METHODS OF ANALYSIS FOR STEREO OBSERVATION OF PLANETARY SURFACES AND LIBRATIONS

Scuola di Dottorato in Scienze Tecnologie e Misure Spaziali (STMS)
Curriculum: Misure Meccaniche per l'Ingegneria e lo Spazio (MMIS)
Cicle XXXIV

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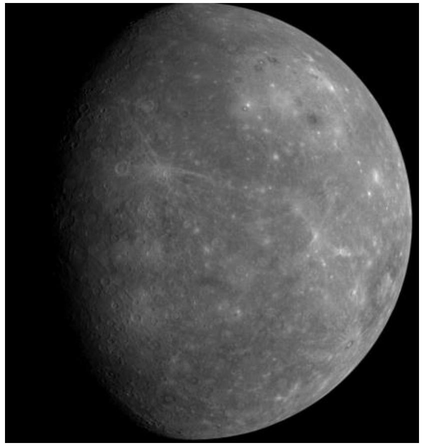
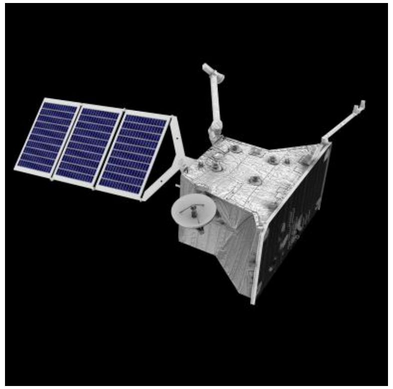
BepiColombo Mission

- **Collaboration between ESA and JAXA, launch 2018, arrival 2025**

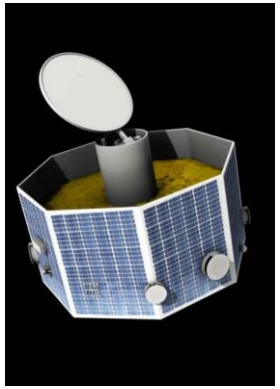
- **Scientific goal: exploration of Mercury**
  - Geology
  - Volcanism
  - Origin of the planet
  - Core of the planet
  - Magnetosphere

- **Two spacecraft:** Mercury Planetary Orbiter MPO (ESA)
  Mercury Magnetospheric Orbiter MMO (JAXA)





MPO

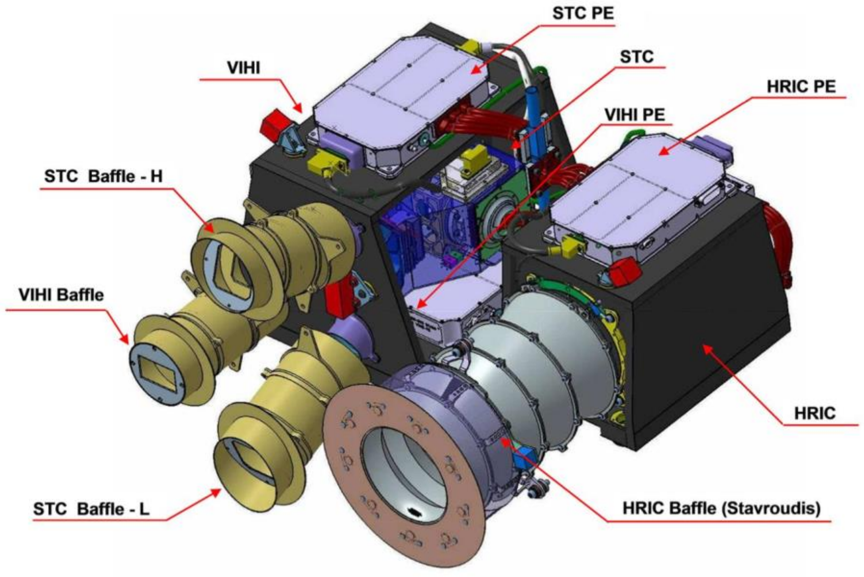


MMO

SIMBIO-SYS

Camera suite including three channels:

1. **High Resolution Imaging Camera (HRIC):** high resolution images (6 m/pixel) of more than 20% of the surface
2. **Stereo Camera (STC):** mapping of the full surface in stereo mode with 60 m/pixel resolution
3. **Visual and Infrared Hyper-Spectral Imager (VIHI):** mapping the planet in visible and infra-red to provide a global mineralogical composition



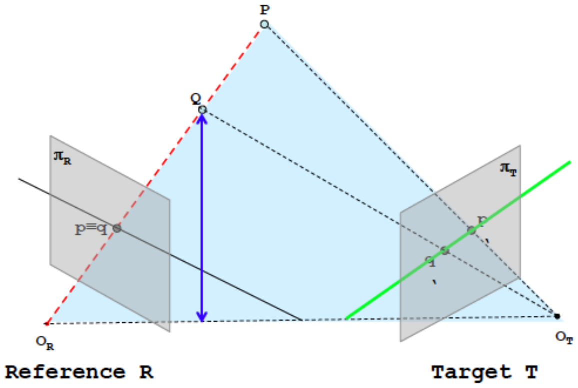
SIMBIO-SYS suite, PI: Gabriele Cremonese

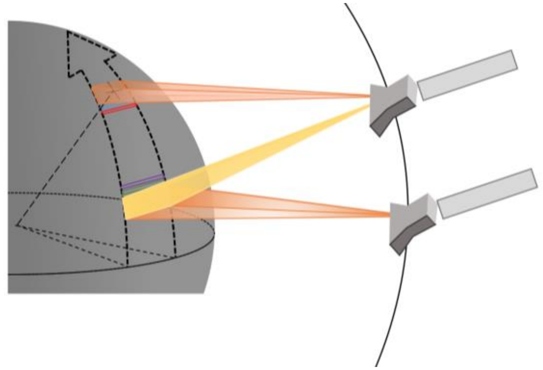
Stereo Vision

Technique aimed at inferring depth from two or more cameras:

- **Un-distortion:** remove the lens distortions
- **Rectification:** obtain images row-aligned and rectified
- **Find correspondence:** find the same features in the left and right camera views, obtain a disparity map
- **Triangulation:** a depth map is calculated from the disparity map

