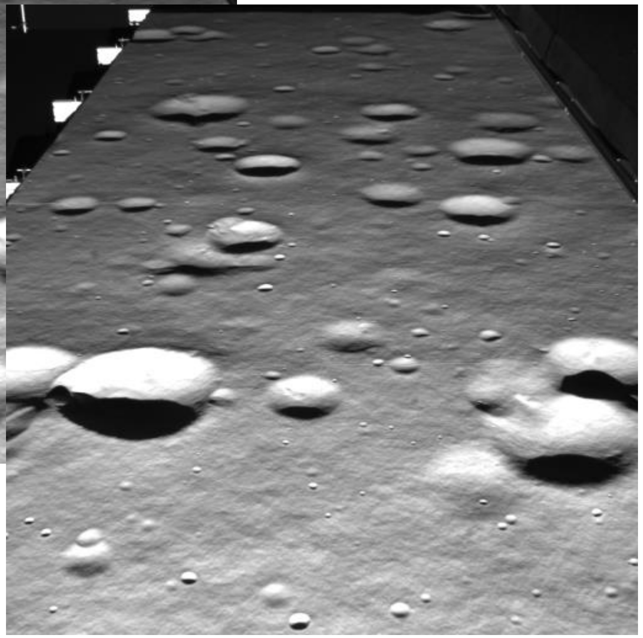
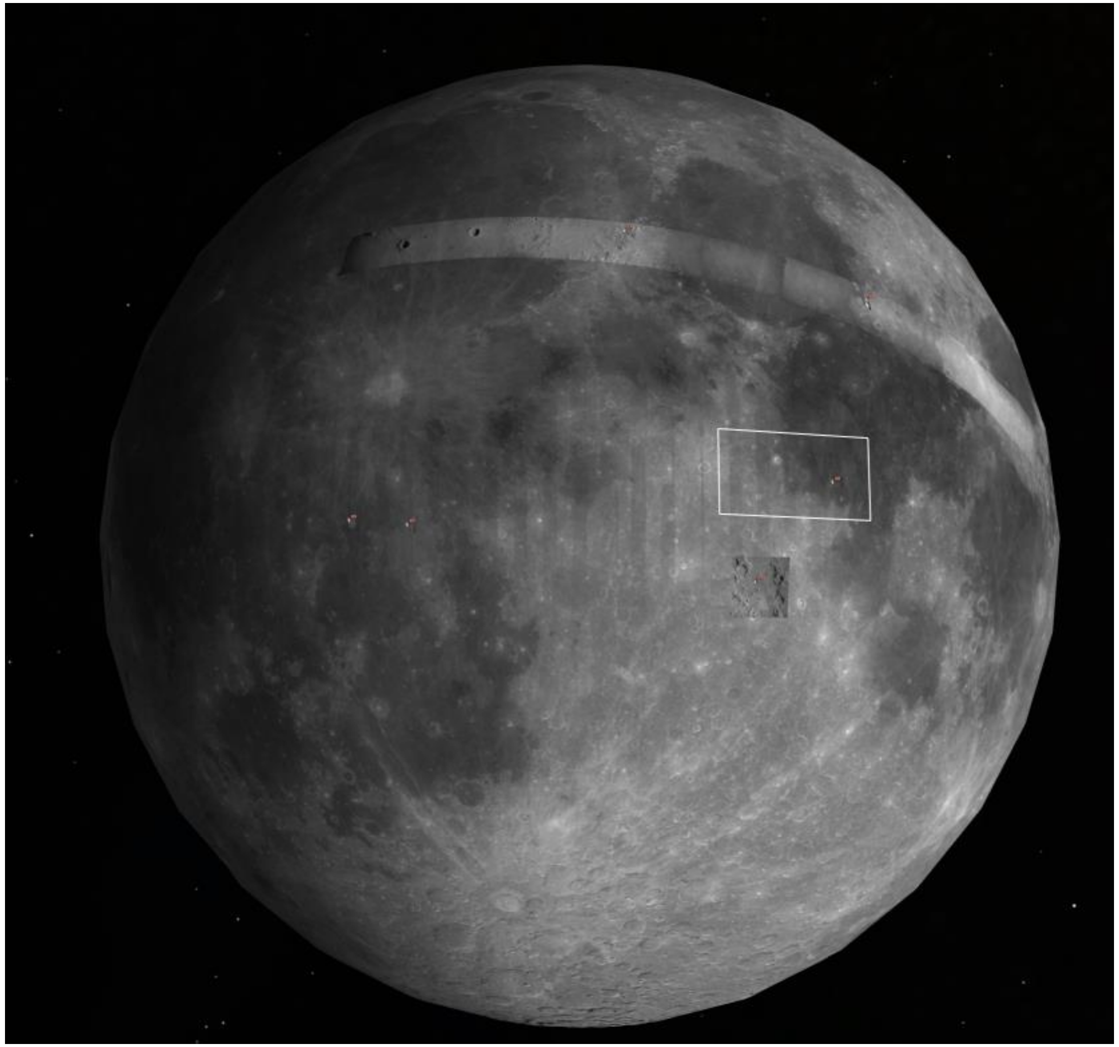


Example image of Moon 1

TRON building blocks
Terrain models: Moon 2

- Size: 4 m x 2 m
- Z-dynamic: 190 mm
- Resolution: 1 mm
- Scale: 1:125000
- DEM: Kaguya



Terrain model Moon 2 location illustrated in Google Earth

Terrain model Moon 2 DEM from Kaguya data

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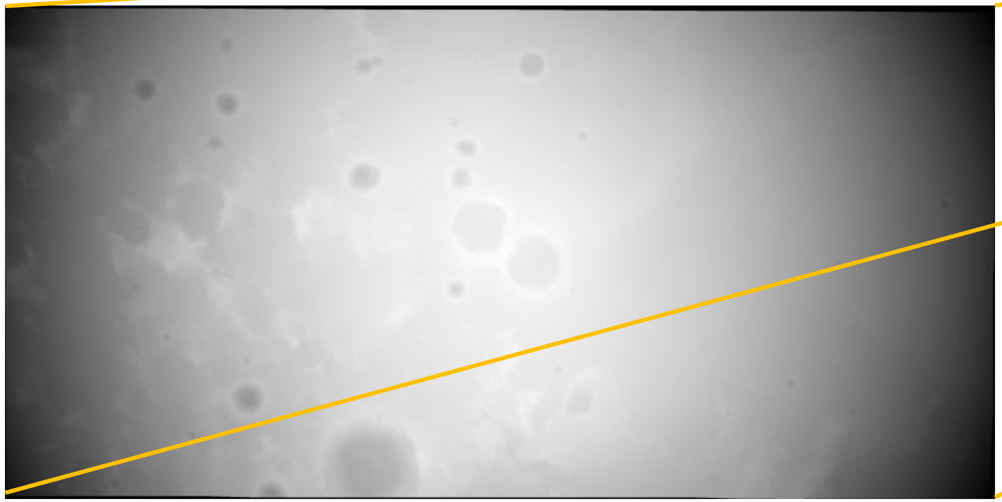

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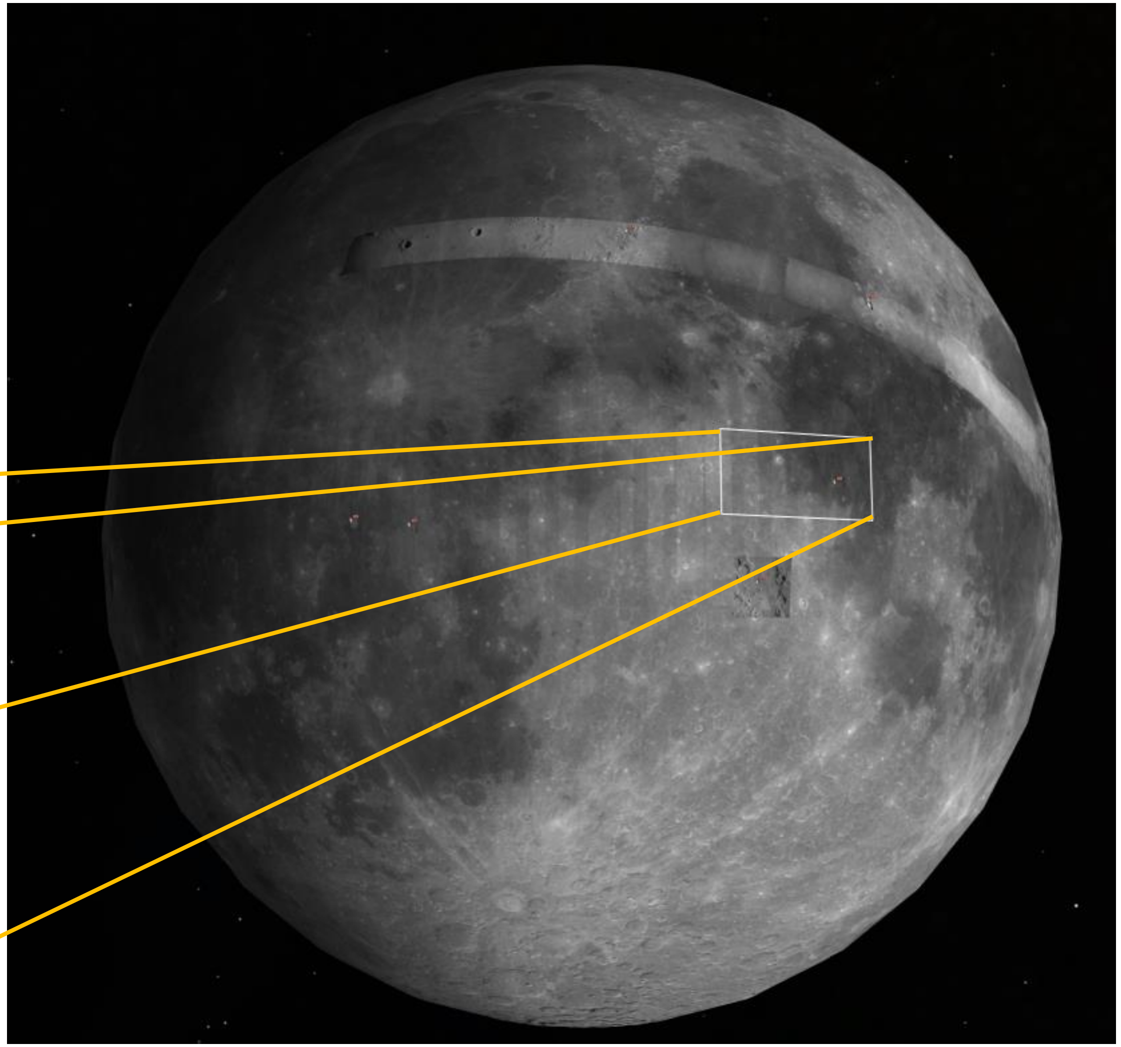

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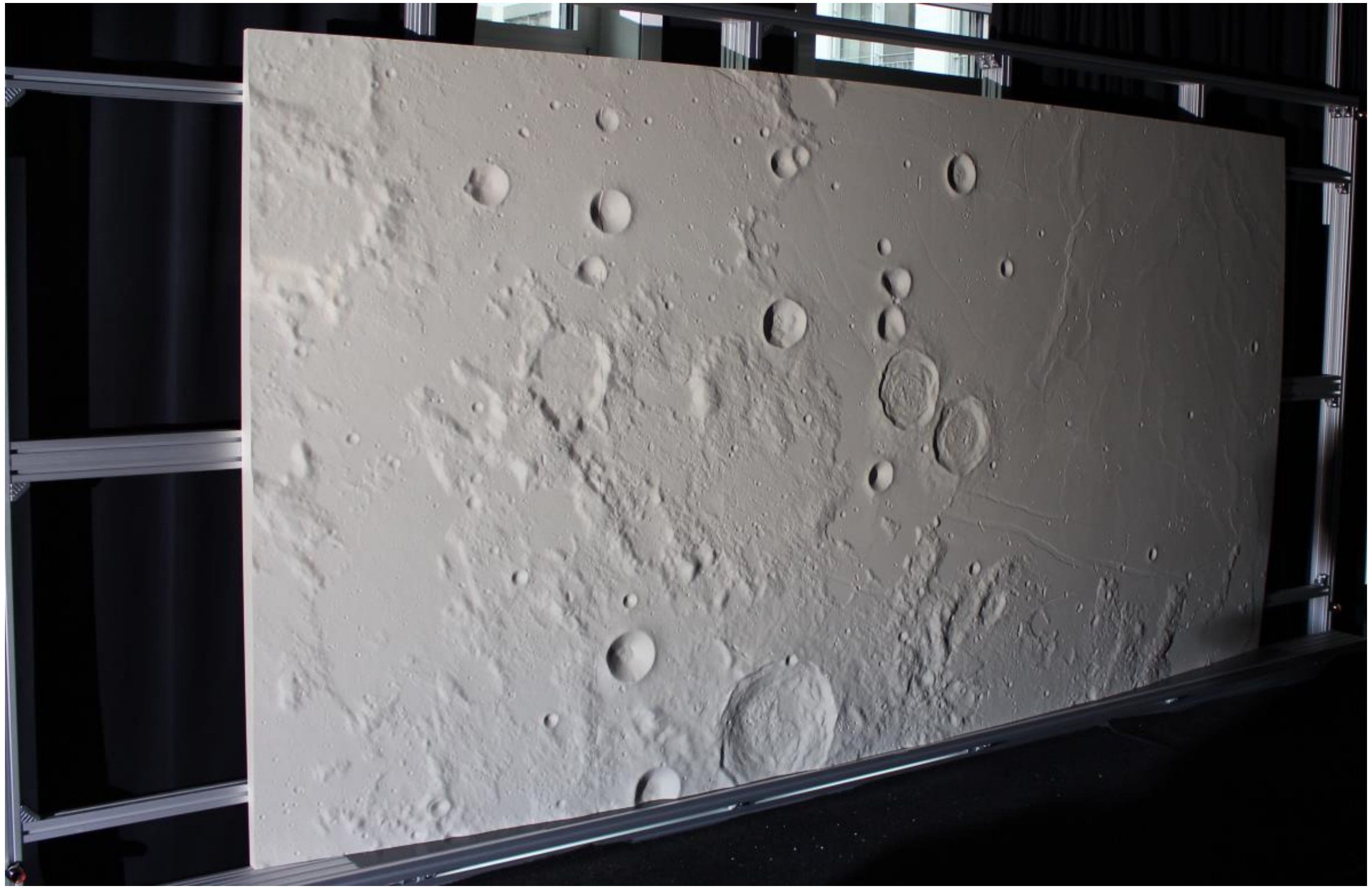

Terrain model Moon 2 in TRON

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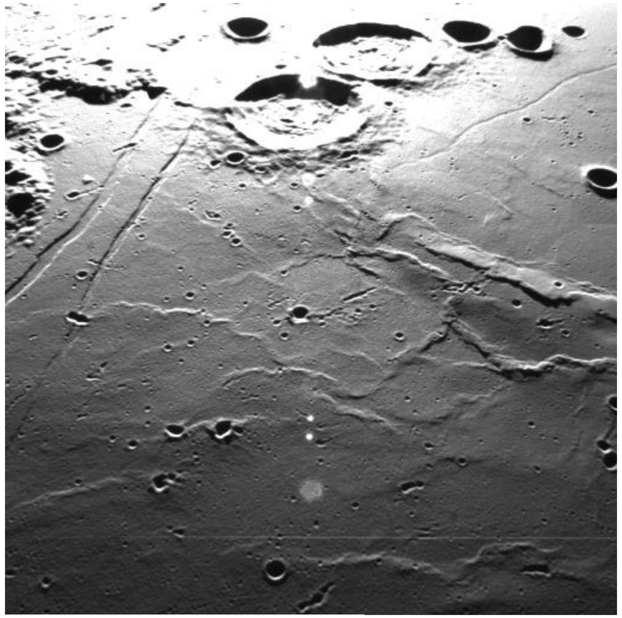

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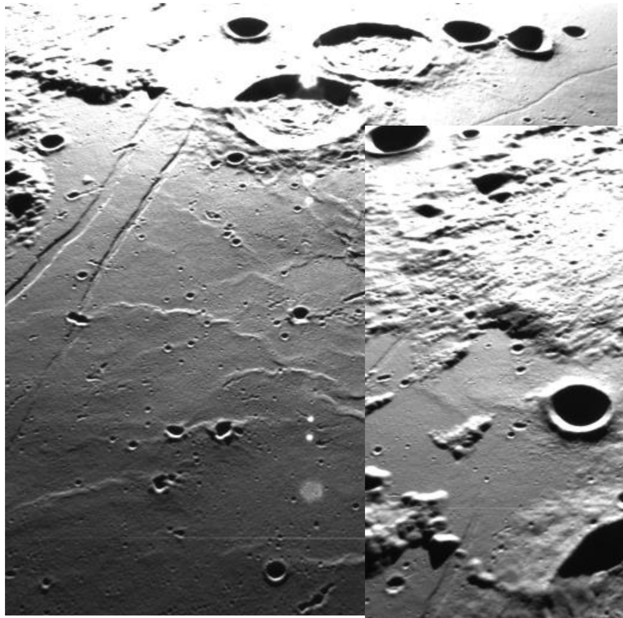

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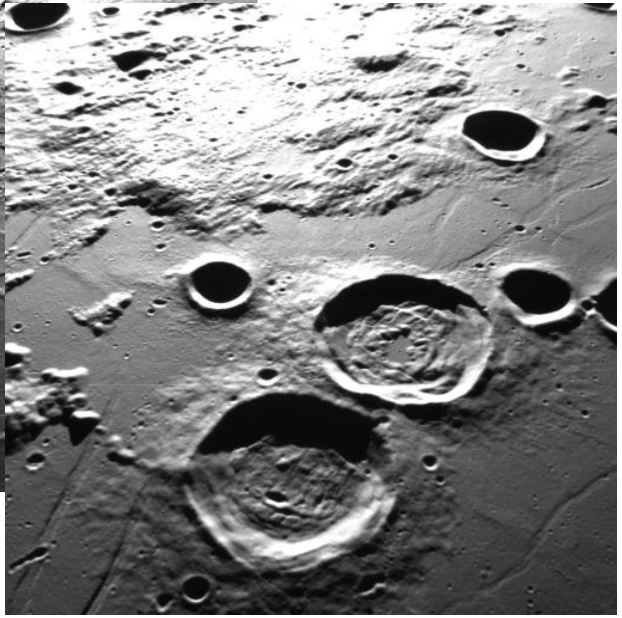

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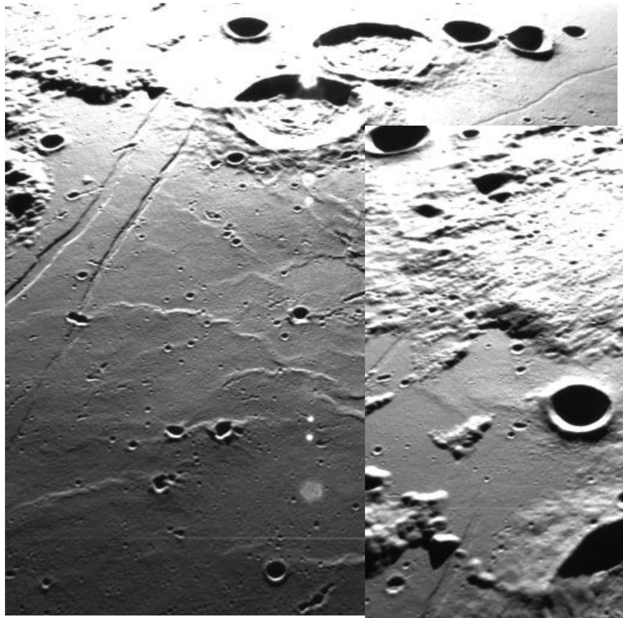