Alternatively, it is possible to use the same camera from two different points





Concept of stereo acquisition with STC

Two tasks

High resolution DTMs with HRIC

Find observation strategies to obtain stereo images

Creation of high resolution Digital Terrain Models

Integration of HRIC and STC acquisitions → stereo pair with images both of HRIC and STC

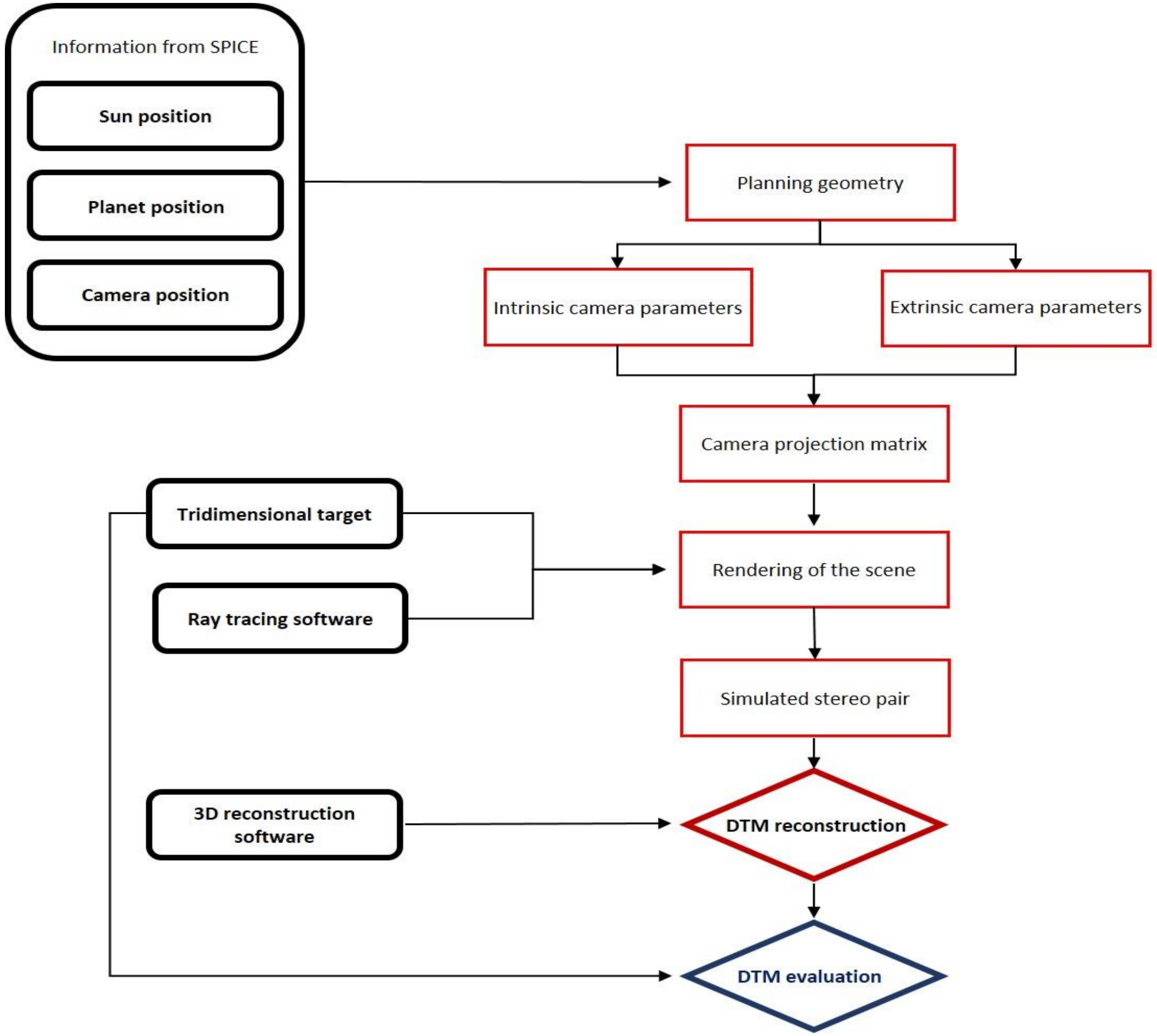
Mission planning

Identify observation strategy compatible with the mission's constraints

Investigation of the polar regions

Mosaicking of HRIC images

DTM reconstruction flow chart



Calculate orbital parameters: using SPICE kernels

SPICE: Spacecraft Planet Instrument Camera-matrix Event

SPICE kernels: contain navigation and ancillary information providing precision information geometry for planetary science

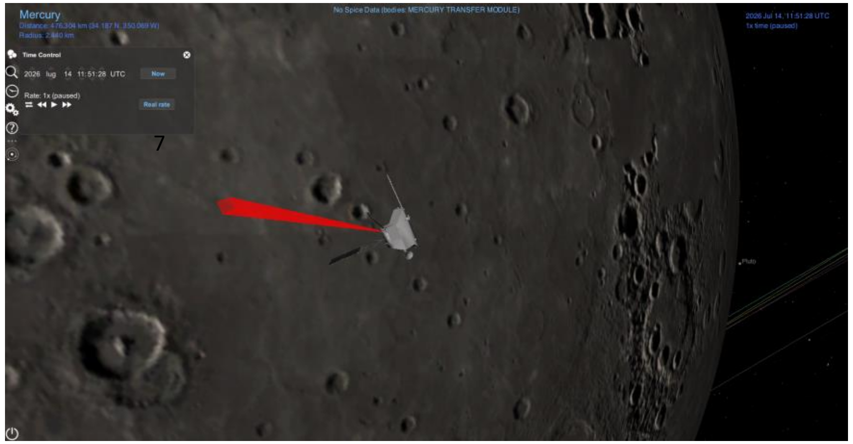
Navigation and Ancillary Information Facility

Input

Instant of time

Output

- Position of the spacecraft
- Position of the Sun
- Orientation and parameters of the camera
- Position of the target

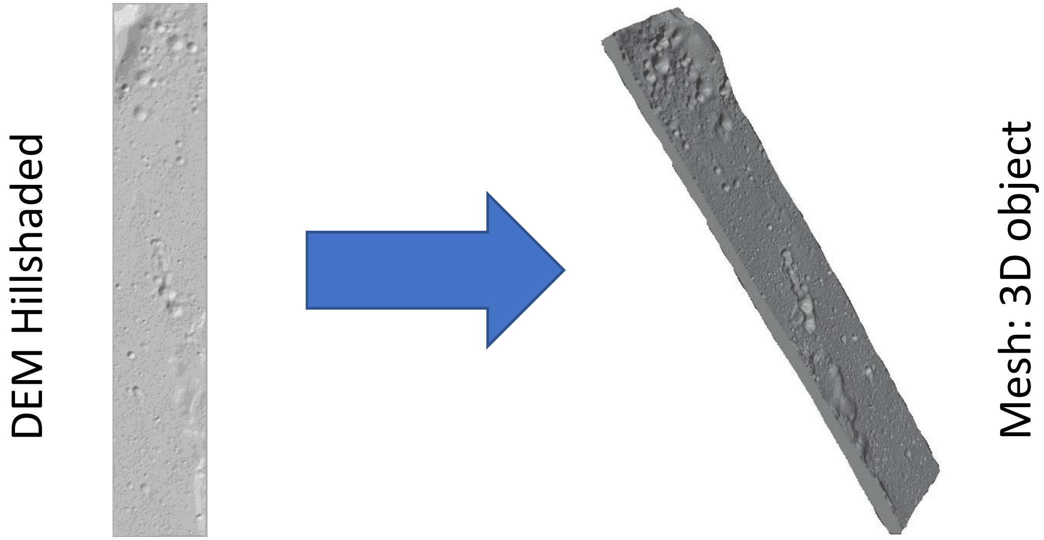


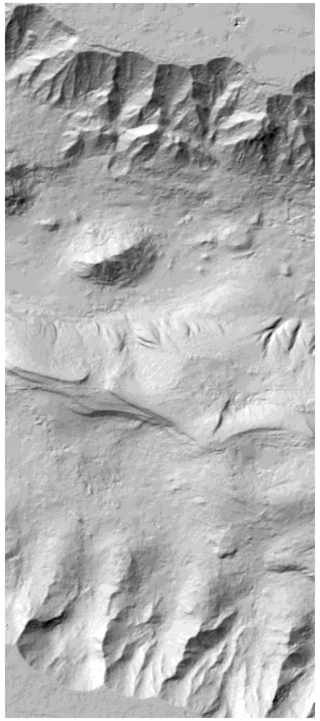
Representation of MPO pointing with Cosmographia

The choice of the target

Mesh: 3D model made of triangles that represents a real object

Mesh created from DEM (Digital Elevation Models) of planetary surfaces images→ Moon images (good resolution, similarity to Mercury), Mars images (good resolution, big size)





Crop from h2028_0000_dt4 DTM from MEX mission

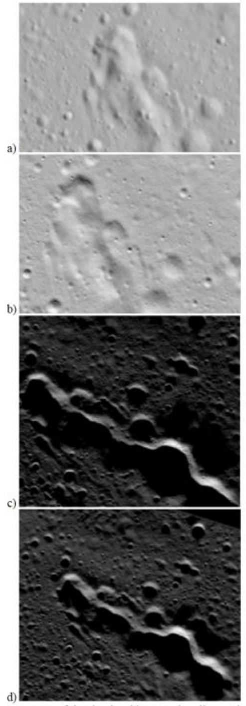
Obtaining synthetic images: the workflow

SPICE data

MESH

SurRender software developed by Airbus (Brochard, R., 2018)

Ray-tracing software



Simulate image acquisition

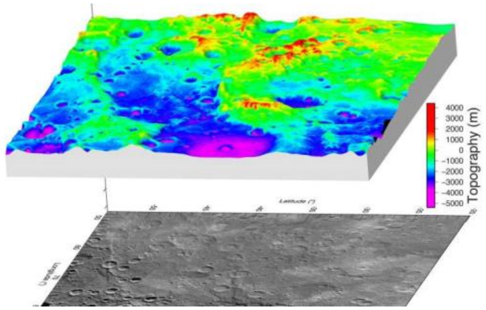
Different synthetic images taken at different latitudes under different illumination conditions

Stereo images with HRIC

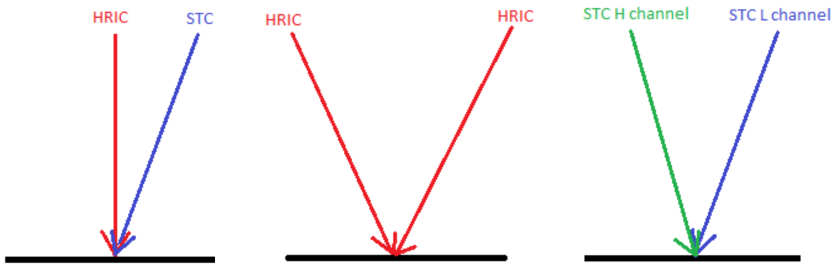
HRIC is nadir-pointing, but stereo images can be obtained rotating the spacecraft

Simulation workflow:

- Selection of a DTM to use as sample
- Simulation of image acquisitions of the DTM with ray tracing technique
- Obtain stereo couple of images
- Reconstruct a DTM and compare it with the original one
- Evaluation of camera performances changing different parameters (illumination, altitude, light inclination, characteristics of the stereo pair…)