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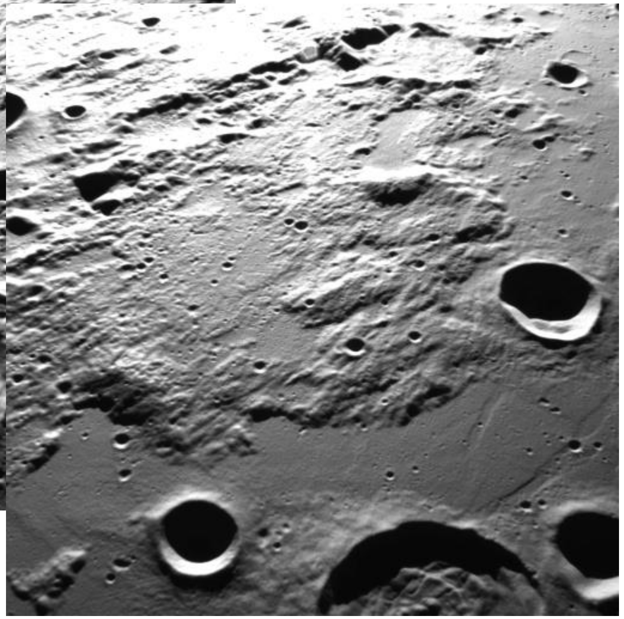
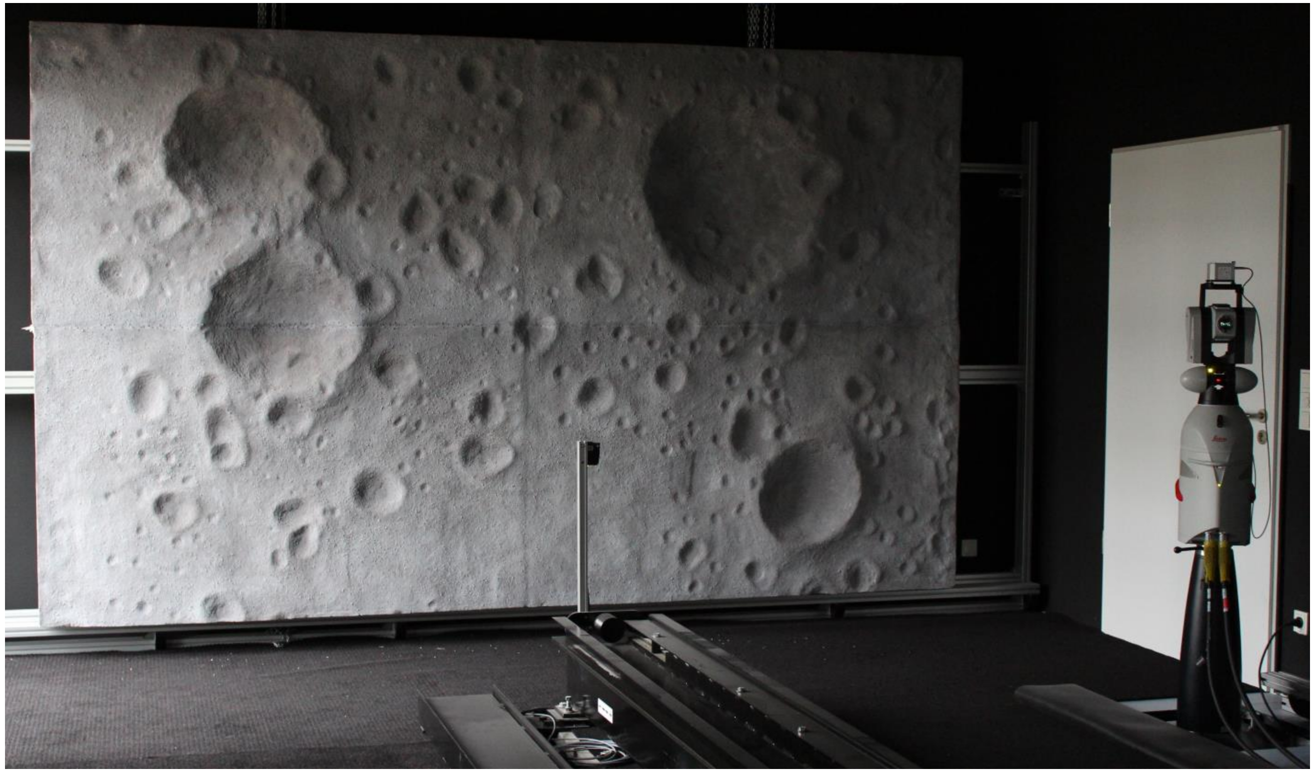


Example image of Moon 2 in TRON

TRON building blocks
Terrain models: Moon 3

- Size: 4 m x 2 m
- Dynamic: 260 mm
- Resolution: infinite
- Scale: user defined
- DEM: DLR modeled



Terrain model Moon 3 in TRON, laser tracker to the right

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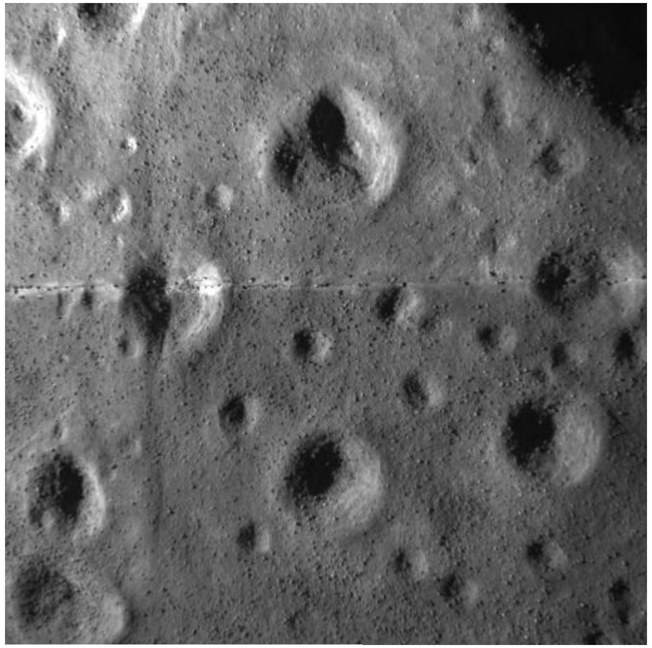

Example image of Moon 3 in TRON

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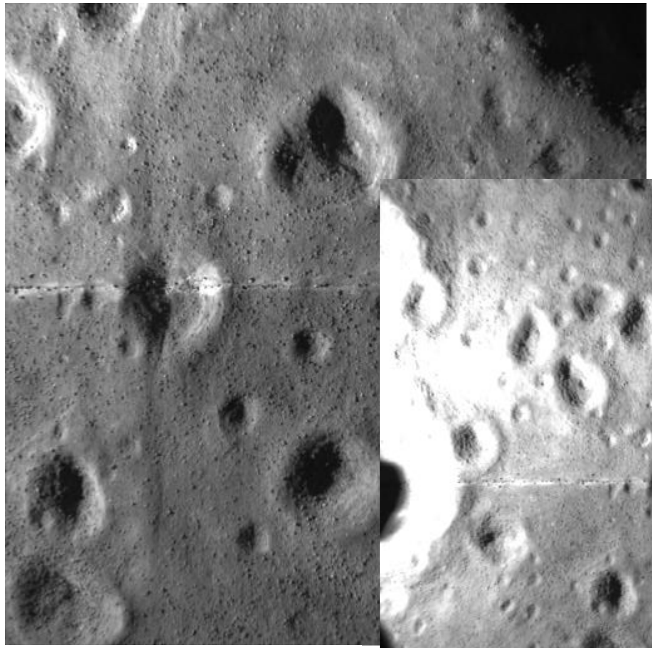

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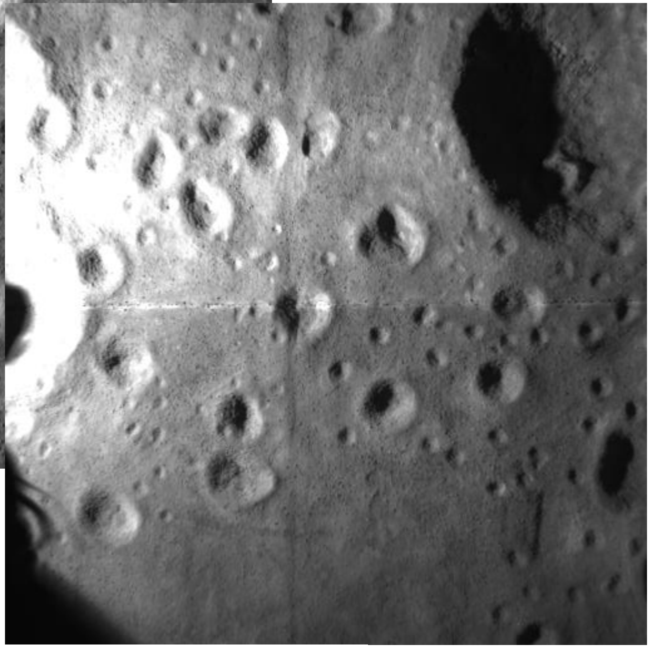

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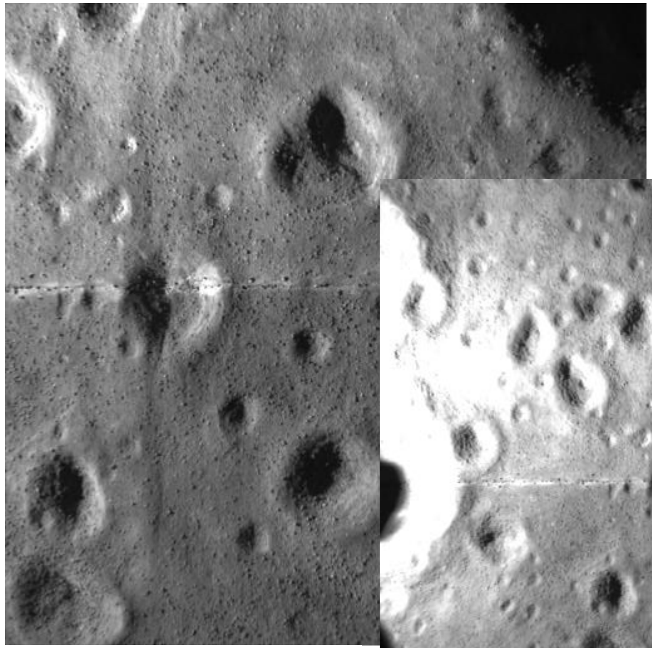

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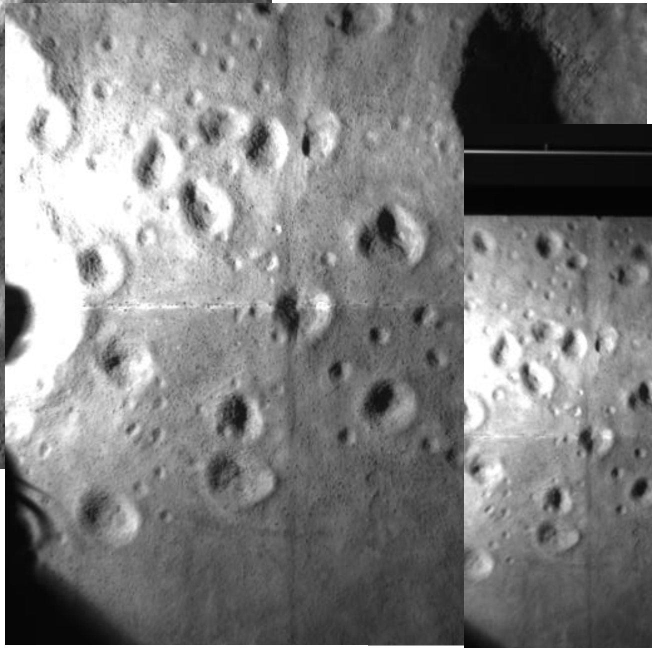

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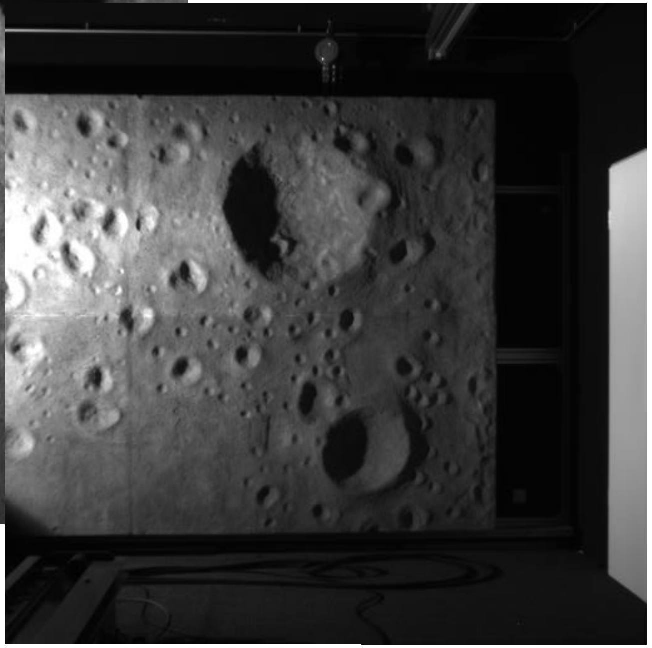

Example image of Moon 3 in TRON

TRON building blocks
other models

- More models available

TRON building blocks
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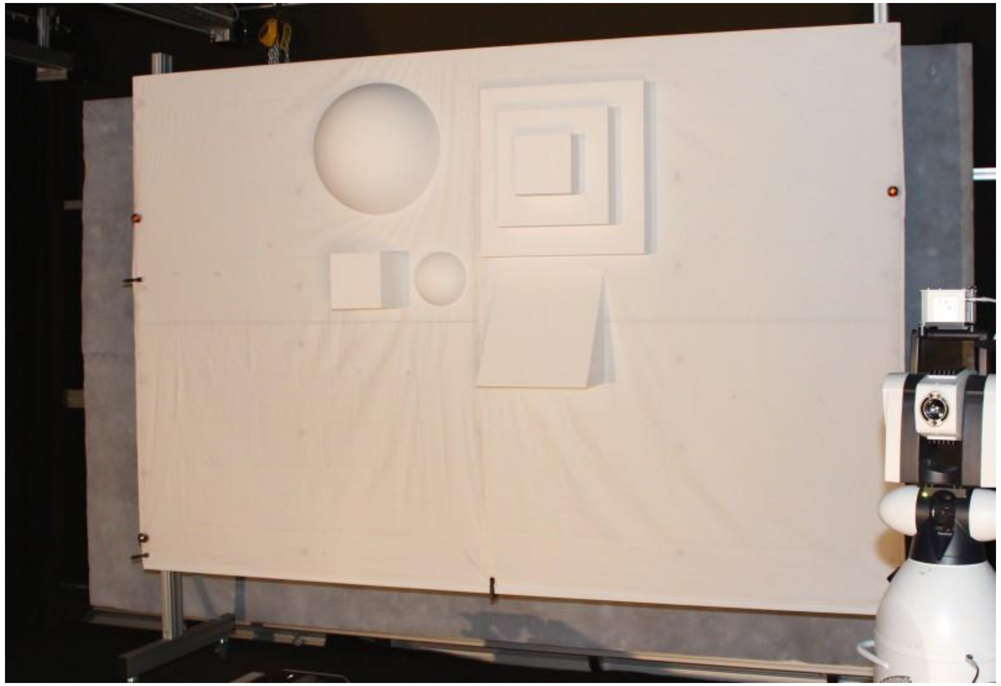

Primitives as targets

TRON building blocks
other models

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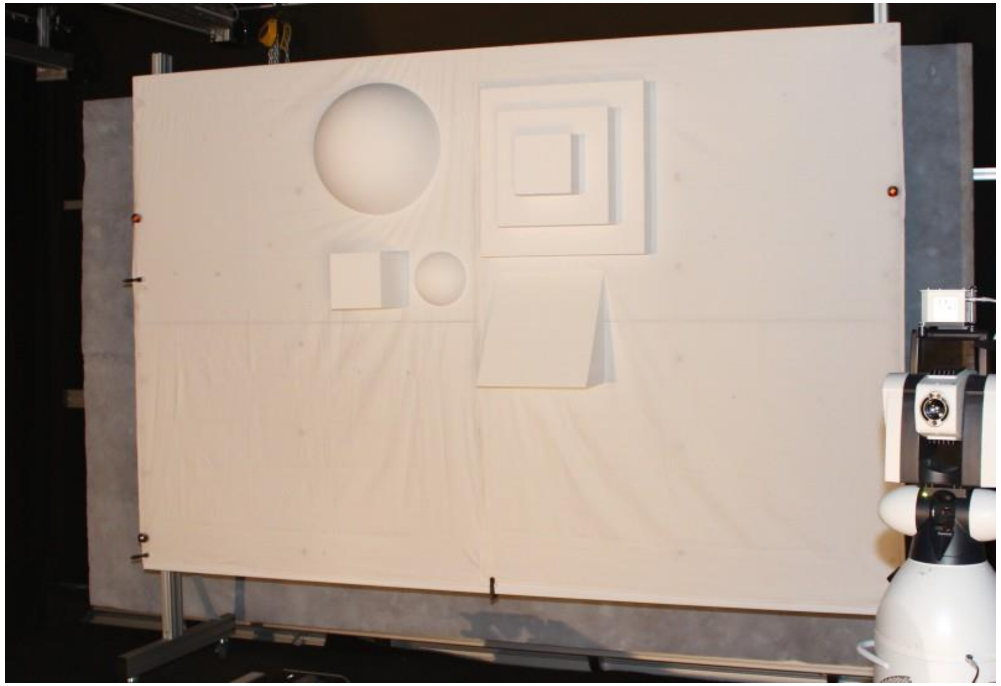
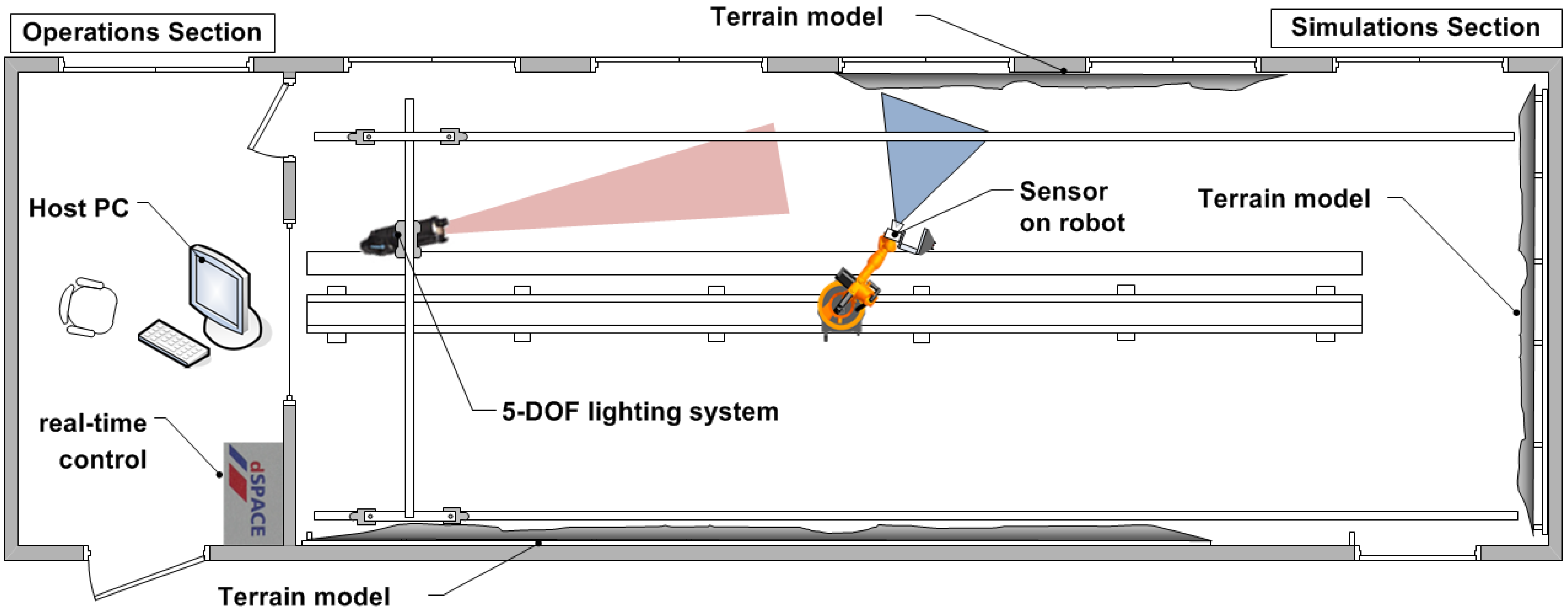


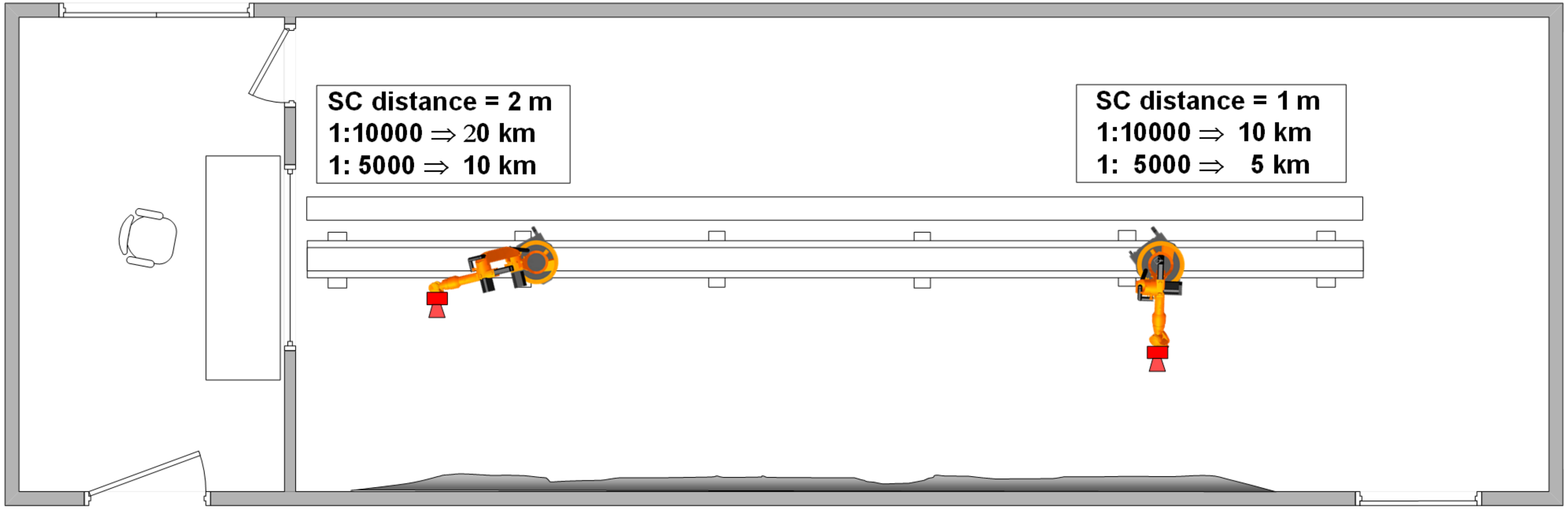
Primitives as targets

Eros, 1m length, scale 1:34400

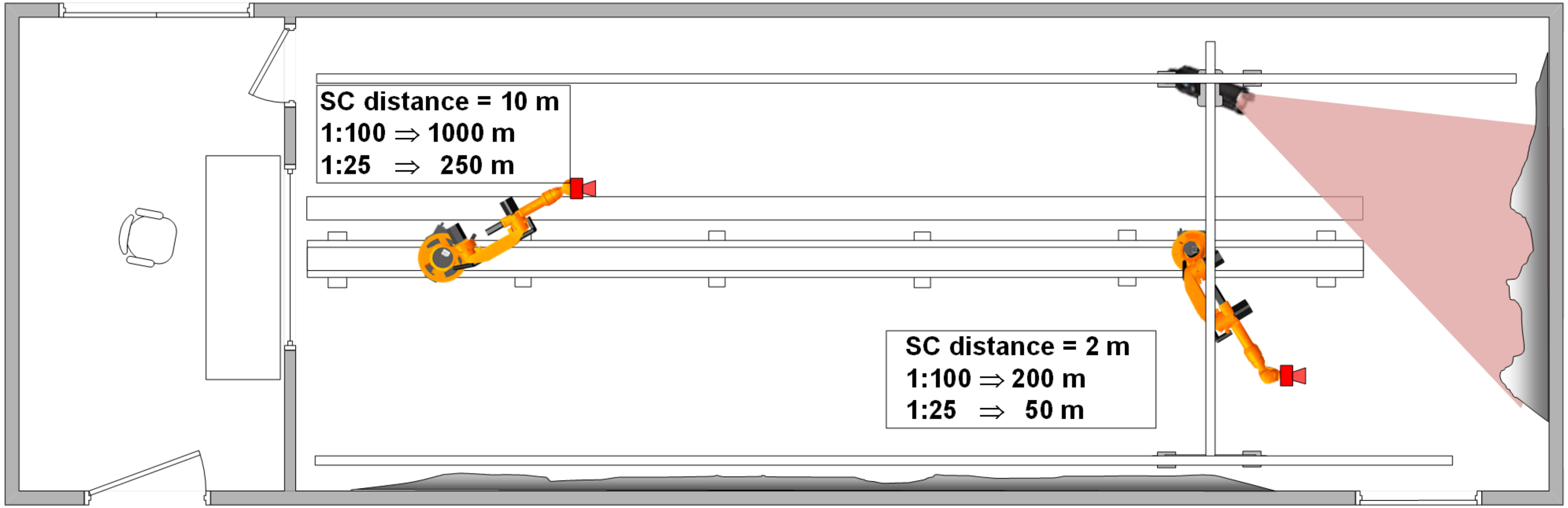
Application examples
Moon 02 for descent orbit



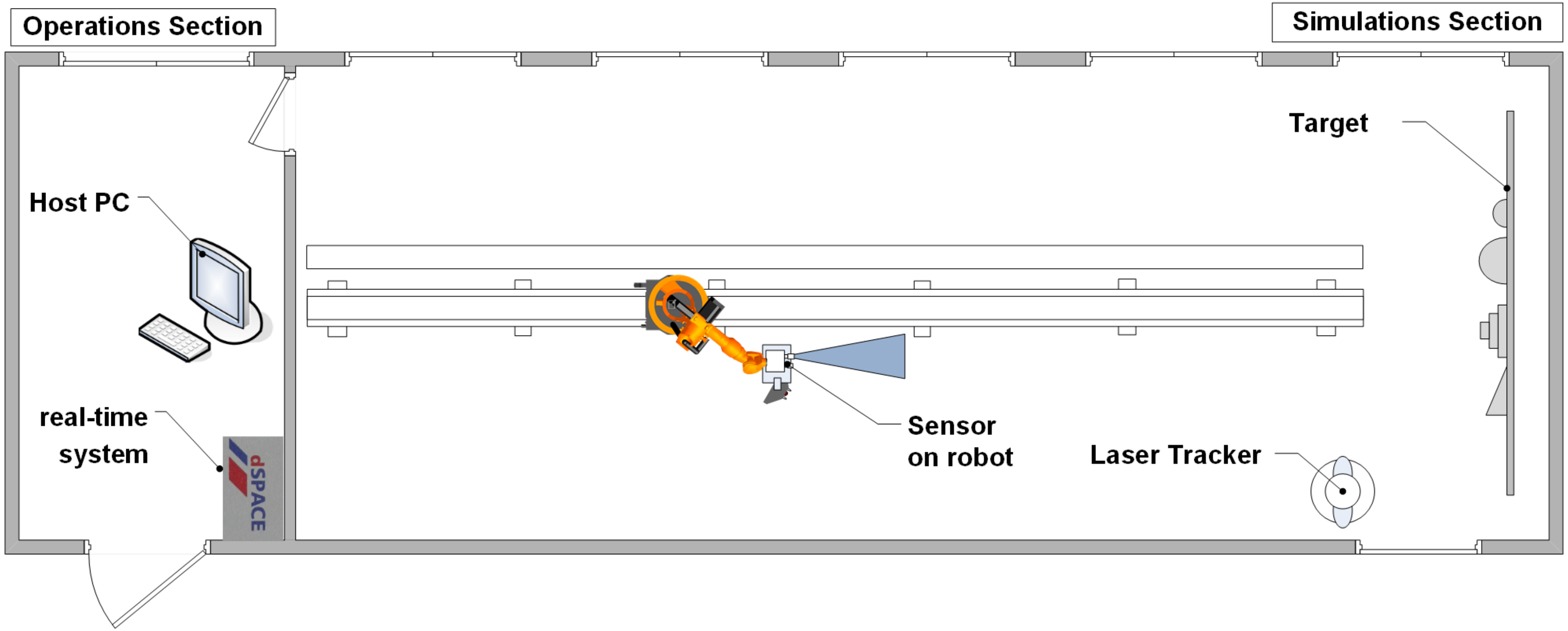
Application examples
Moon 01 for powered descent



Application examples
Moon 03 for landing



Application examples
Primitves for lidars



Application examples
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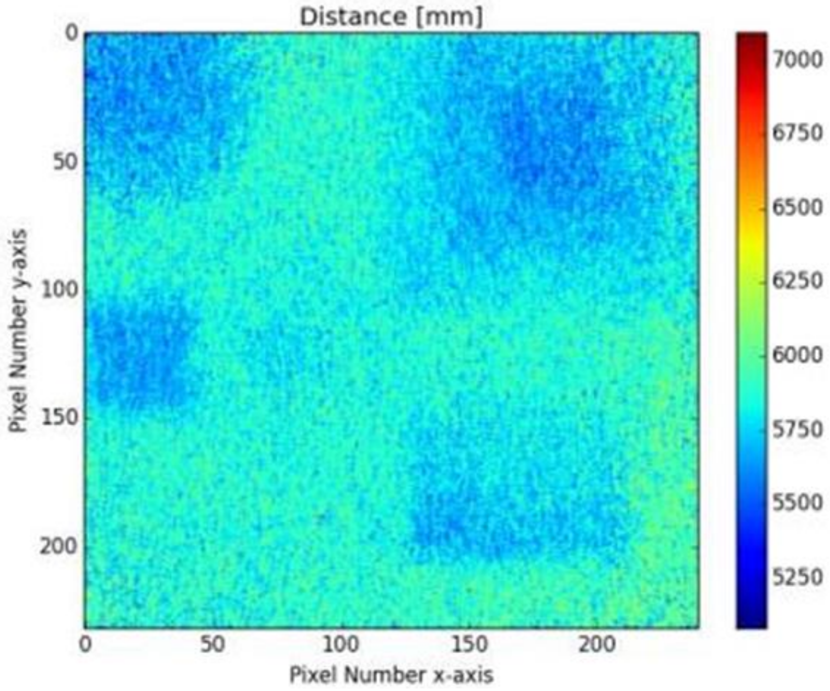
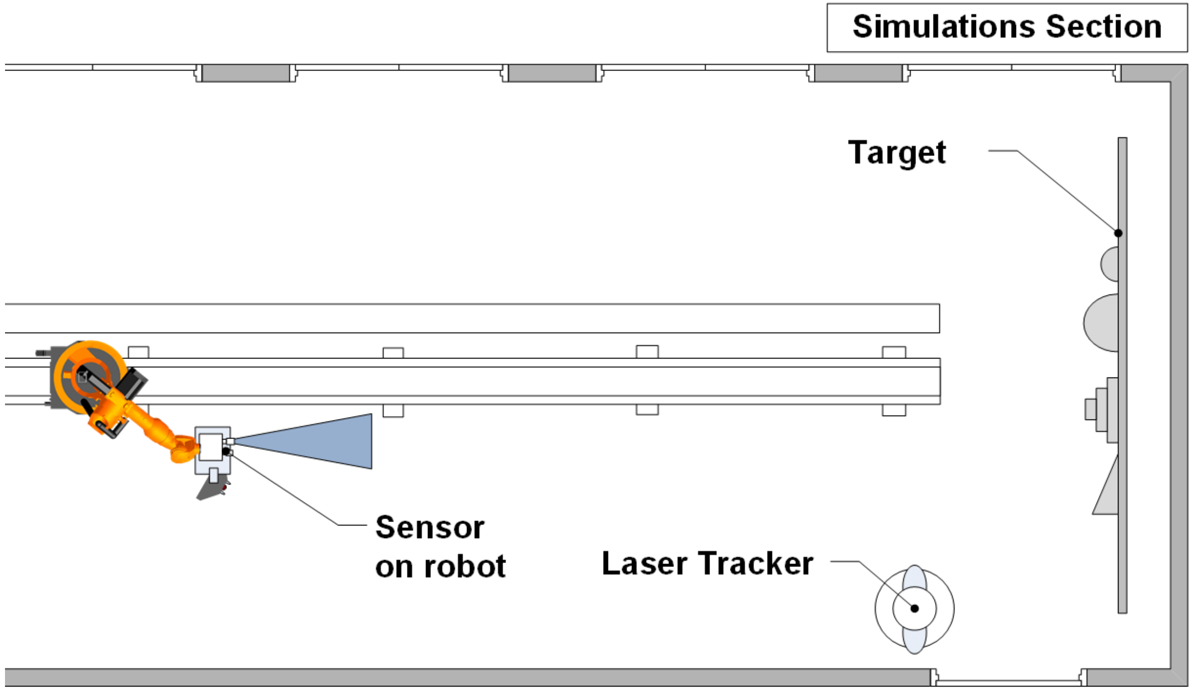
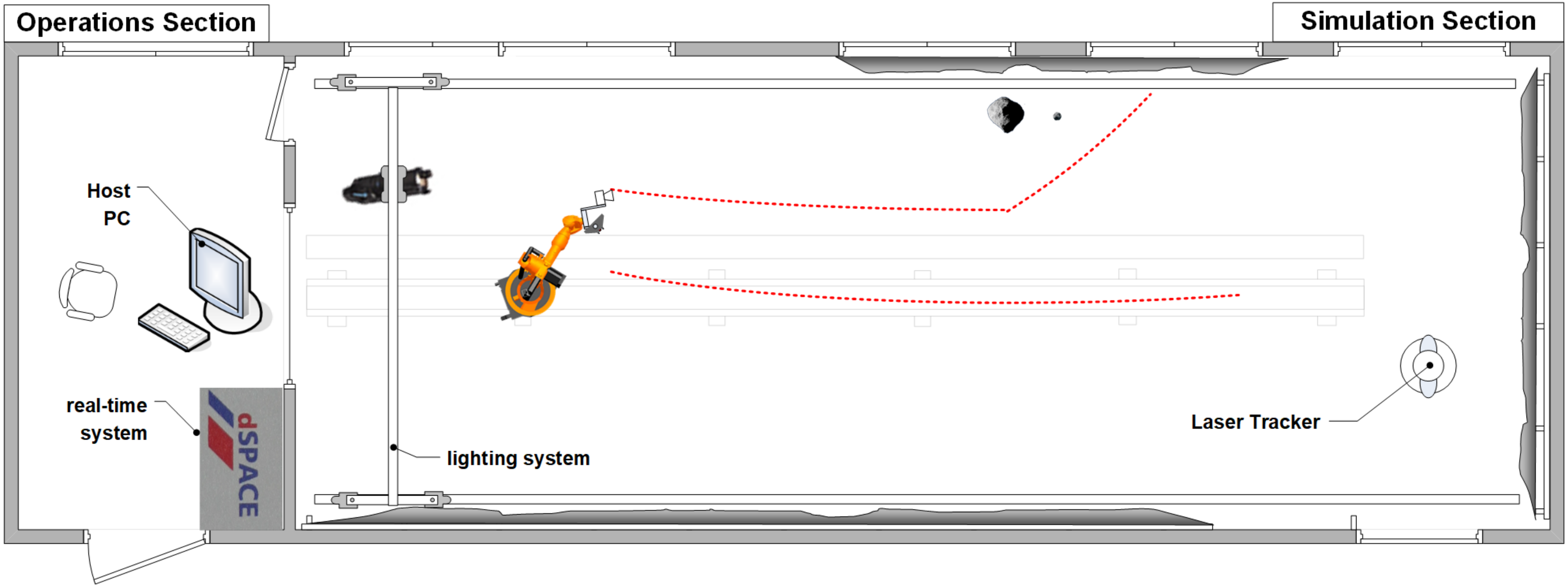


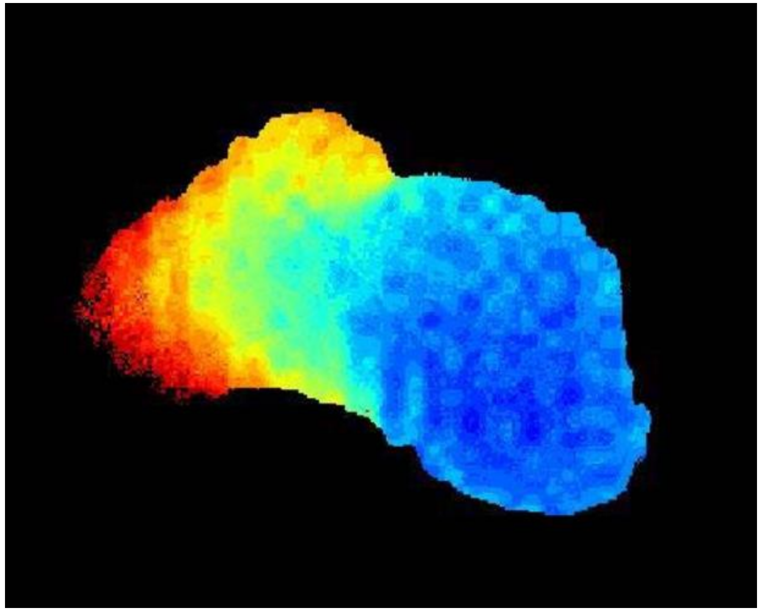
Flash lidar measurement of the primitives



Application examples
Asteroids



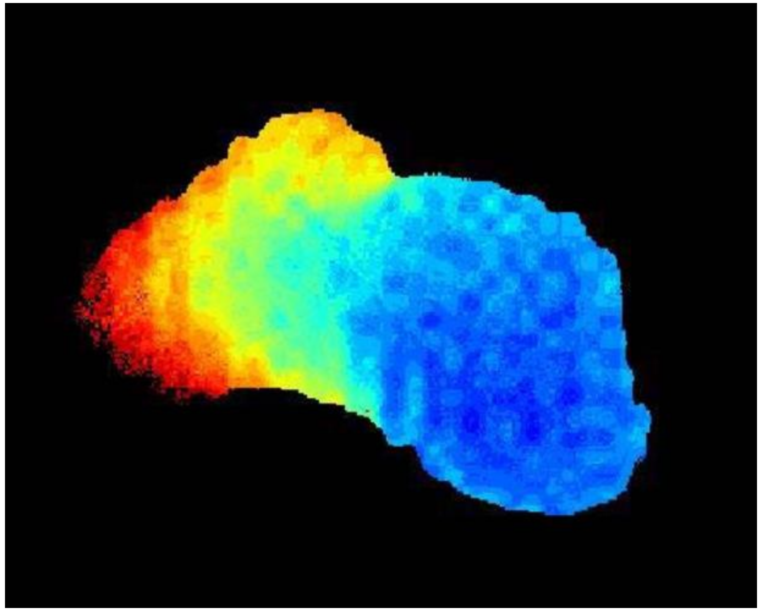
Application examples
Asteroid imaging in TRON



Flash lidar measurement of the Eros model in TRON

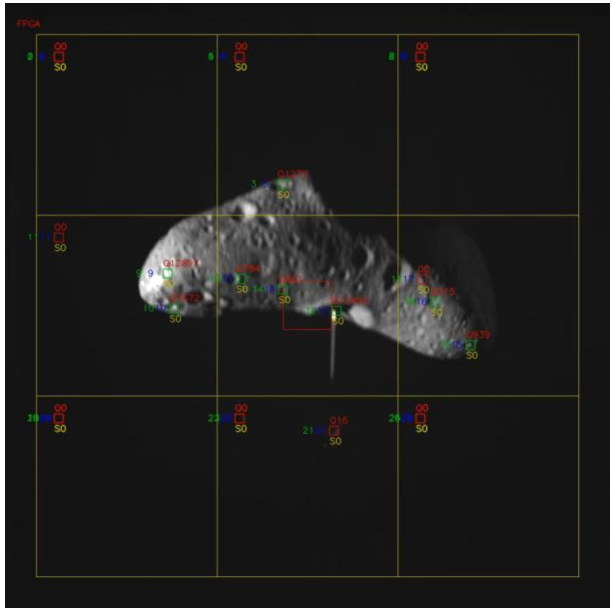
Flash Lidar image of Eros model in TRON, Crater detection applied on images

Application examples
Asteroid imaging in TRON



Flash lidar measurement of the Eros model in TRON

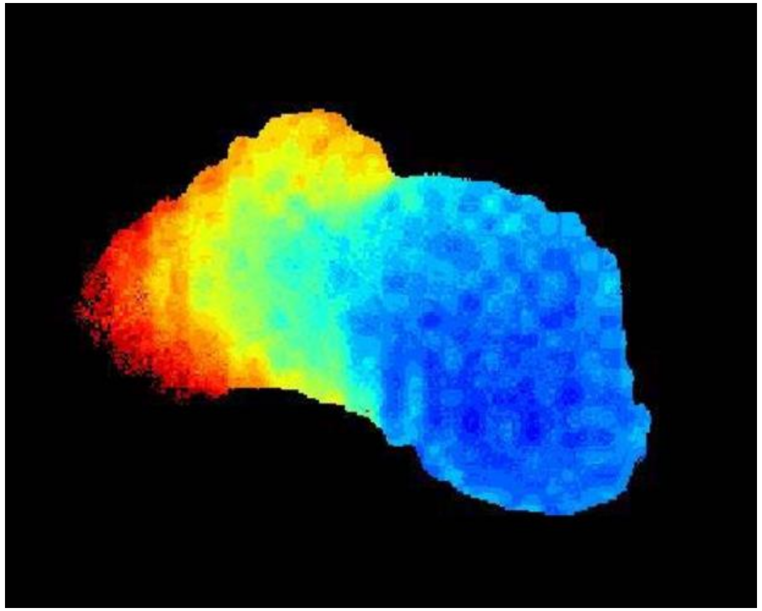
Camera measurements of the Eros model in TRON



Feature tracking applied to images

Flash Lidar image of Eros model in TRON, Crater detection applied on images

Application examples
Asteroid imaging in TRON



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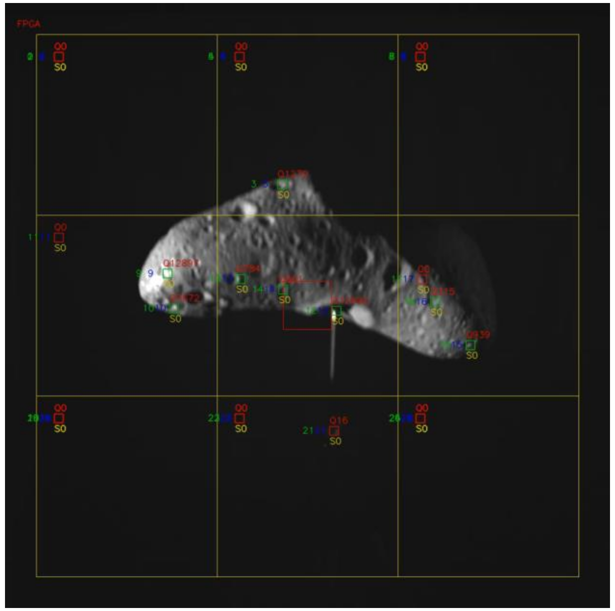

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TRON ground truth

- In most cases people doing tests in TRON require the pose of the sensing element with respect to the target geometry
- Enables relating sensor models with real-world test data
- E.g. pose of the pin-hole camera frame with respect to a pointcloud