DTM example



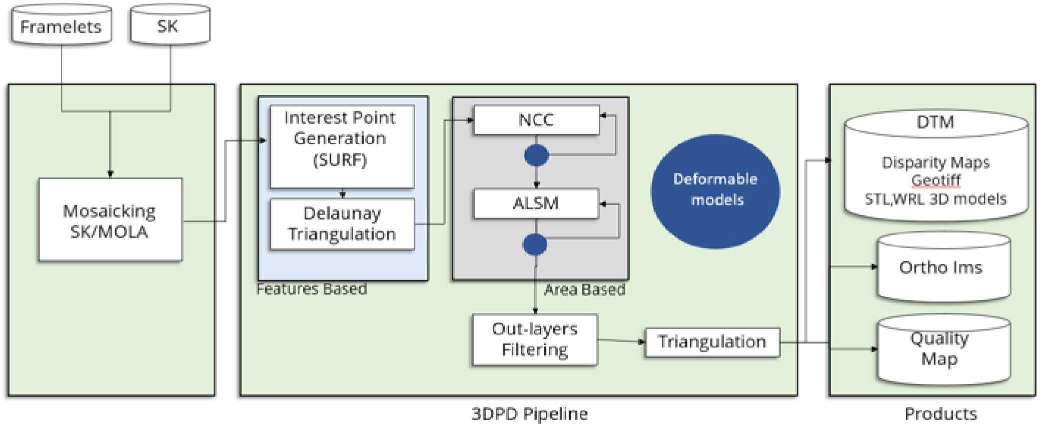
Different stereo pair acquisition modality: HRIC-STC, HRIC-HRIC and STC-STC

3DPD

Software of the tridimensional reconstruction of planetary surfaces

Used for the CaSSIS camera onboard the ExoMars Trace Gras Orbiter

The software will be slightly modified in the future and used for SIMBIO-SYS



DTM quality assessment

The precision of the obtained DTM is measured in terms of **root mean square error** (RMSE) and **mean error** (ME).

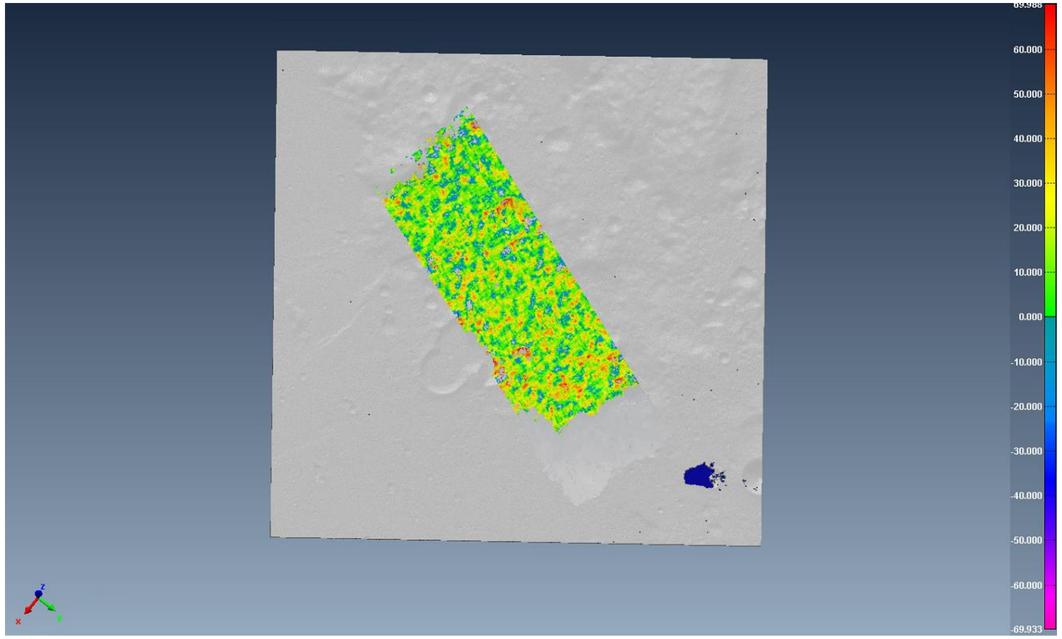
$$\text{RMSE} = \sqrt{n^{-1}\sum_{i=-1}^{n}\left(DTM_{ref} - DTM\right)^2}$$

$$\text{ME} = \left[n^{-1}\sum_{i=-1}^{n}\left(DTM_{ref} - DTM\right)\right]$$

Expected vertical precision (theoretical formula):

$$\text{EP} = \Delta p \ H/B \ \text{GSD}$$

Δp = matching error in pixel
H = height of the center of perspective
B = baseline of the stereo block
GSD = Ground Sample Distance (pixel resolution)

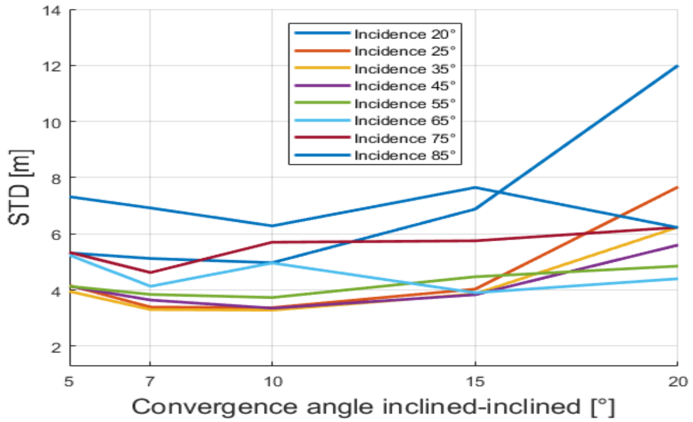


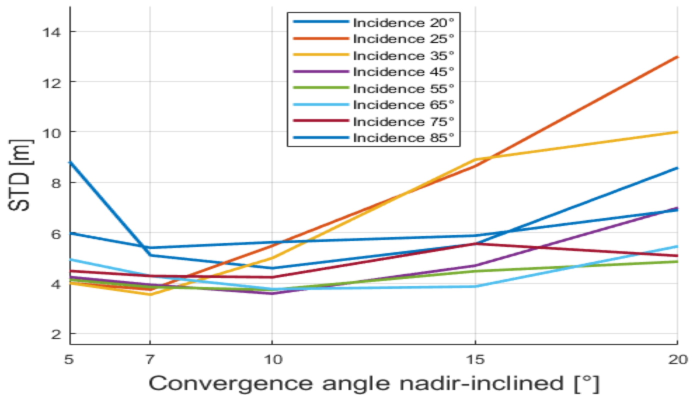
Comparison between the simulated DTM and the original DTM (ground truth)

DTM quality comparison

Several simulations are conducted at different illumination conditions and convergence angles. Moreover, the stereo pairs are obtained in two configurations: nadir-inclined and inclined-inclined