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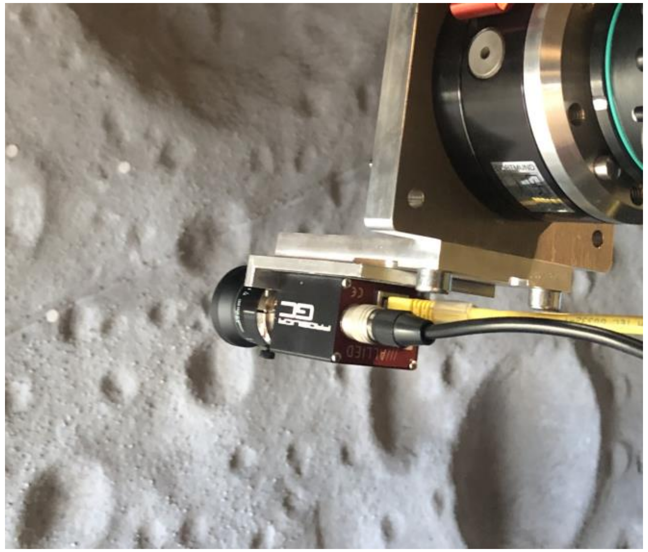
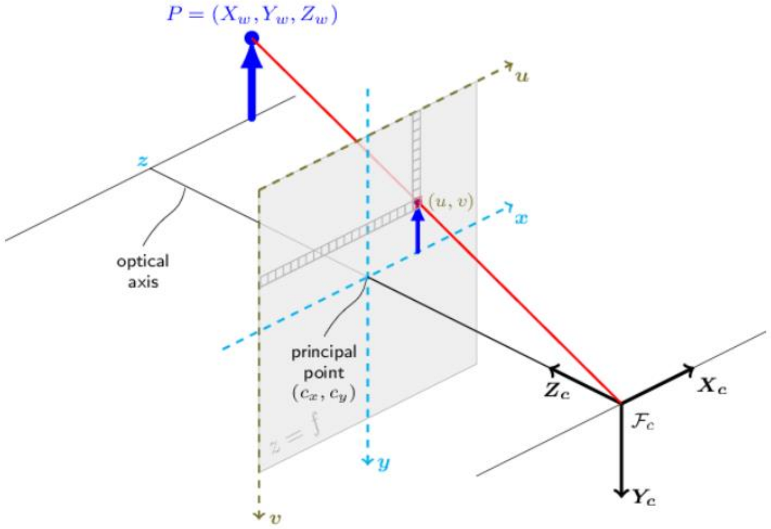


Camera with respect to Moon 3 model

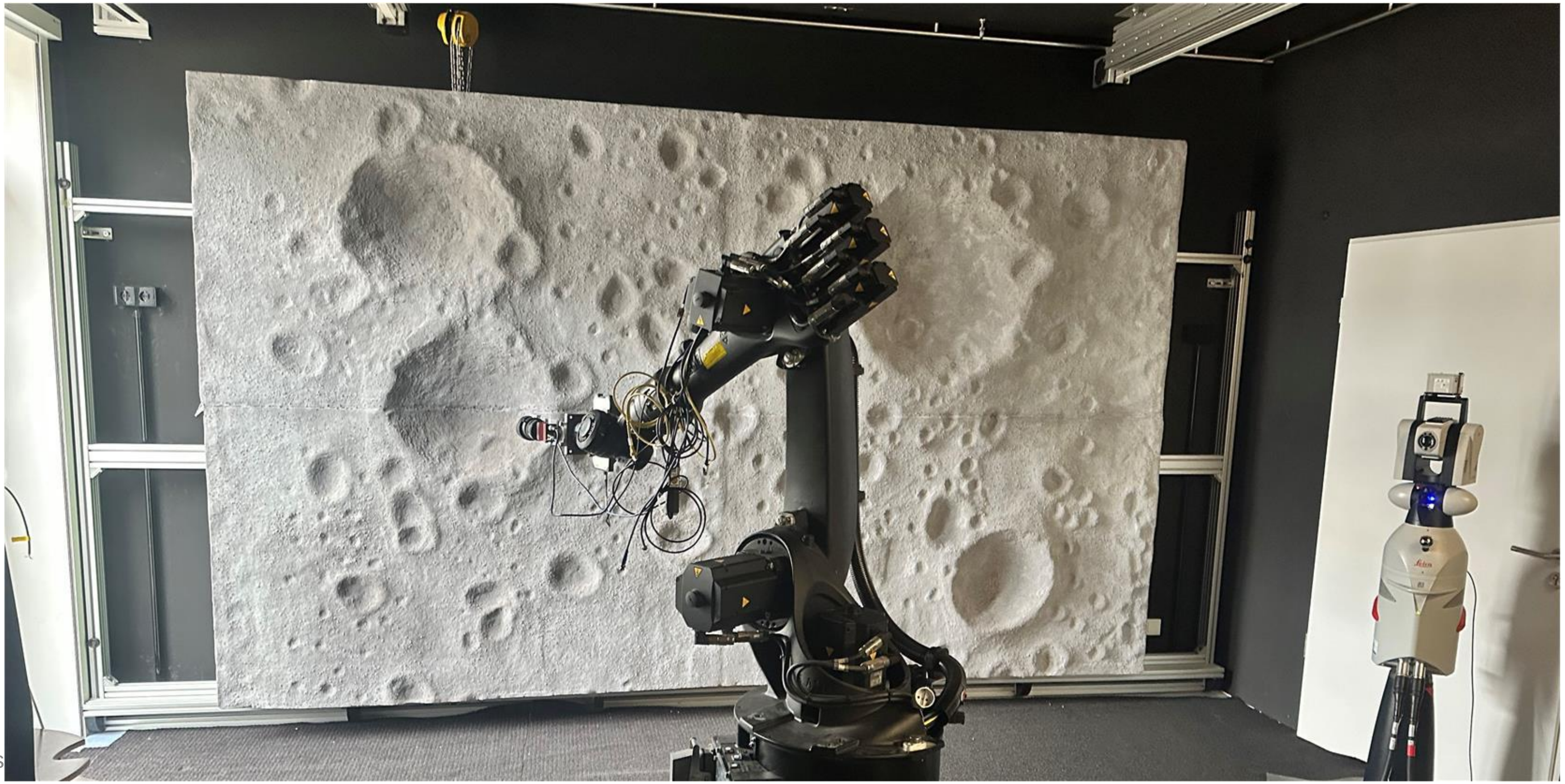


Pinhole camera model

OpenCV pin-hole camera model with respect to a point P in world frame

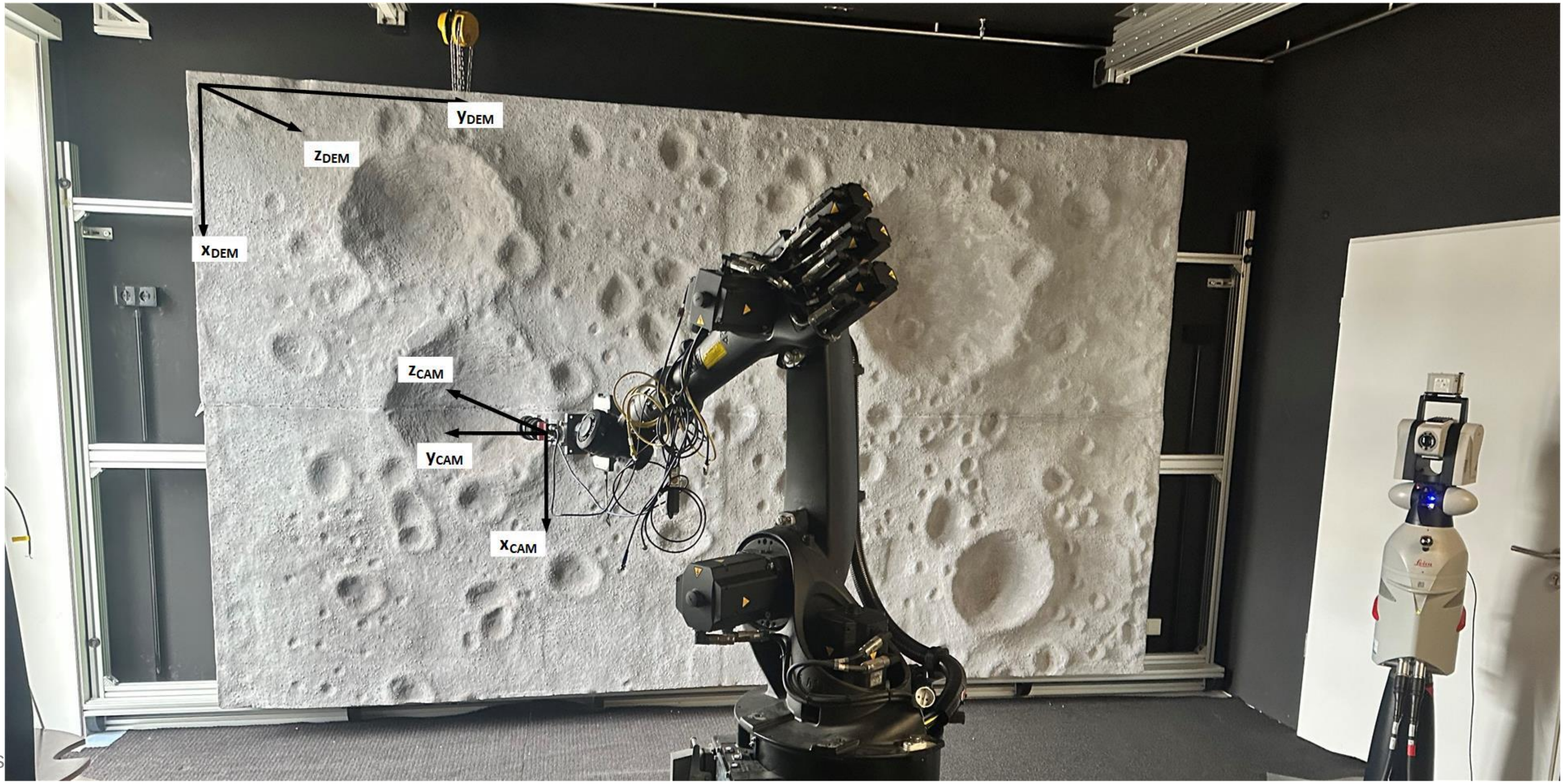
TRON ground truth
Mono-camera with respect to Moon 03

- Placement of a camera with respect to Moon 03 in TRON



TRON ground truth
Mono-camera with respect to Moon 03

- Goal is to relate to each other the frames DEM and CAM



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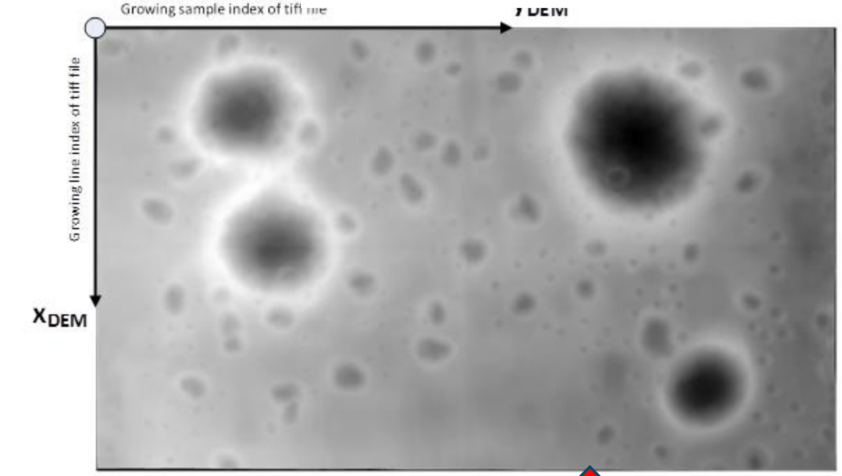
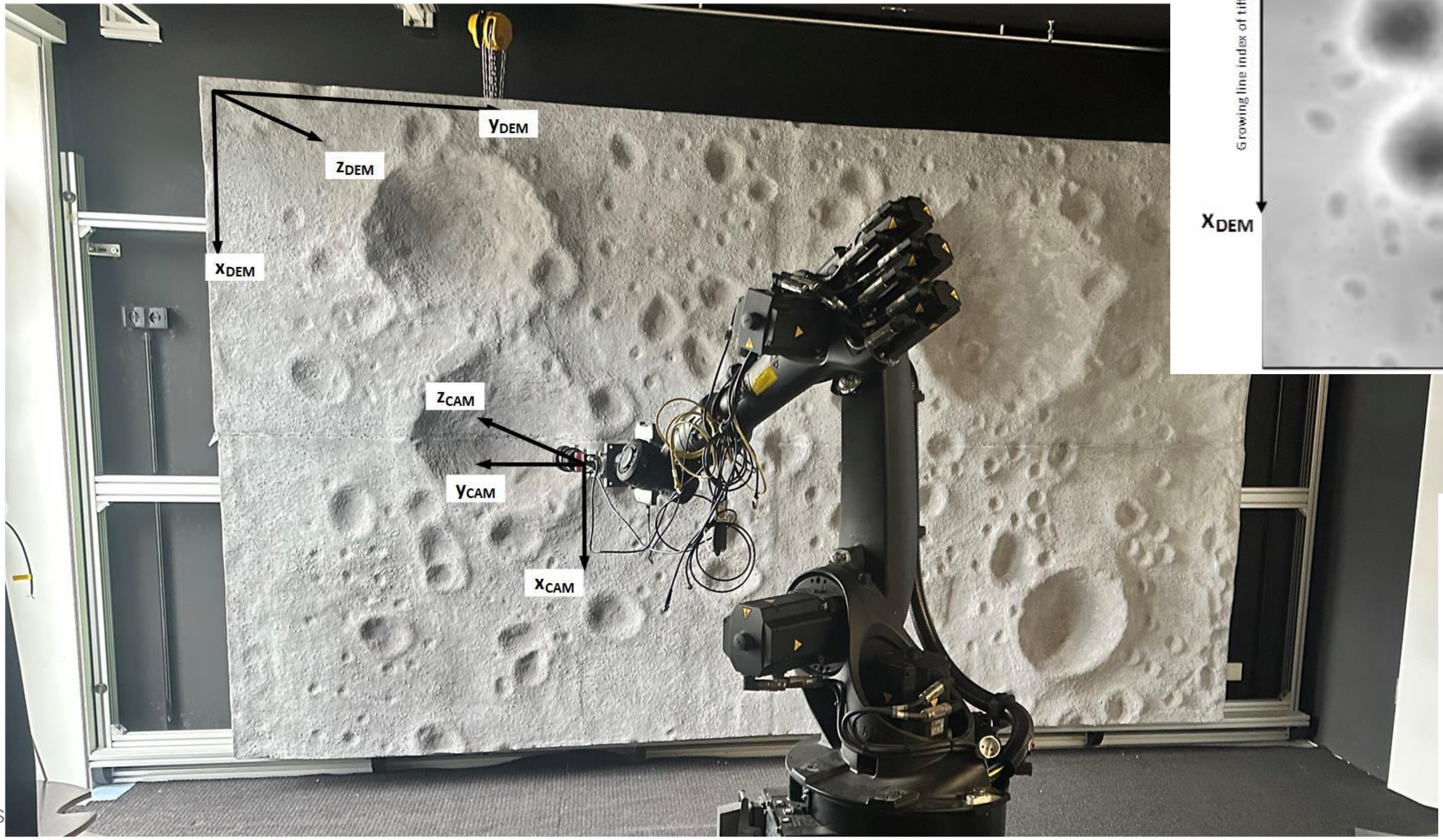
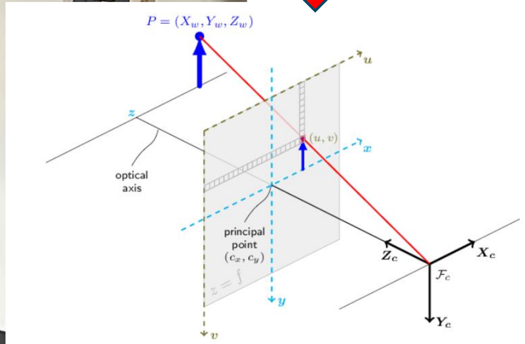
Terrain geometry defined in DEM frame





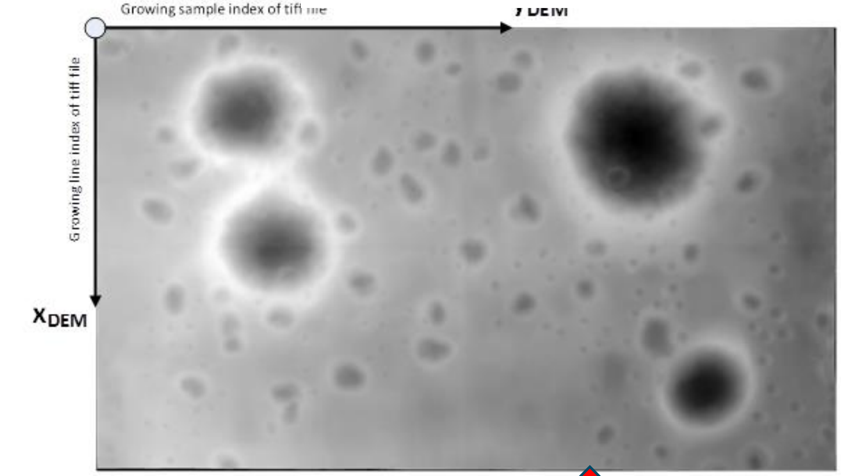


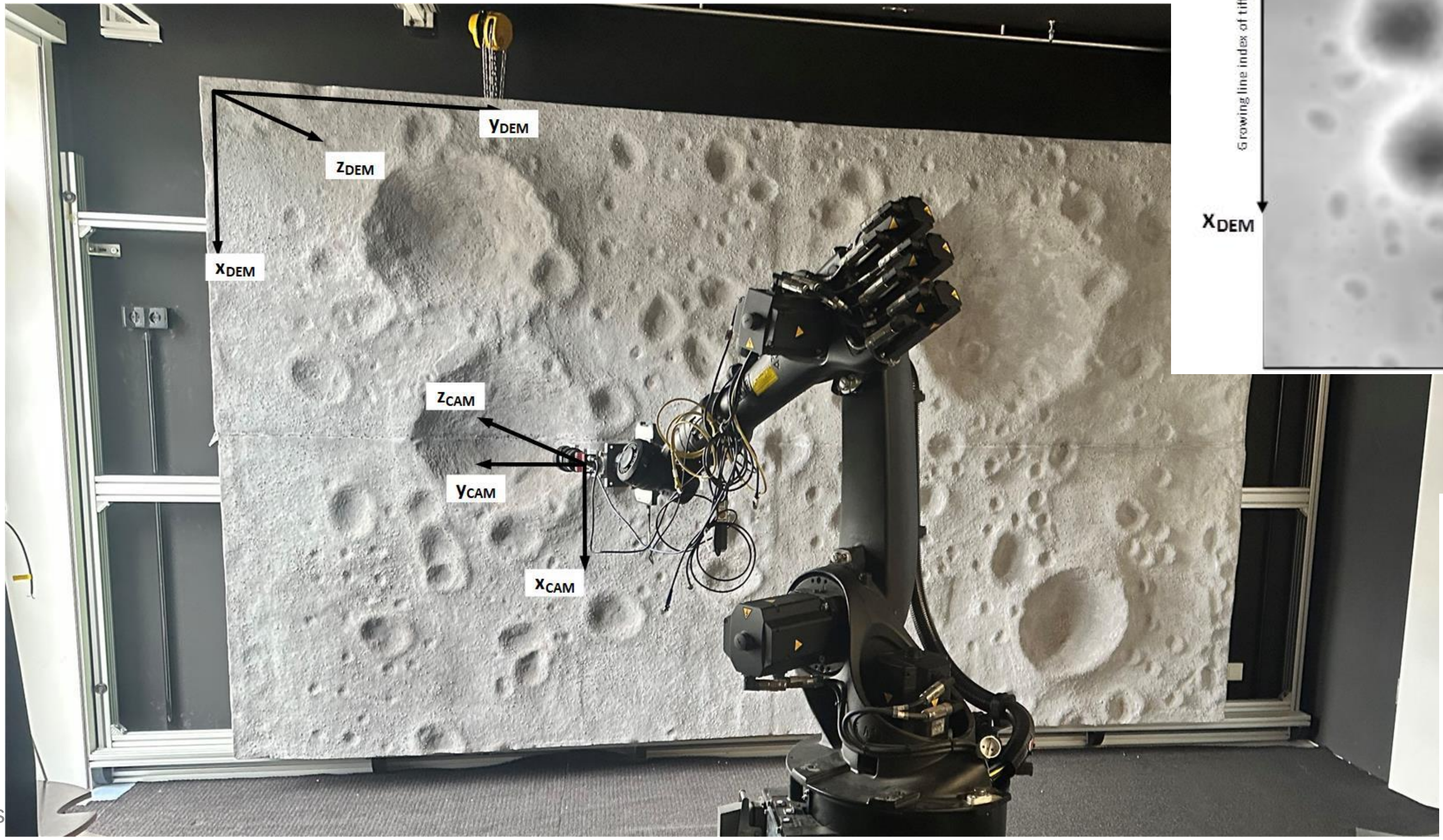
Pinhole camera model

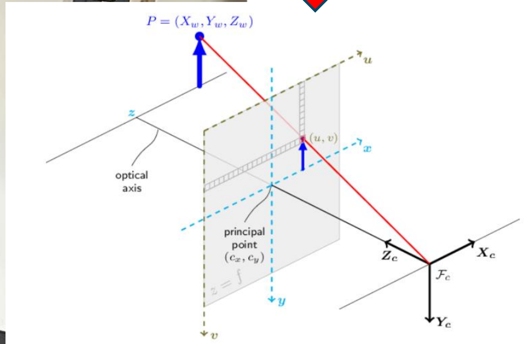
TRON ground truth
Mono-camera with respect to Moon 03

- Goal is to relate to each other the frames DEM and CAM
- Not directly measurable

Terrain geometry defined in DEM frame



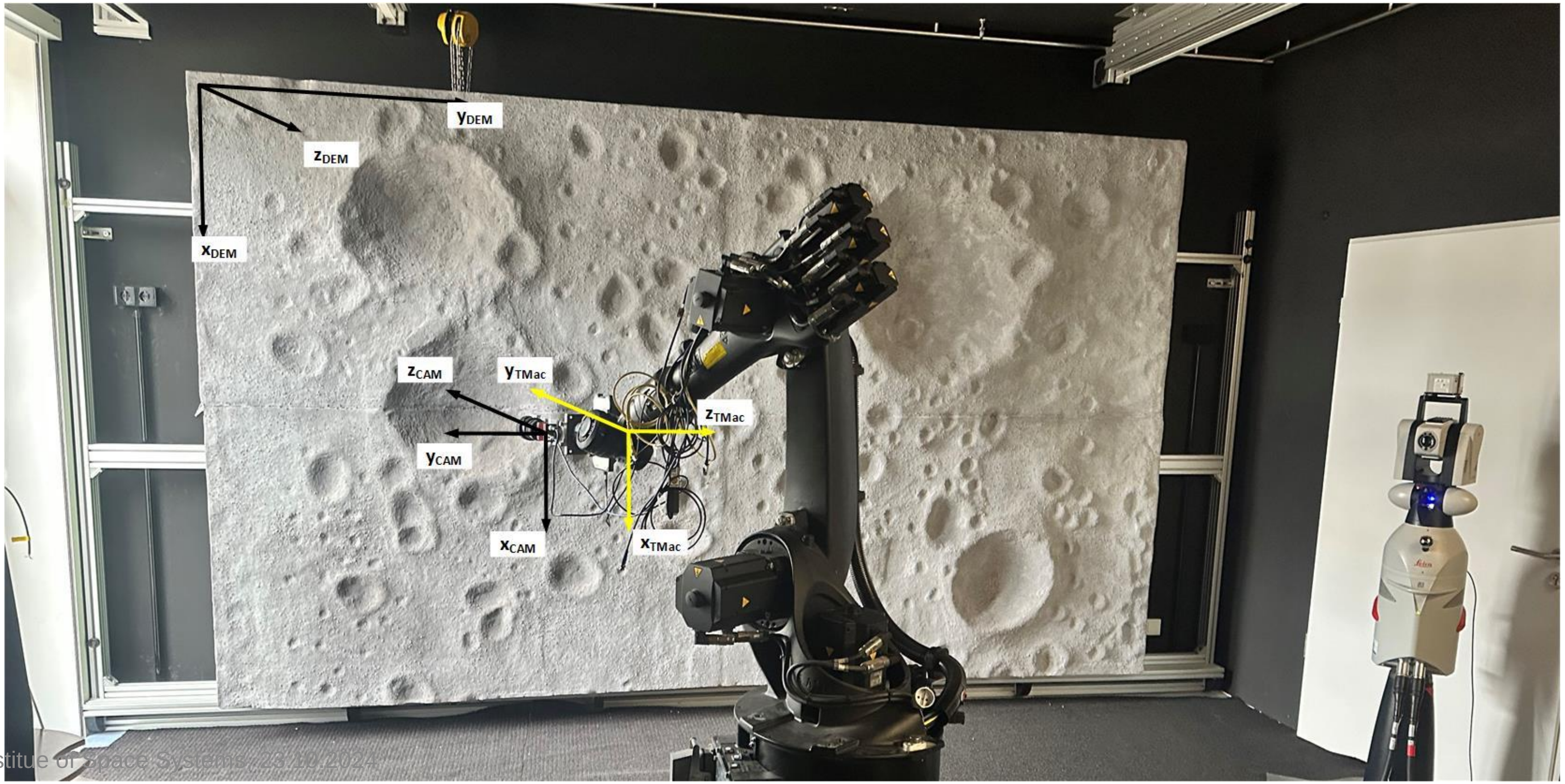




Pinhole camera model

TRON ground truth
Mono-camera with respect to Moon 03

- Make a transformation chain that is measurable
- First Link: Camera ↔ TMac



TRON ground truth
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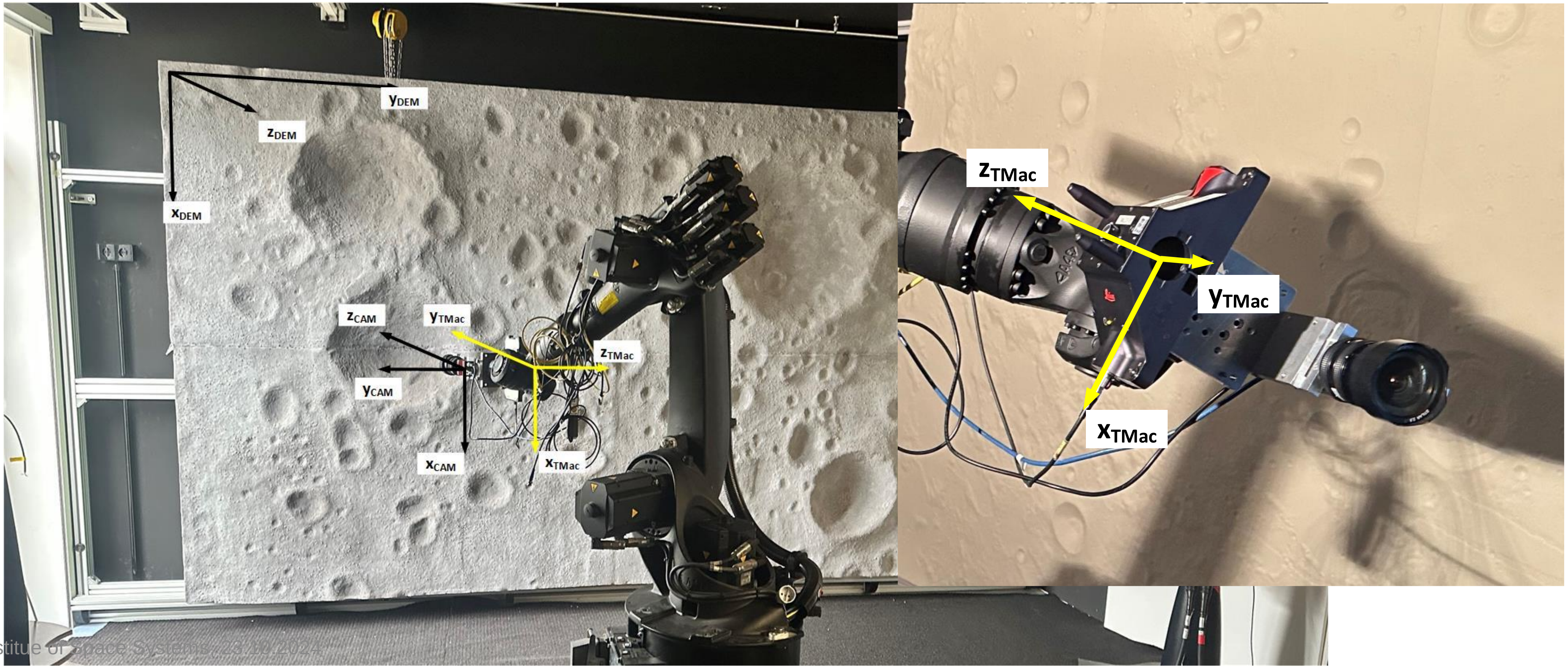

TRON ground truth
Mono-camera with respect to Moon 03

- Camera ↔ TMac determined by hand-eye calibration

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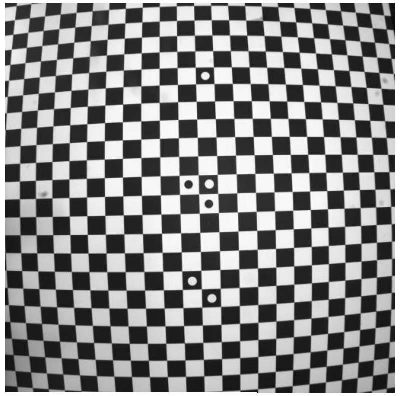

Data acquisition for hand-eye calibration

TRON ground truth
Mono-camera with respect to Moon 03

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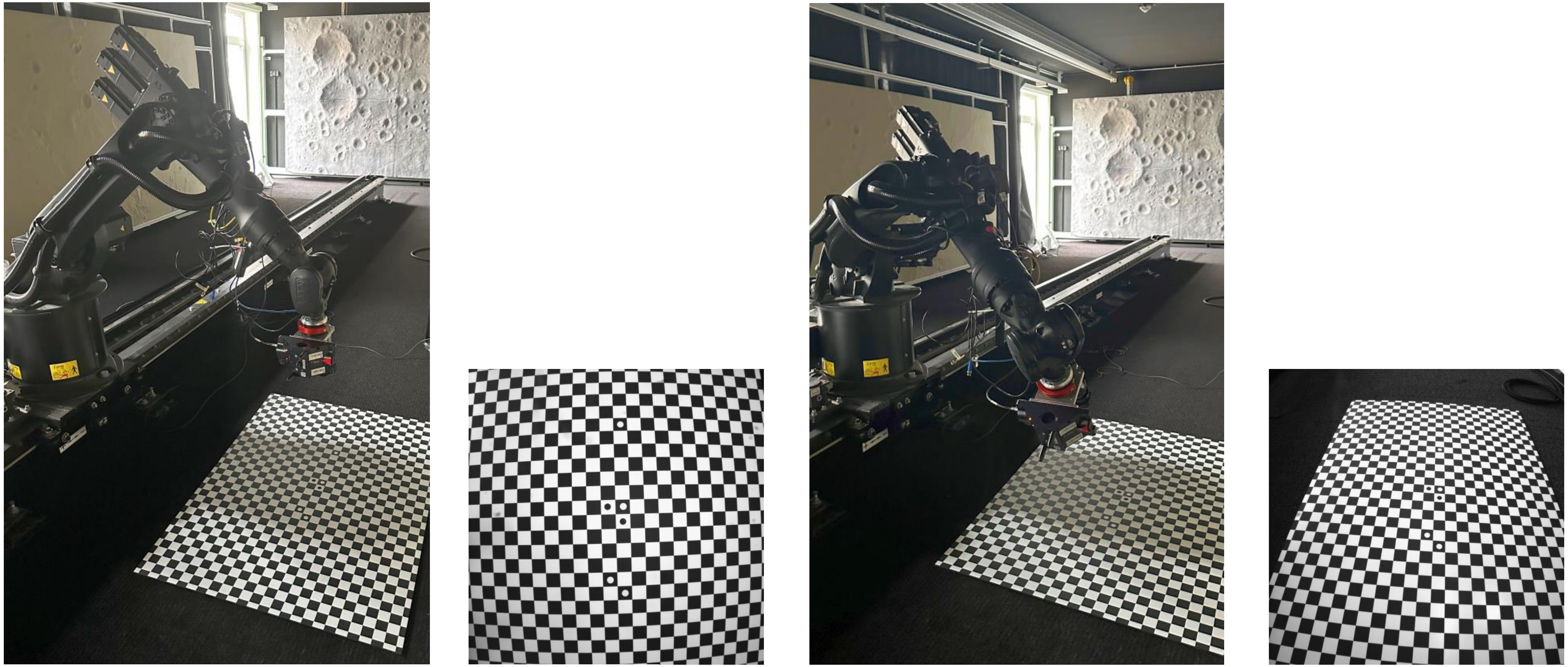
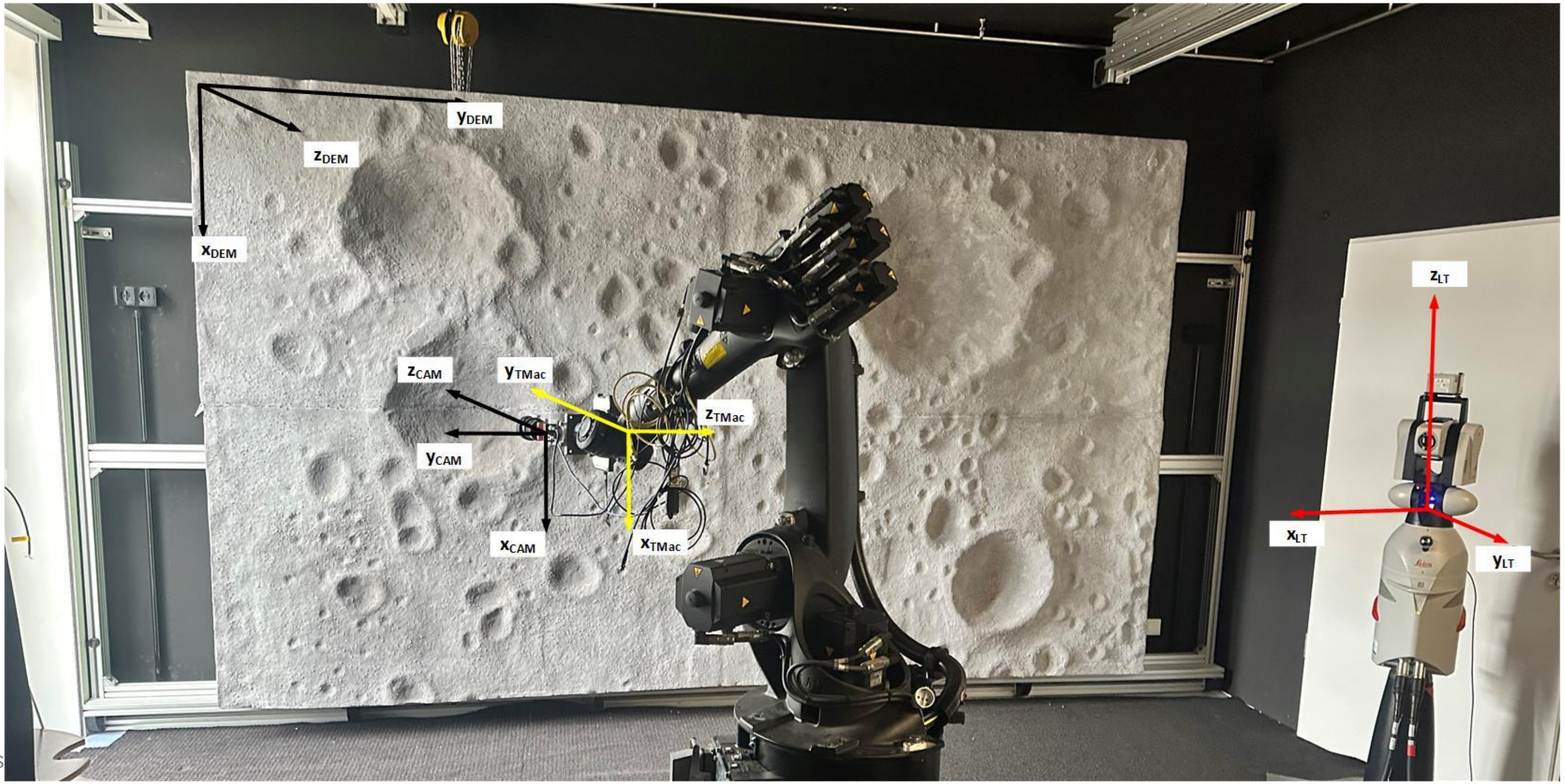


Data acquisition for hand-eye calibration

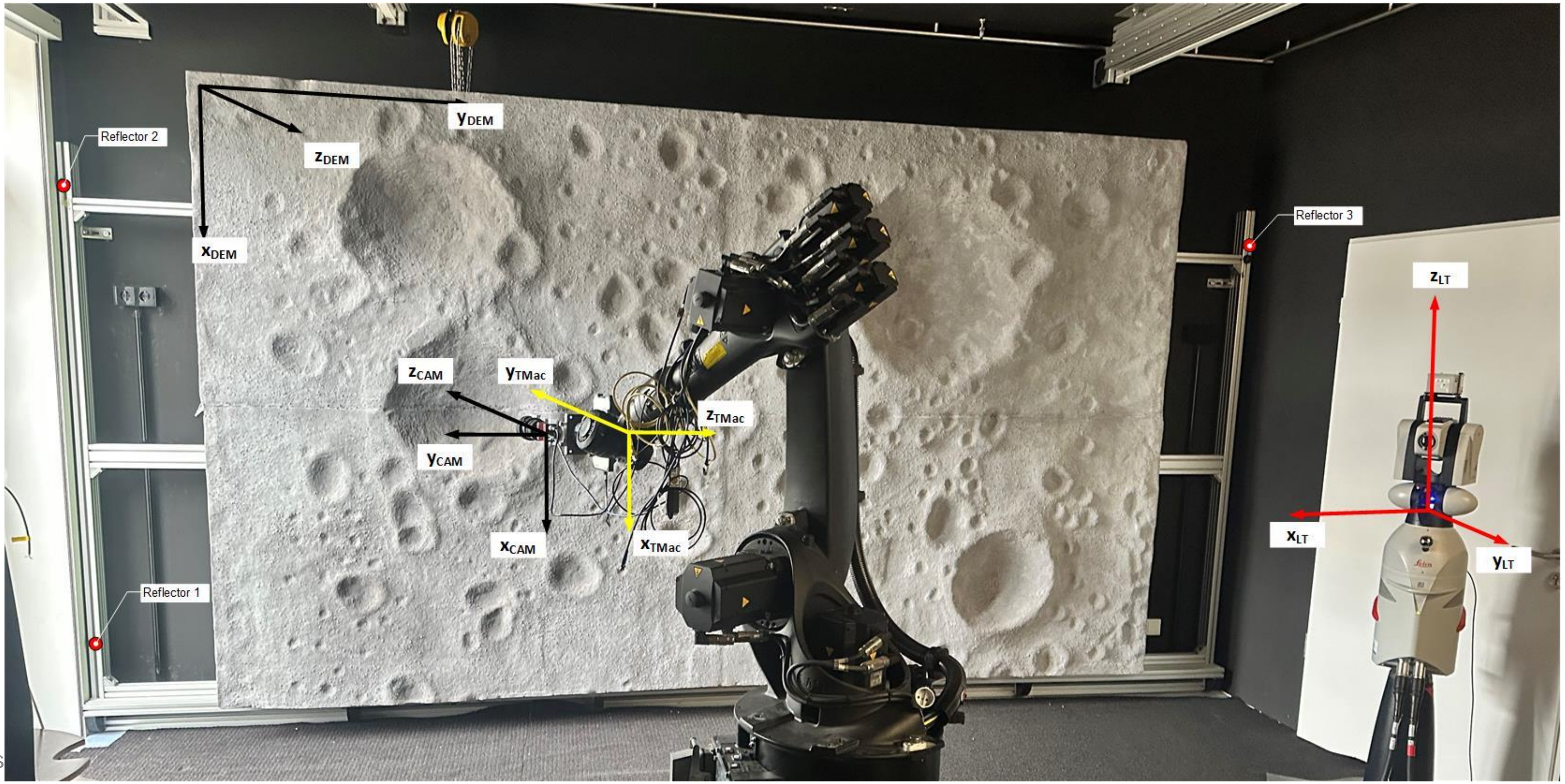
TRON ground truth
Mono-camera with respect to Moon 03