- **Best incidence angle:** 40°-50°
- **Worst incidence angle:** <20° (no recognizable features), >85° (long shadows and occlusions)
- **Best convergence angle:** around 10°
- **Best stereo configuration:** the two configurations have quite similar results

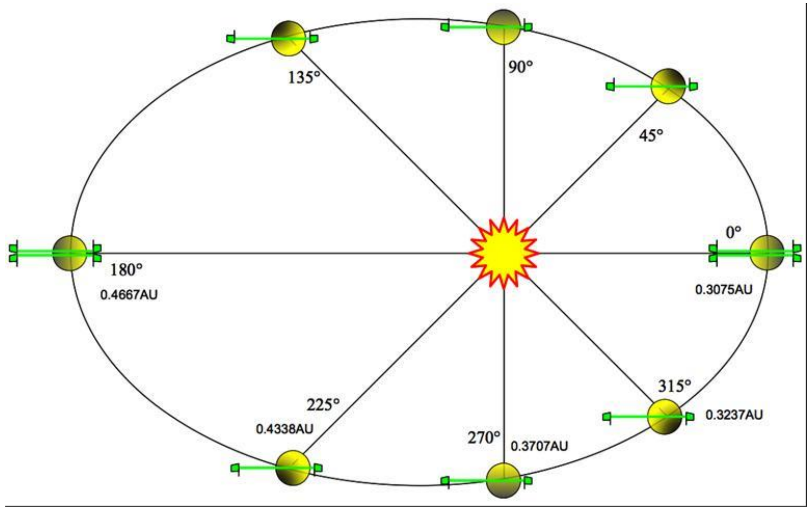




Mission planning

Different aspects to take into account:
- Orbits of the spacecraft
- Rotation of Mercury
- Revolution of Mercury
- Dayside/Nightside
- Temperature of the surface

Goal: find the optimal conditions for taking images (time, illumination, resolution, repeatability conditions…)



Orbit of MPO (green) around Mercury

All these information can be stored and processed using the SPICE kernels → real positions and times that will be cover during the mission

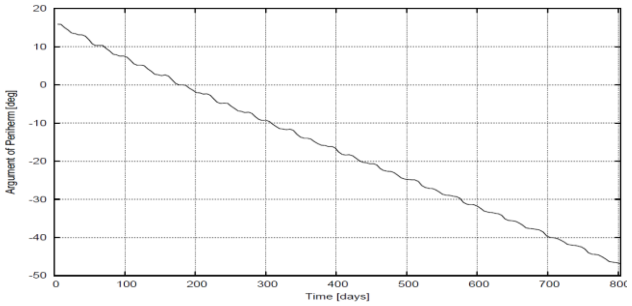
Changes of mission parameters

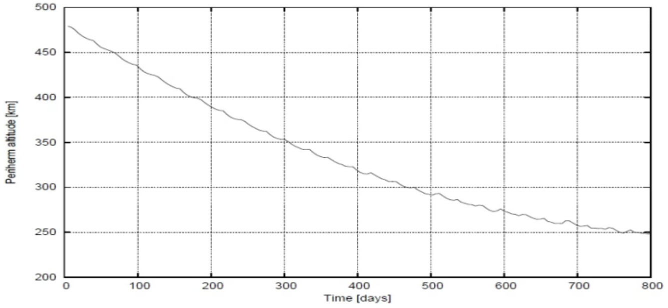
Periherm: the Periherm (Apoherm) changes in time both in position and altitude

Illumination: the illumination conditions depend on the position of the target on the surface and the position of Mercury respect to the Sun

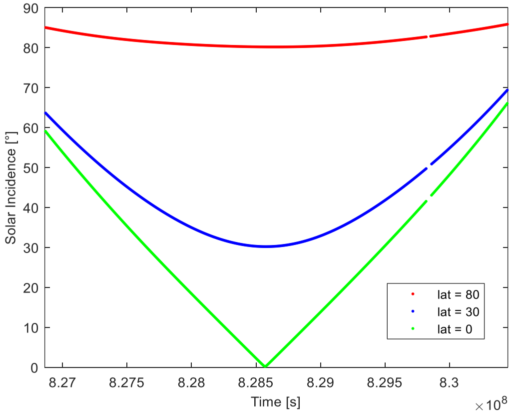
Resolution: depends on the altitude of the spacecraft

Mission is divided in different phases





Periherm changes



Illumination conditions

Phase	Position	Latitude [°]	Altitude [km]	Velocity of the S/C [km/s]	Pixel on ground [m/px]	Footprint dimension FPAN [km^2]
Beginning of the mission	Periherm	15.9	480	2.94	6	12.31 × 3.84
	Apoherm	-15.8	1500	2.18	18.7	38.48 × 12.02
End of the first year mission	Periherm	-18.3	316	3.09	3.95	8.10 × 2.53
	Apoherm	18.4	1666	2.07	20.8	42.73 × 13.35