- 2nd link: TMac ↔ Laser Tracker (LT) directly measured



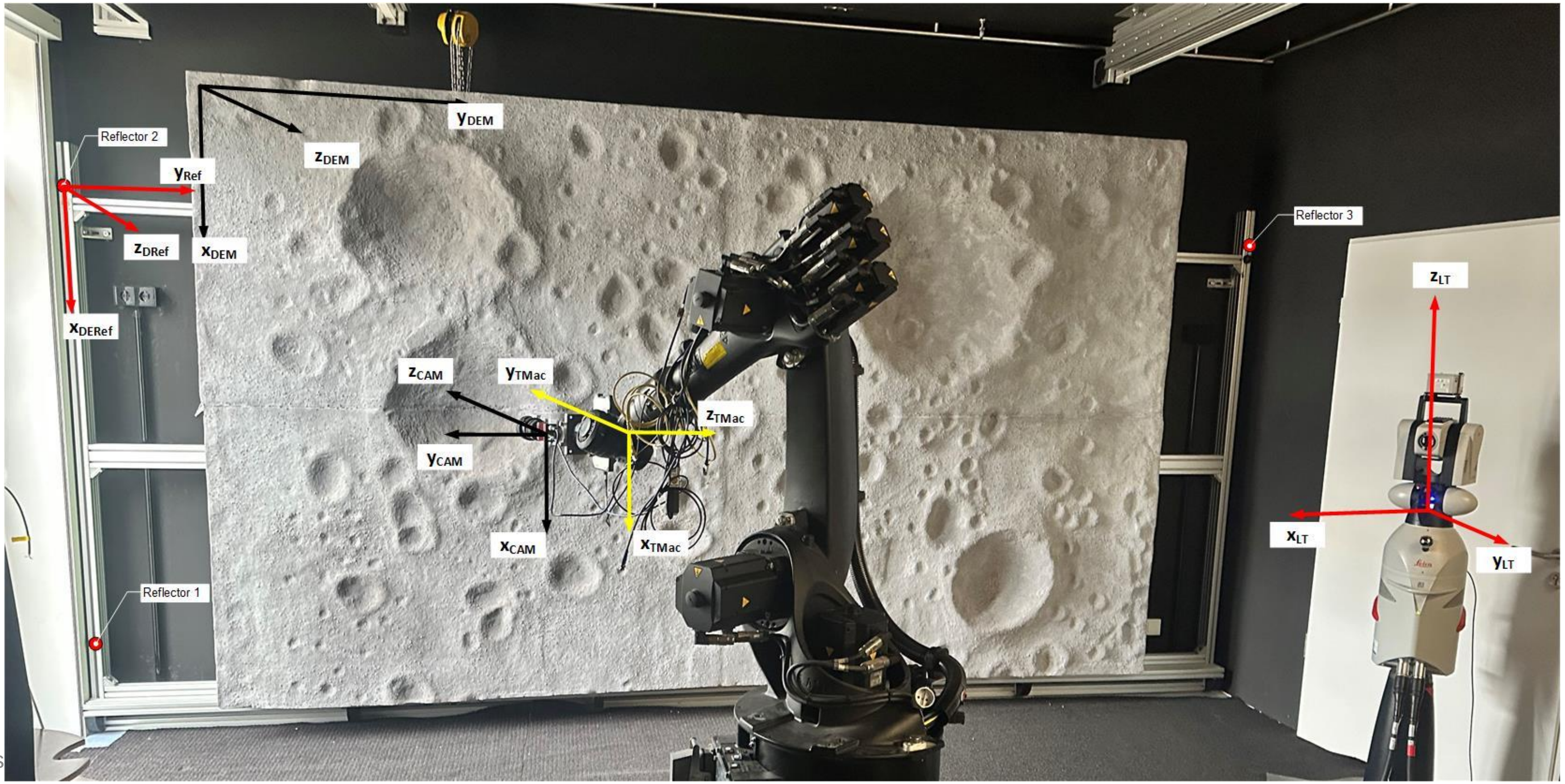
TRON ground truth
Mono-camera with respect to Moon 03

- 3rd link: LT ↔ Ref
- Ref is defined by three reflectors fixed to Moon 03 frame



TRON ground truth
Mono-camera with respect to Moon 03

- Quickly measurable by laser tracker



TRON ground truth
Mono-camera with respect to Moon 03

- 4th link: Ref ↔ DEM
- Determined by processing surface scan and reflector measurements

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Mono-camera with respect to Moon 03

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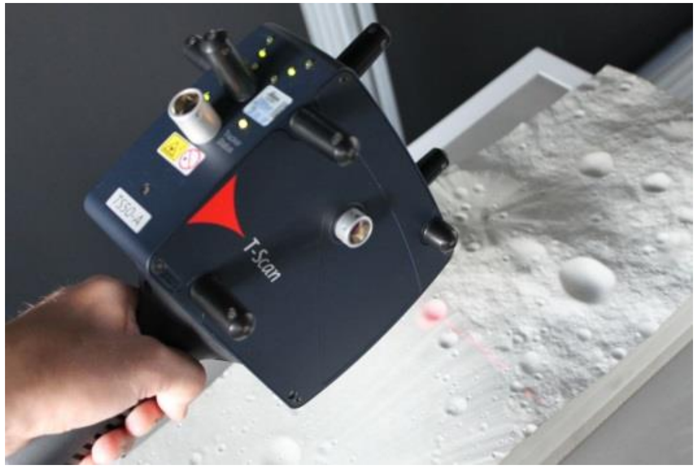

Laser scanning a surface

TRON ground truth
Mono-camera with respect to Moon 03

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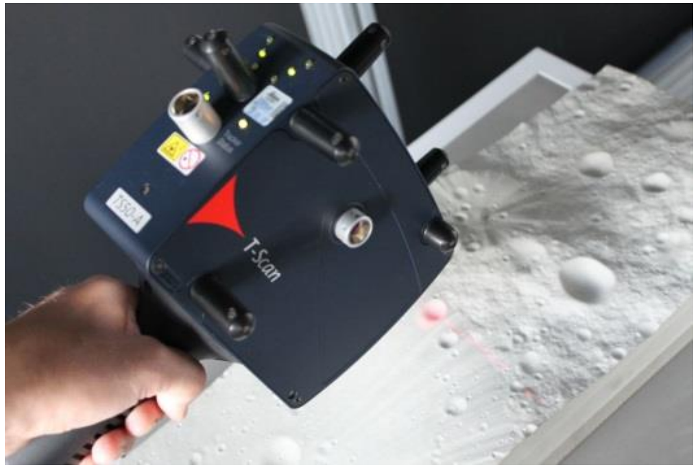

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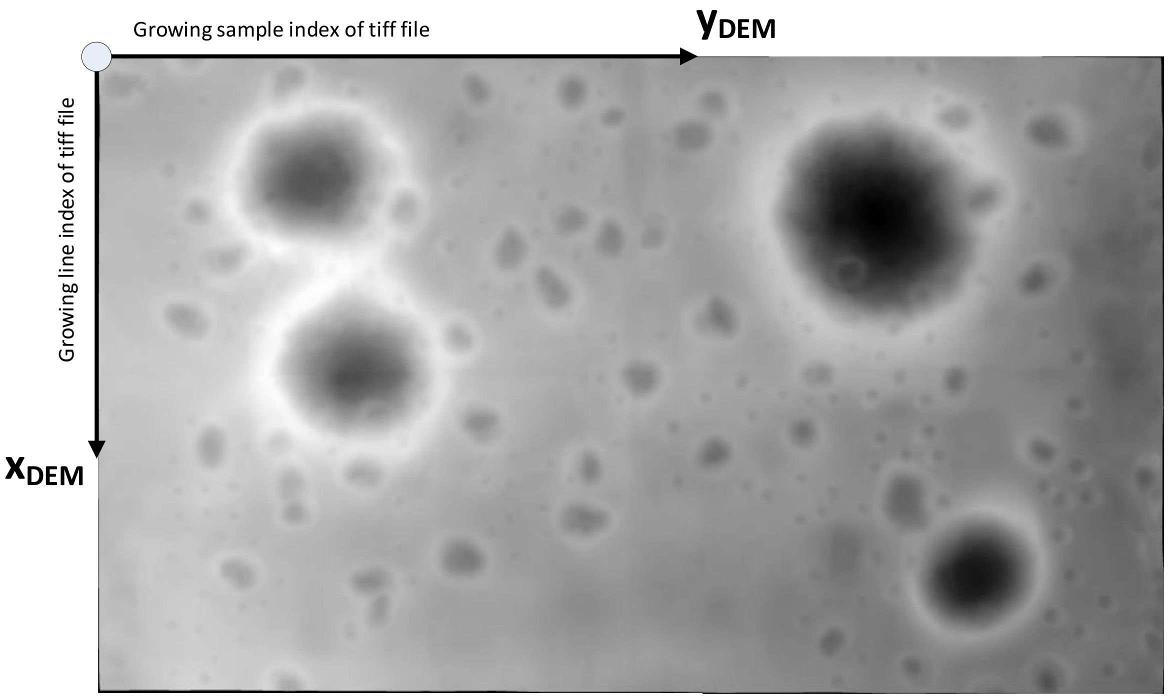
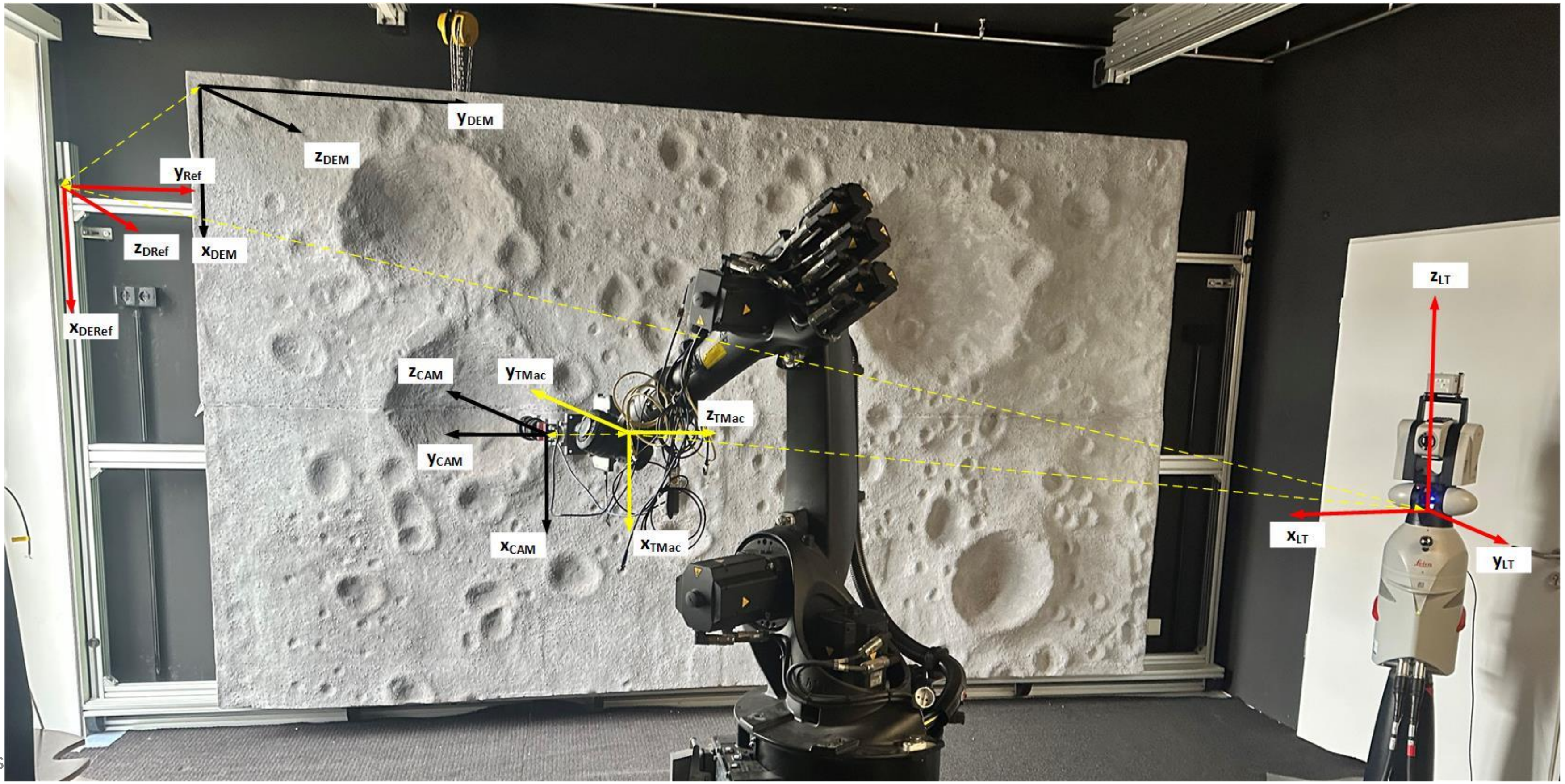


DEM of Moon 03 | 16 Bit gray level

TRON ground truth
Mono-camera with respect to Moon 03

- Result is the transformation chain connecting camera and DEM
- 3 constant links, one dynamic link



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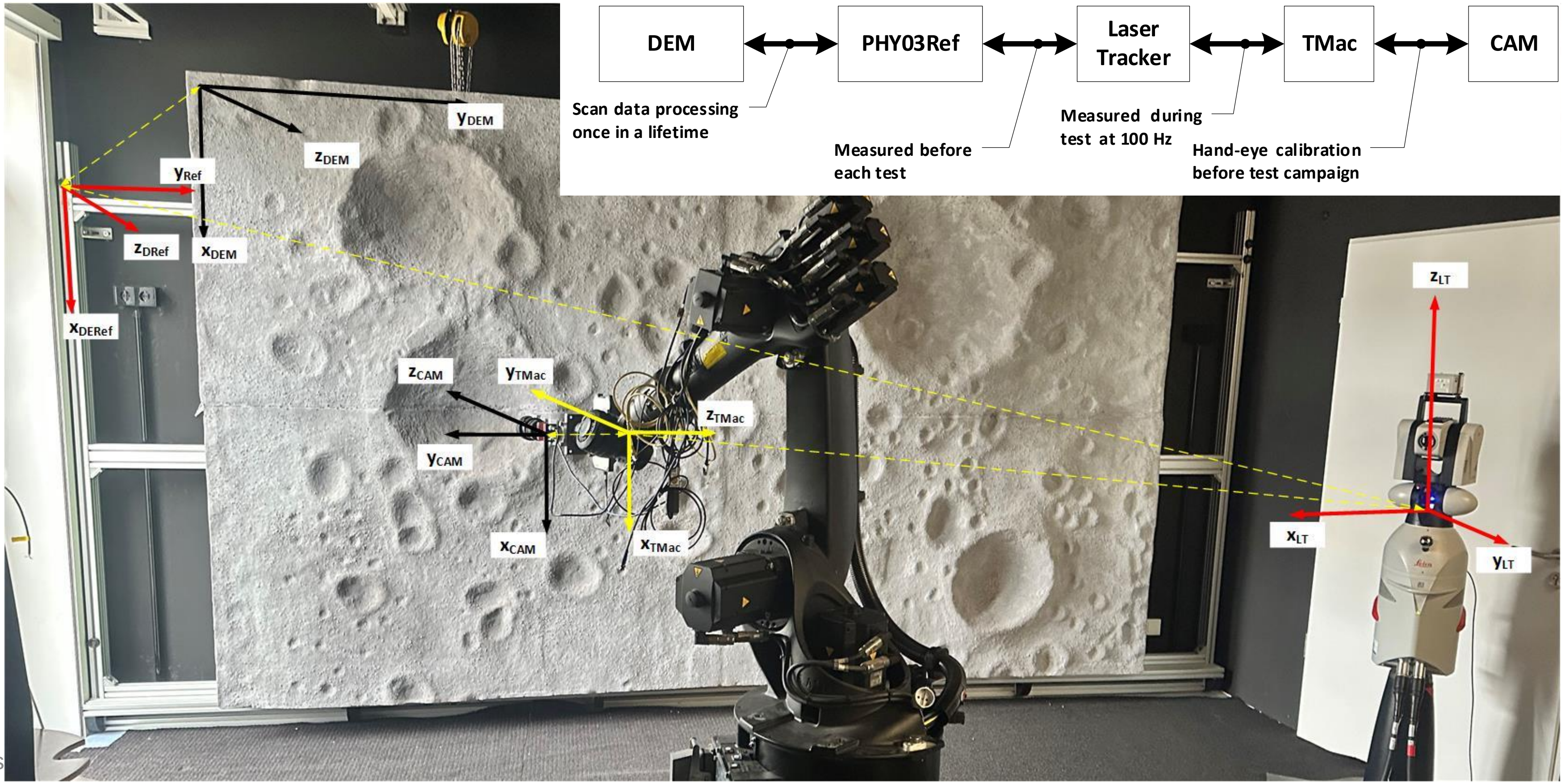


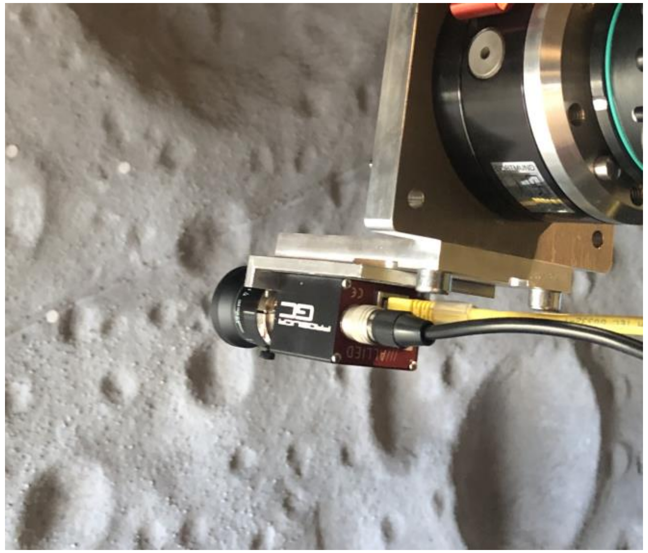
TRON ground truth
Accuracy check for a mono-camera

Estimation of ground truth accuracy by comparing:

TRON ground truth
Accuracy check for a mono-camera

Estimation of ground truth accuracy by comparing:

- Measurement: camera image, undistorted

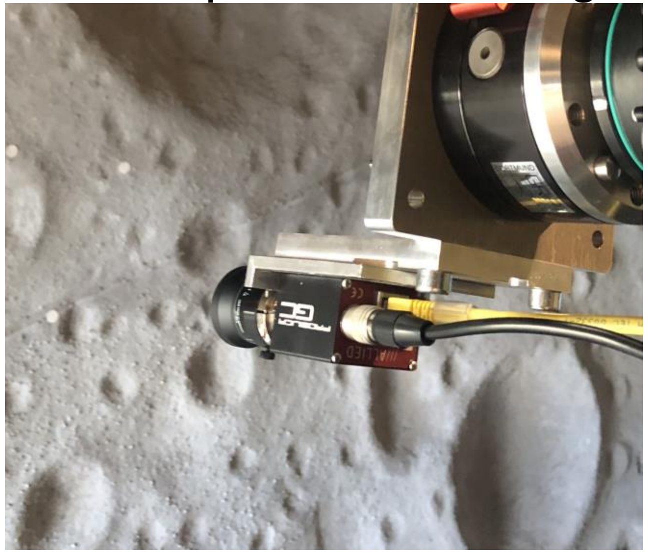


Camera with respect to Moon 3 model

TRON ground truth
Accuracy check for a mono-camera

Estimation of ground truth accuracy by comparing:

- Measurement: camera image, undistorted
- Prediction of the measurement: determined by rendering
  - 3D surface based on DEM
  - Camera pose based on ground truth



Camera with respect to Moon 3 model

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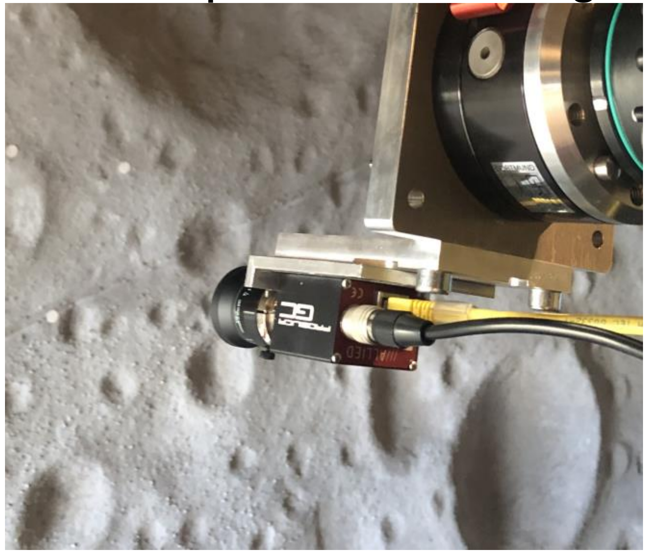

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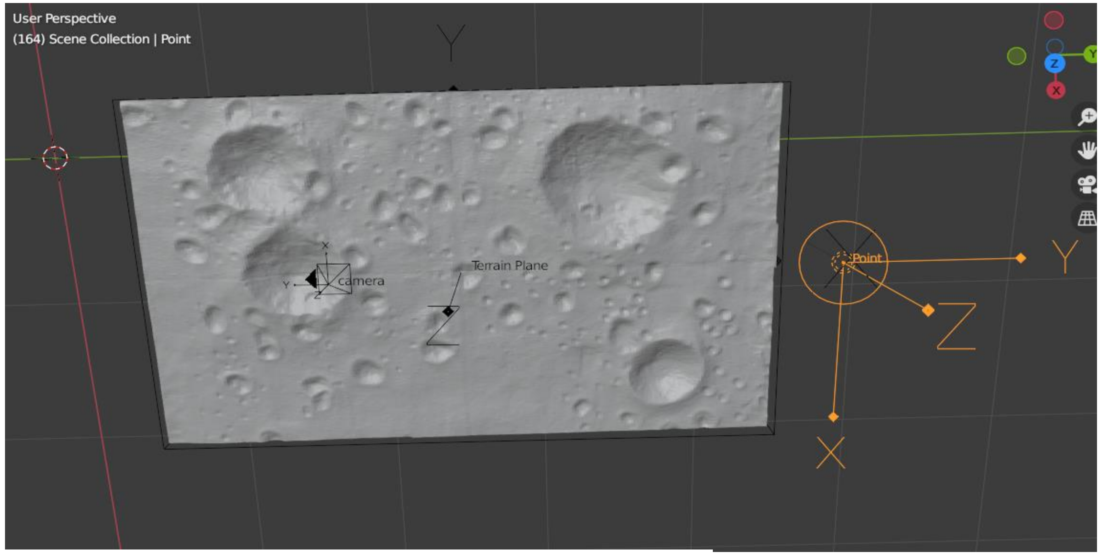