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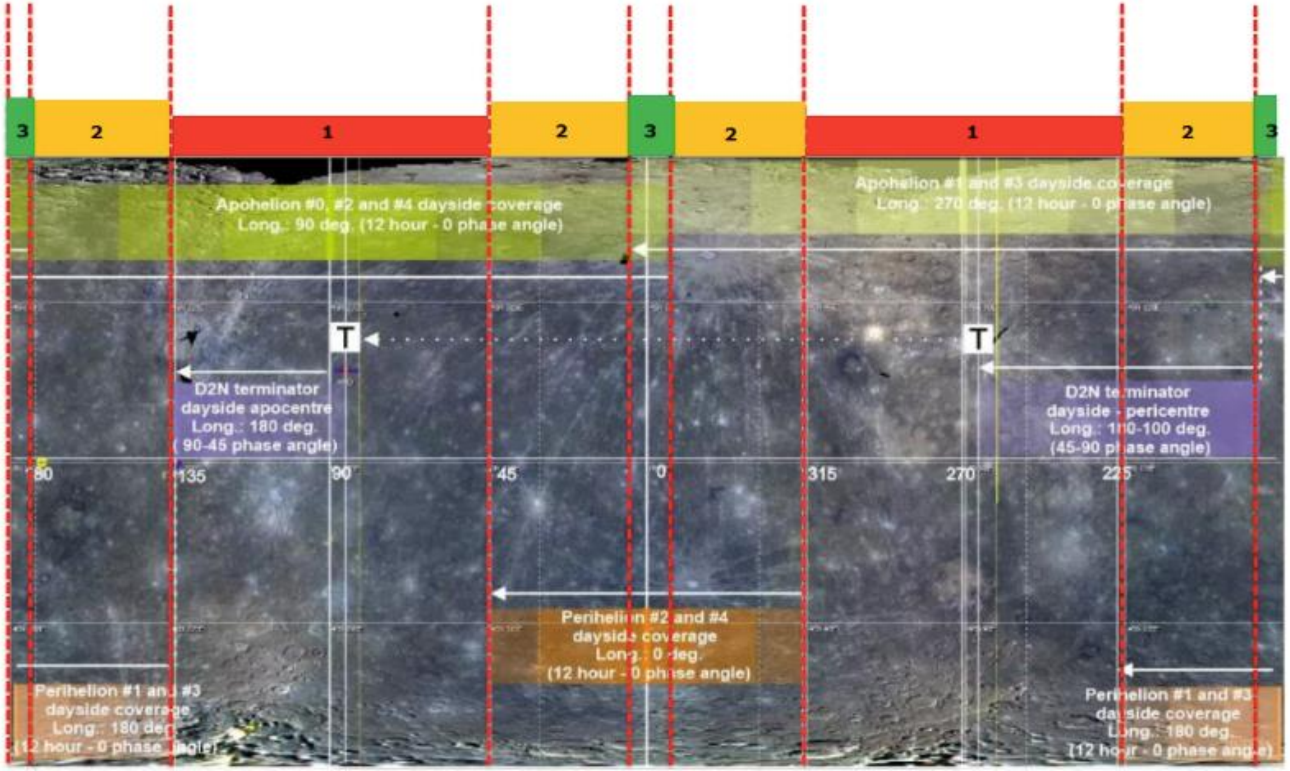
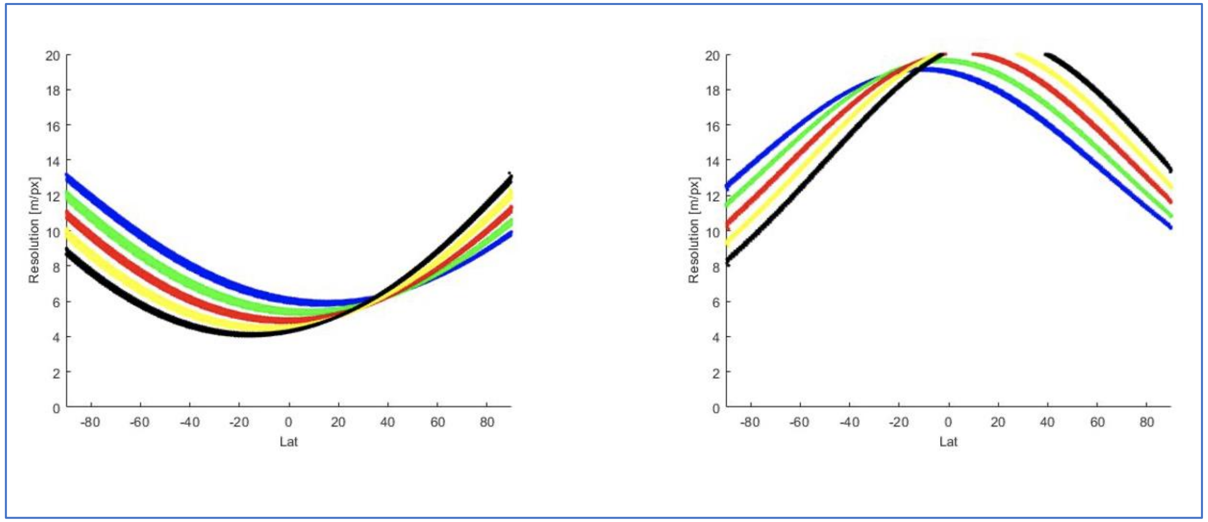
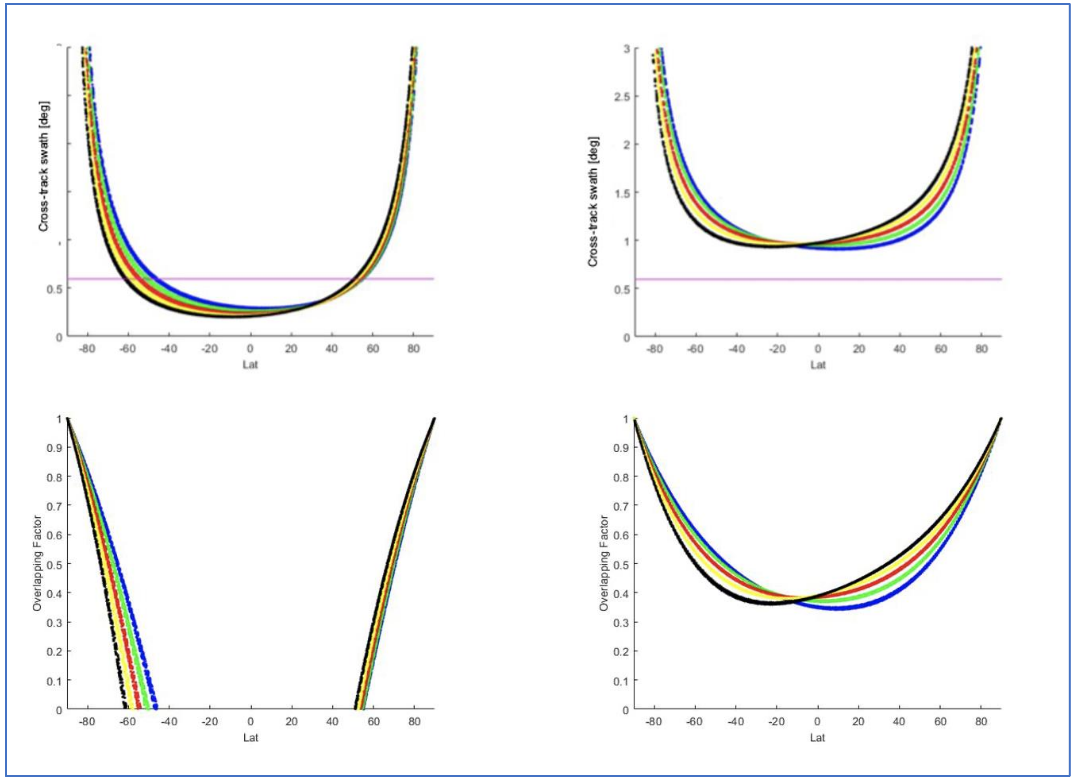
Revisitation conditions