Camera with respect to Moon 3 DEM in Blender

Example 1
Moon 3

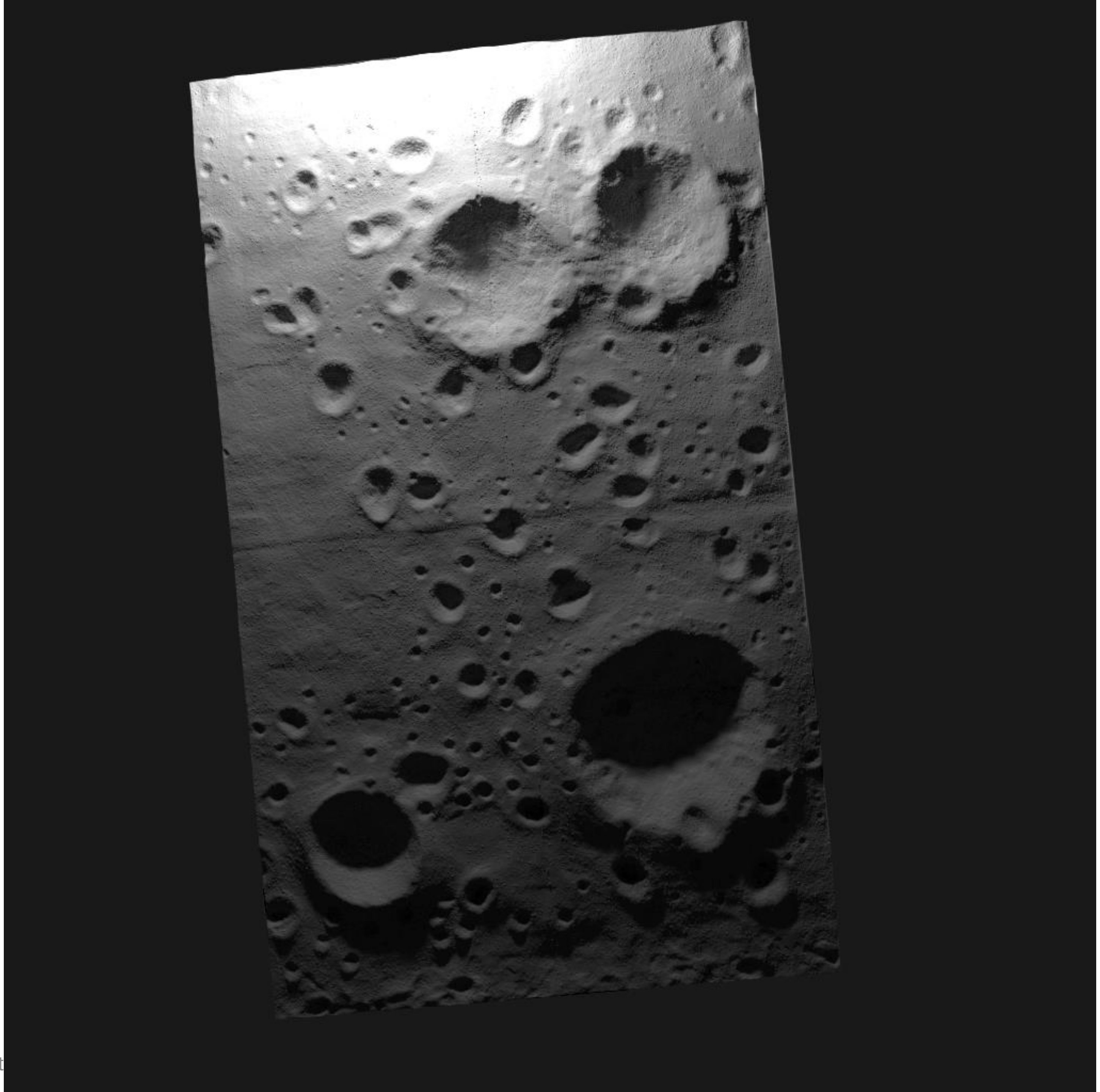
Original camera image

Example 1
Moon 3

Undistorted camera image

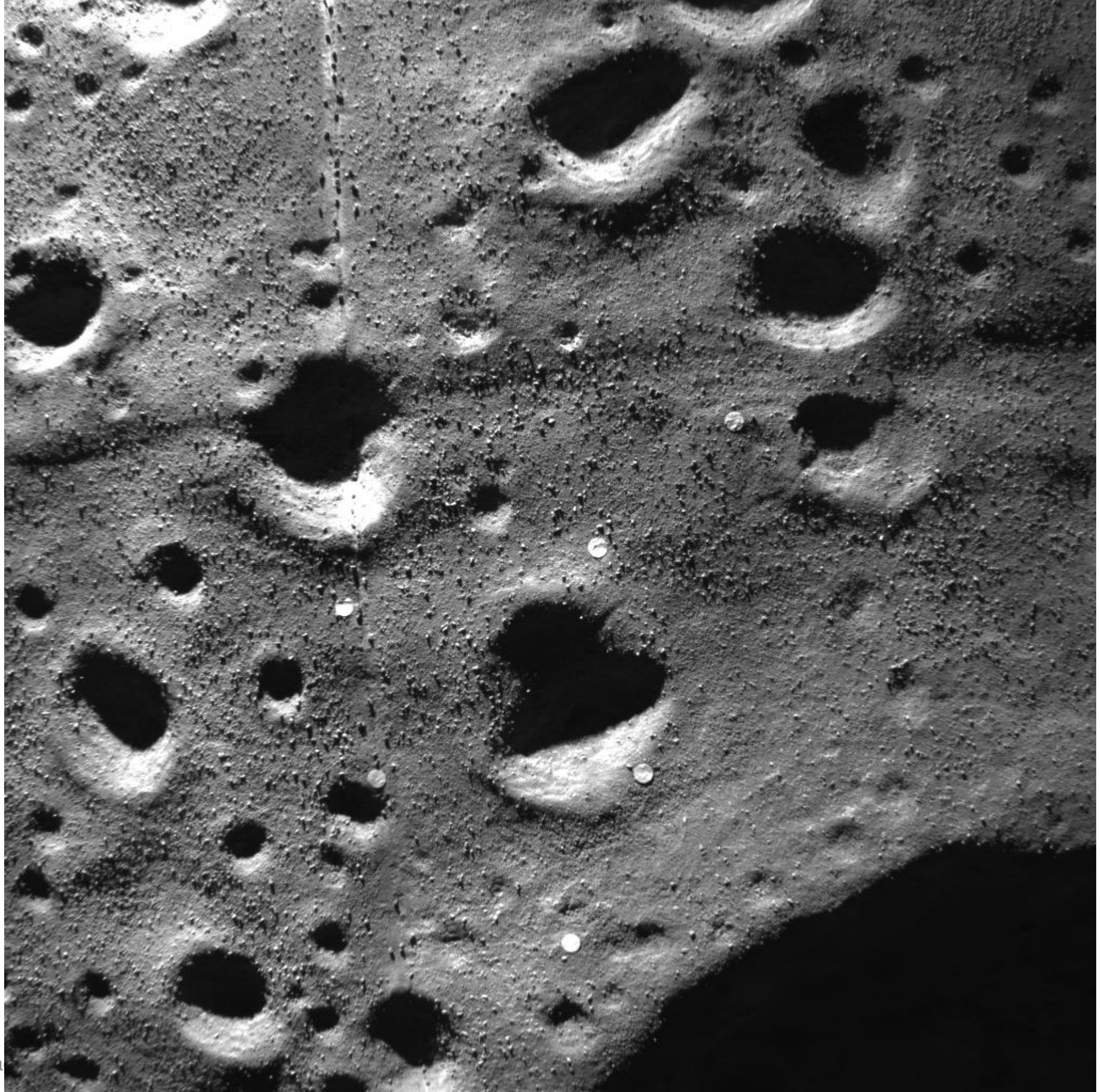
Example 1
Moon 3

Rendered camera image



Example 2
Moon 3

Original camera image



Example 2
Moon 3

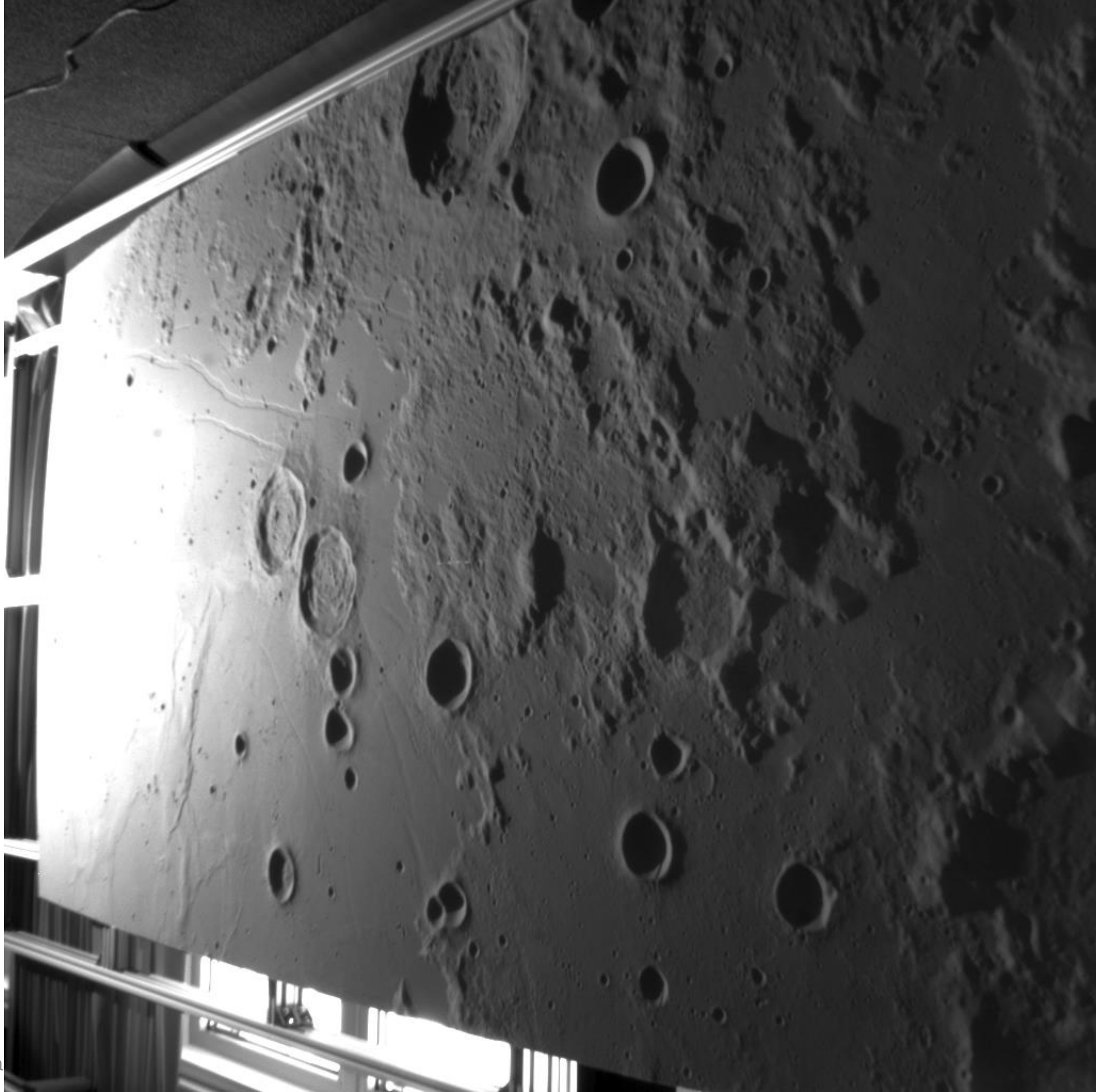
Undistorted camera image

Example 2
Moon 3

Rendered camera image

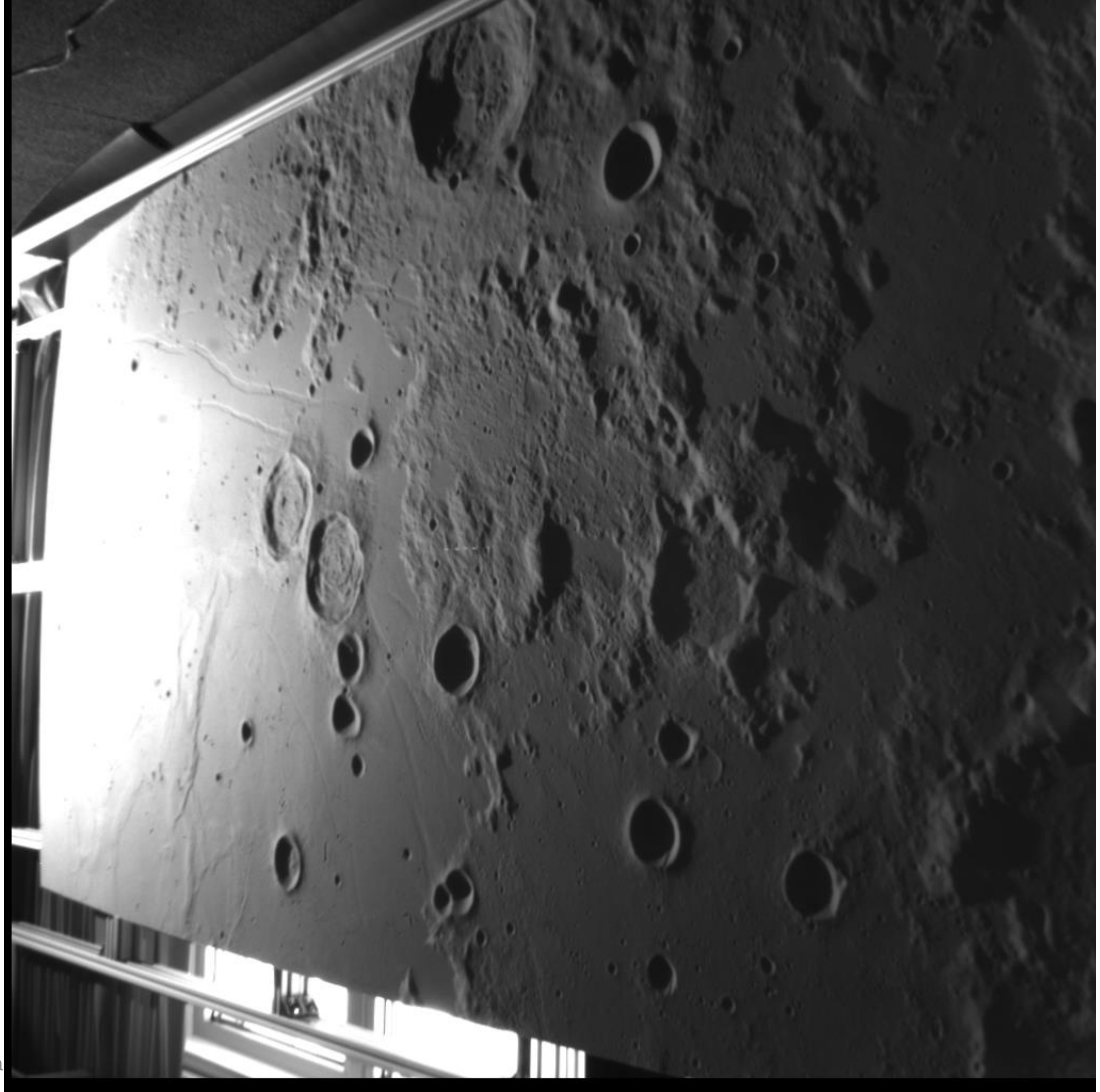
Example 3
Moon 2

Original camera image



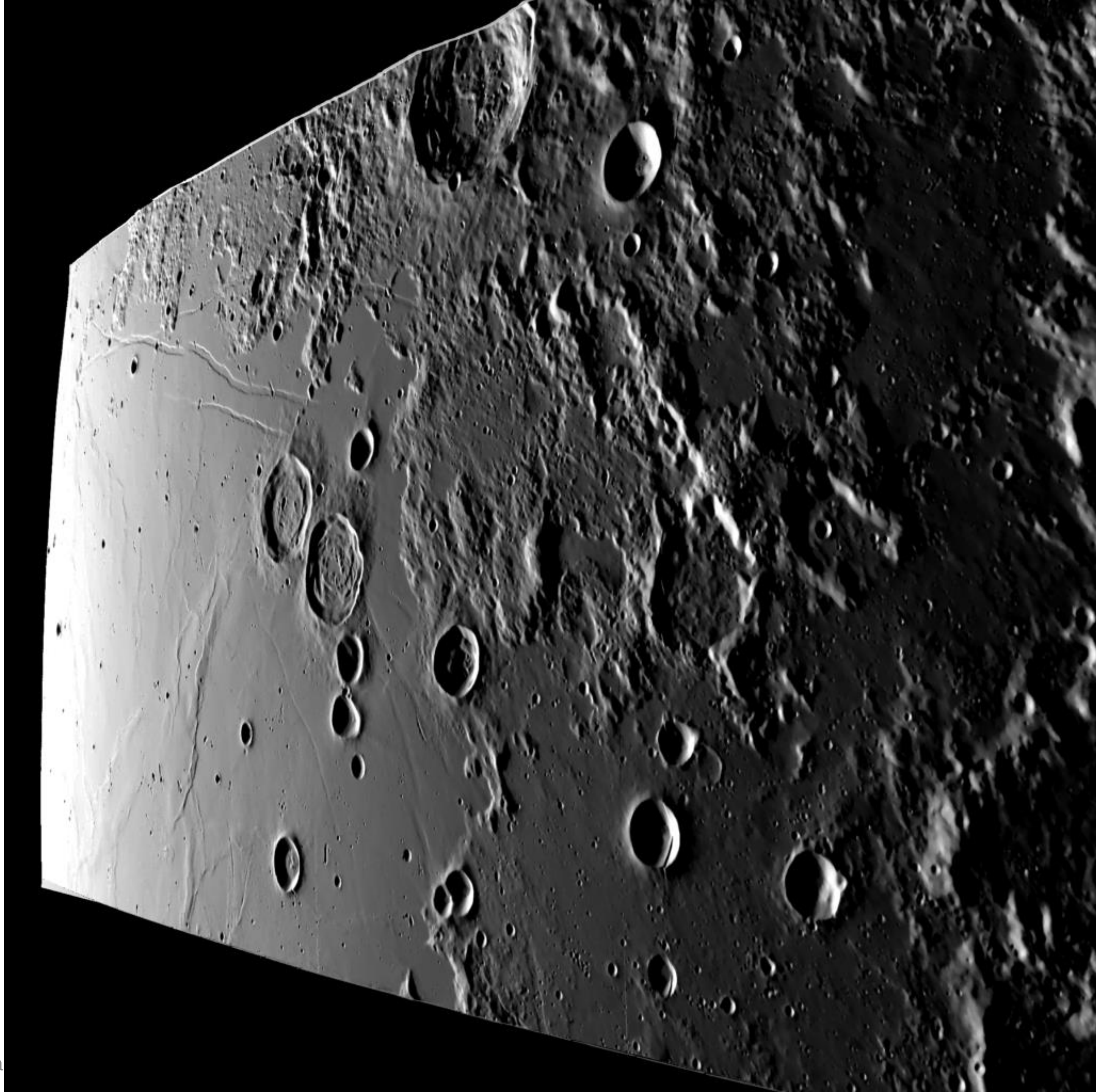
Example 3
Moon 2

Undistorted camera image



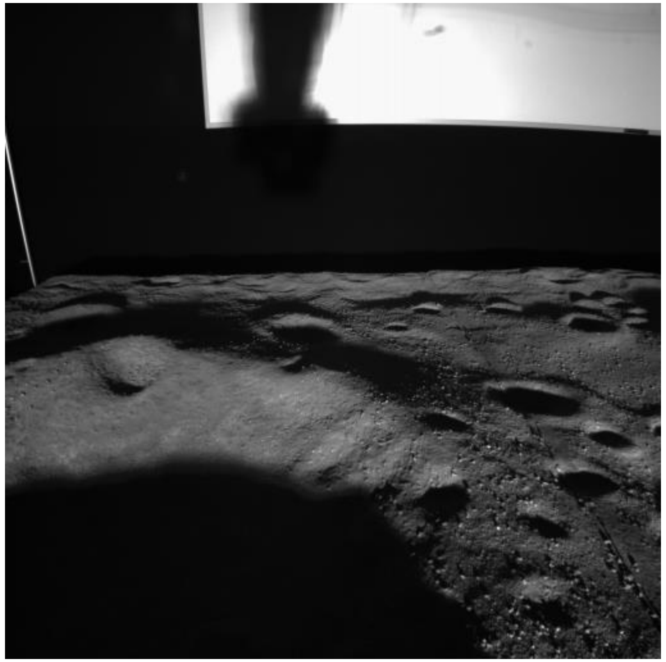
Example 3
Moon 2

Rendered camera image

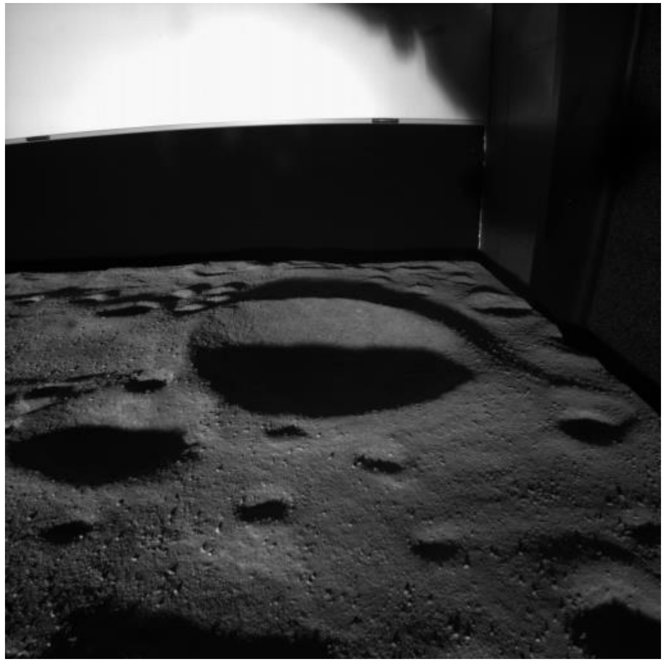


Augmentation using ground truth

- Segmentation of target from background sometimes is common task
- DEM and ground truth allow production of a mask



Original camera image



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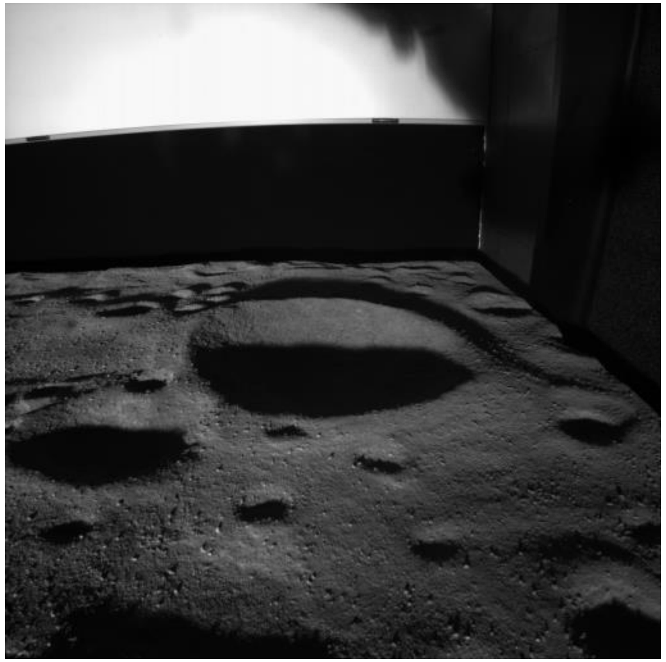
Mask: White = target



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Some recent activities
Data acquisition | later post-processing

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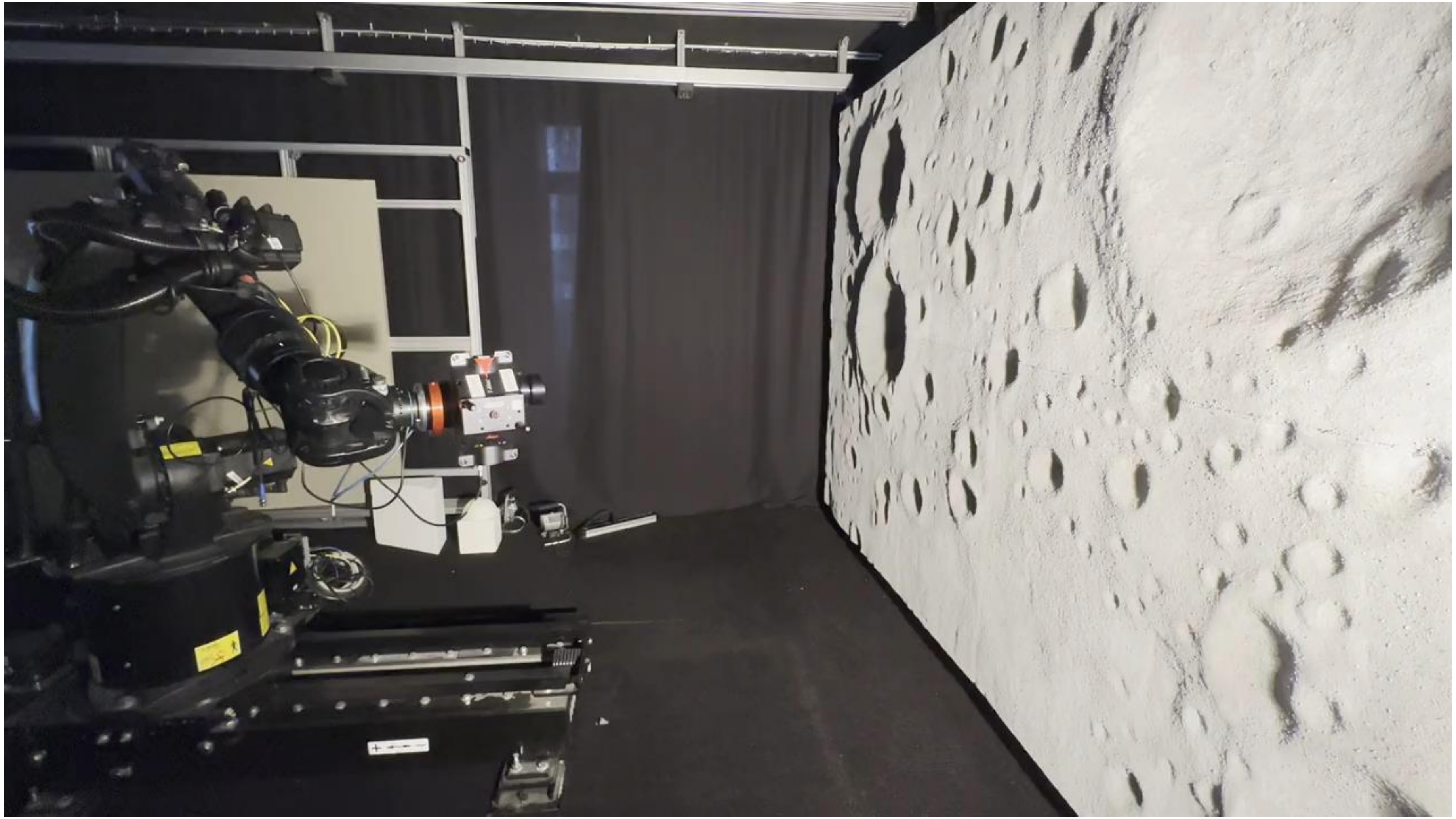
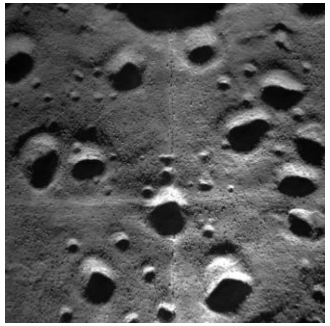
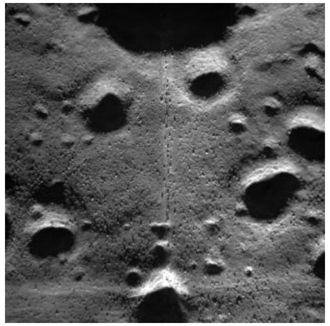
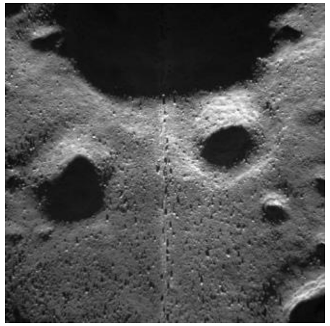


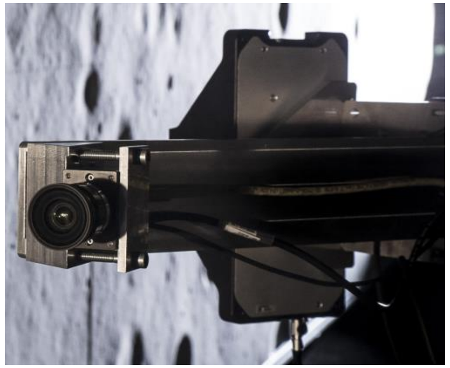






Test examples
Data acquisition for Crater Navigation | post processing

- Image acquisition of Moon 2
- Post-processing of images with CNav algorithm



Camera installed on robotic arm

Robot positioning camera in TRON

CNav running on images acquired in TRON
Red: detected craters
Green: crater catalog mapped into image based on pose estimation

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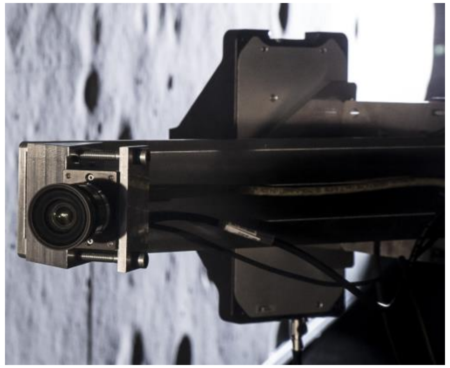

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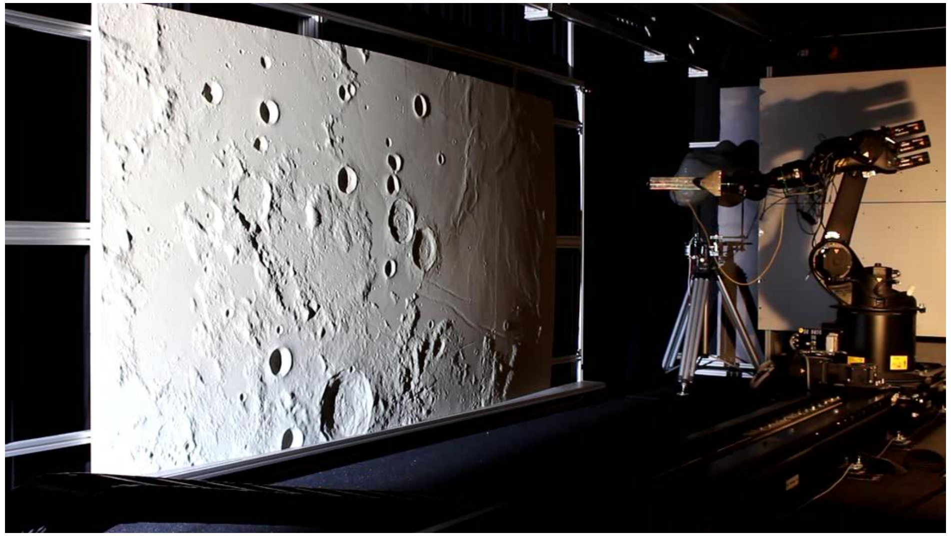
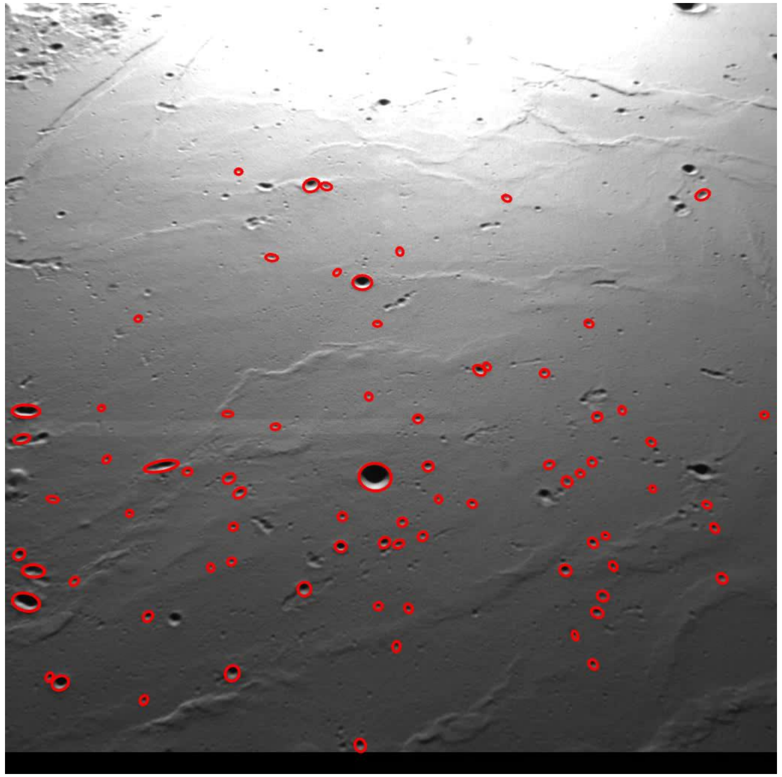


Robot positioning camera in TRON



CNav running on images acquired in TRON
Red: detected craters
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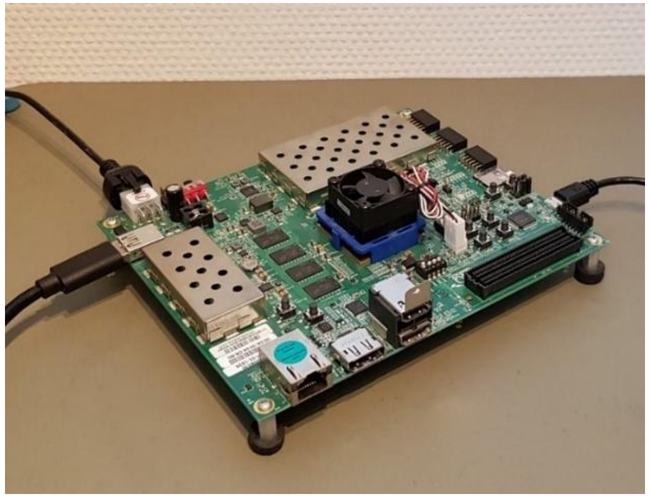
Test examples
Crater Navigation real-time PiL

PiL set-up

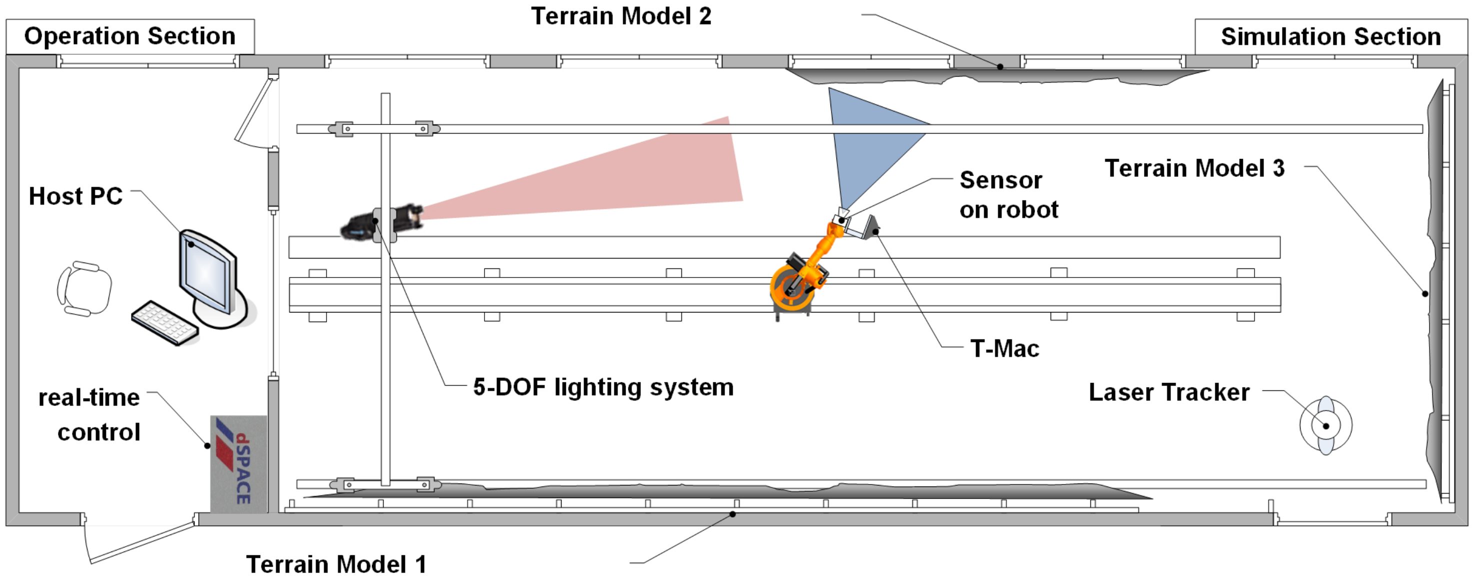
- Space equivalent hardware: Zynq UltraScale+ ARM Cortex-A53 processorarmv8-A architecture. four cores, each at 1.2 GHz
- CNav deployed on 2 cores (realistic as per mission studies)



UltraScale+ in TRON | connected to camera

TRON set-up

- Model: Moon 2
- Camera live input to UltraScale+
- Rotot runs at representative speed



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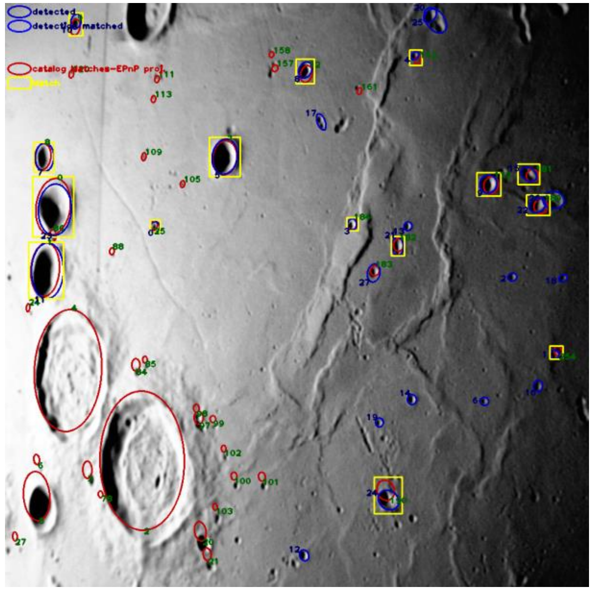

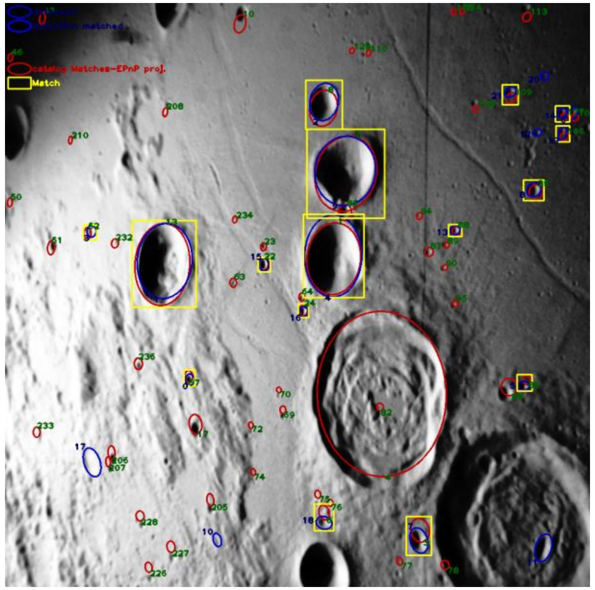

Test examples
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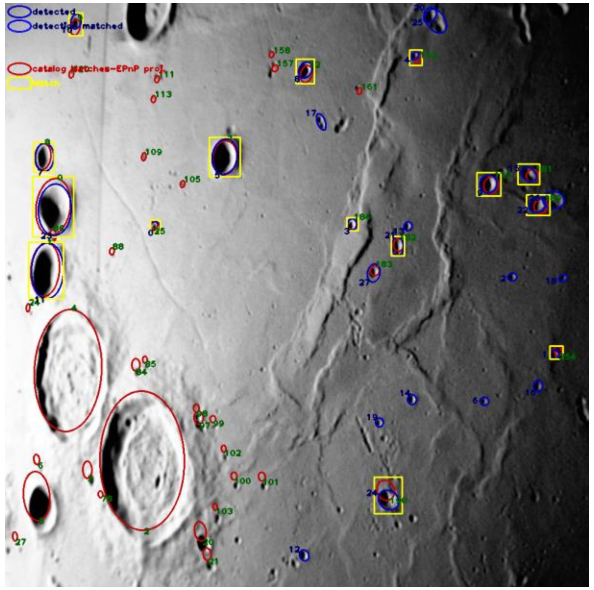

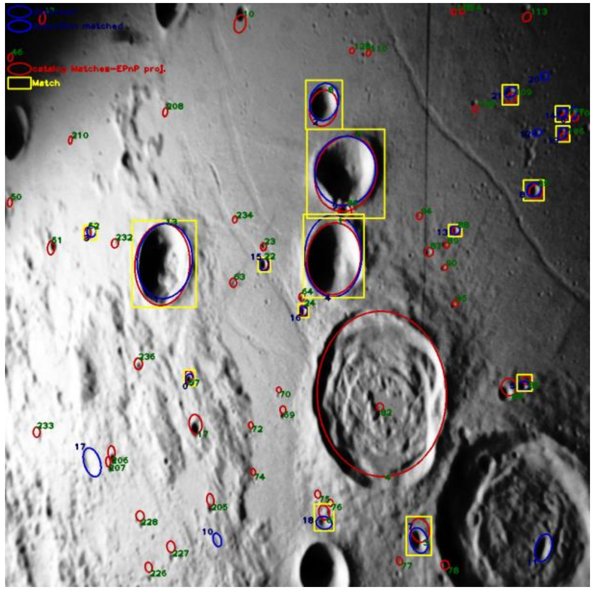

Upcoming activities

- Image recording for reference data sets
- Crater navigation for lunar missions
  - Beresheet-2
  - Argonaut
- We are happy to discuss your ideas for testing or data acquisition