Different illumination conditions in dependence of the longitude of the target

Mission planning outcomes



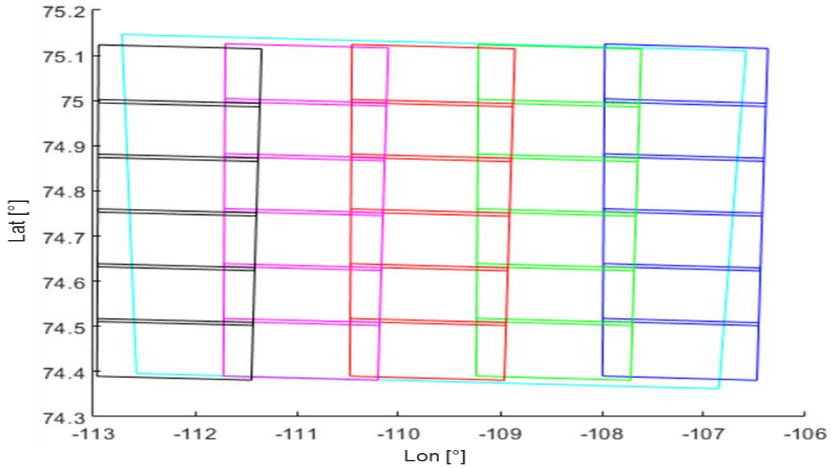


Cumulative graphs: Left rect: the pixel on ground. On the left for HR, on the right for LR. Right rect: on the top the Cross-track swath amplitude for HR (left), LR (right) and below the overlapping percentage for HR (left) and LR (right). In blue: HR/LR 1, in green: HR/LR 2, in red: HR/LR 3, in yellow: HR/LR 4 and in black HR/LR 5

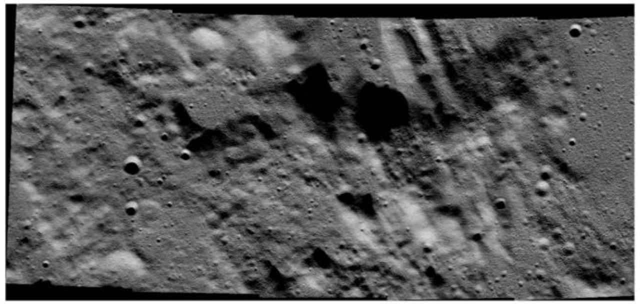
Combine different images: mosaic

Image are simulated with the dimension of the camera sensor: small area covered

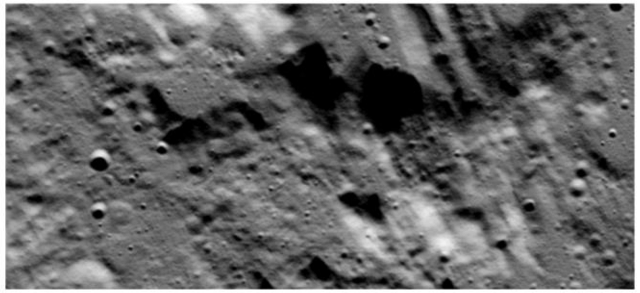
Mosaic: combine different images in an unique one



In cyan the footprint of a single acquisition of STC. In blue, green, red, magenta and black the sequence of images of HRIC. Repetition time = 2,4 s; HRIC acquisition every orbit. In this example 30 images of HRIC are necessary to mostly cover the area of a single STC image



(a)



(b)

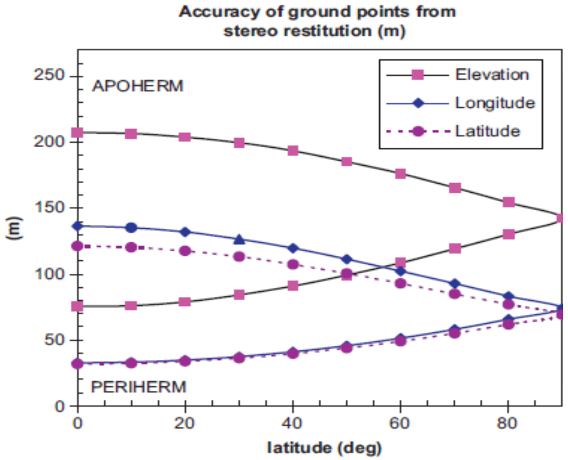
a) mosaic of 30 HRIC images to approximately cover an area of one STC image b) the STC image for the equivalent area.

Exploration of the poles

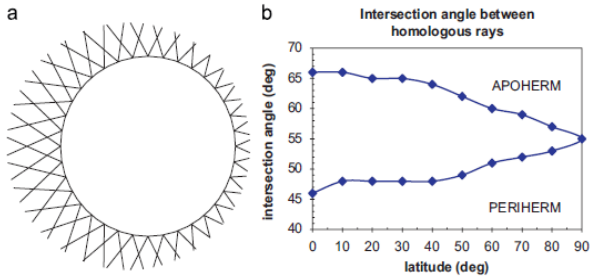
- Important scientific targets (water inside the craters?)
- Possibility to perform a mosaic with consecutive orbits
- STC is not optimized

New acquisition strategy integrating HRIC and STC images for the stereo pair:

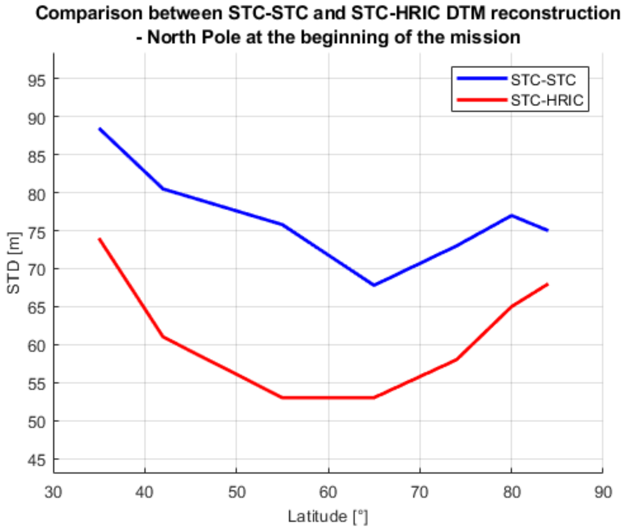
→ One image is a mosaic of HRIC images (nadir)
→ The second image is a normal STC image

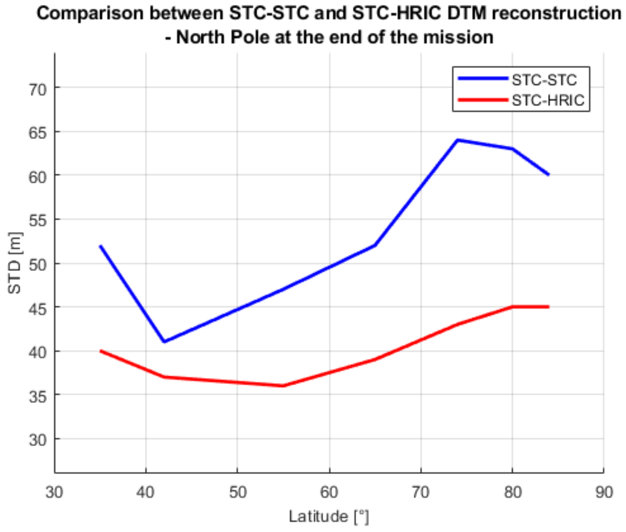


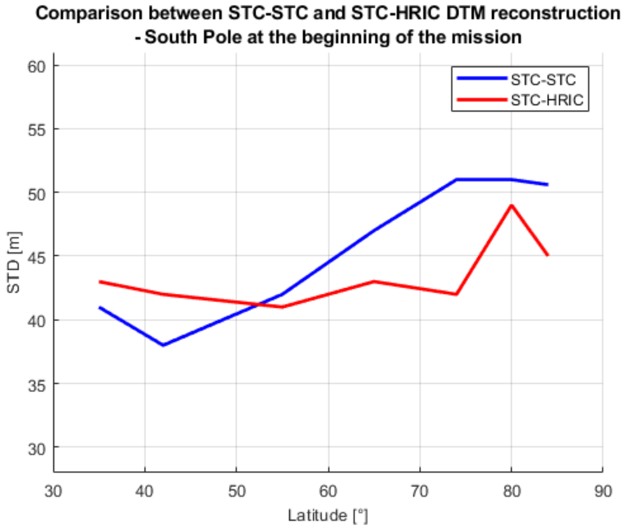
Expected accuracy of STC DTM in function of the latitude

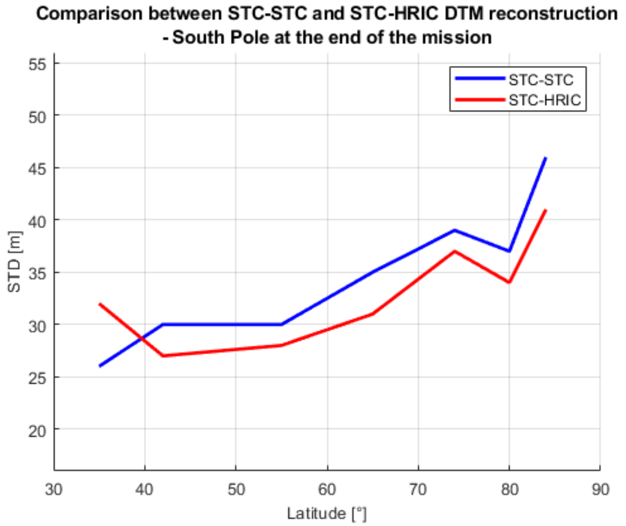


Intersection angle of STC in function of the latitude


Comparison between STC-STC and STC-HRIC DTM reconstruction - North Pole at the beginning of the mission
STC-STC
STC-HRIC
STD [m]
Latitude [°]


Comparison between STC-STC and STC-HRIC DTM reconstruction - North Pole at the end of the mission
STC-STC
STC-HRIC
STD [m]
Latitude [°]


Comparison between STC-STC and STC-HRIC DTM reconstruction - South Pole at the beginning of the mission
STC-STC
STC-HRIC
STD [m]
Latitude [°]


Comparison between STC-STC and STC-HRIC DTM reconstruction - South Pole at the end of the mission
STC-STC
STC-HRIC
STD [m]
Latitude [°]

Error budget

- **Satellite position error:** the position of the satellite respect to the Mercury center
- **Satellite attitude error:** the angular separation achievable with the attitude control system between the desired configuration of the spacecraft and the actual one
- **Camera attitude error:** the direction of the boresight of the camera respect to the frame satellite
- **Image correlation error:** related to the elaboration of images

- **Satellite position error:** constant**,** 10 m
- **Satellite attitude error:**
- **Camera attitude error:**

} Depend on the thermo-elastic deformations

- **Image correlation error:** 1 pixel

Periherm, beginning of the mission = 22 m
Apoherm, beginning of the mission = 45 m

High resolution DTM applications

- **Libration:** perceived oscillating motion of orbiting bodies relative to each other
  Calculate a model capable of describing the libration phenomenon on Mercury
  → Calculate the shifting of markers on the surface
  → 3D model made by HRIC can give better information about the position of the markers

- **BELA calibration and co-registration:** BELA is the laser altimeter onboard BepiColombo and needs a high resolution DTM for the calibration
  → necessary to use HRIC DTMs
  → comparison between the BELA and SIMBIO-SYS DTMs

Thank you for the attention

Questions?