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ABSTRACT

BepiColombo is the first ambitious, multi-spacecraft mission of ESA/JAXA to Mercury. It will be launched in October 2018 from Kourou, French Guiana, starting a 7-year journey, which will bring its modules to the innermost planet of the solar system.

The Stereo Camera (STC) is part of the SIMBIO-SYS instrument, the Italian suite for imaging in visible and near infrared which is mounted on the BepiColombo European module, i.e. the Mercury Planetary Orbiter (MPO). STC represents the first push-frame stereo camera on board of an ESA satellite and its main objective is the global three-dimensional reconstruction of the Mercury surface.

The harsh environment around Mercury and the new stereo acquisition concept adopted for STC pushed our team to conceive a new design for the camera and to carry out specific calibration activities to validate its photogrammetric performance. Two divergent optical channels converging the collected light onto a unique optical head, consisting in an off-axis telescope, will provide images of the surface with an on-ground resolution at perihelion of 58 m and a vertical precision of 80 m.

The observation strategies and operation procedures have been designed to optimize the data-volume and guarantee the global mapping considering the MPO orbit.

Multiple calibrations have been performed on-ground and they will be repeated during the mission to improve the instrument performance: the dark side of the planet will be exploited for dark calibrations while stellar fields will be acquired to perform geometrical and radiometric calibrations.

Keywords: Photogrammetry, Stereo, Mercury

1. INTRODUCTION

BepiColombo is an Interdisciplinary Cornerstone Mission to the planet Mercury, realized as a collaboration between the European, ESA, and the Japanese, JAXA, space agencies. The mission, which owes its name to the space engineer and mathematician Giuseppe Colombo, is part of the Horizon 2000+ (Cosmic Vision) Program and will investigate the magnetosphere, internal structure, environment and surface of the planet.

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1.1 The BepiColombo Mission

The BepiColombo spacecraft (S/C) consists of two scientific orbiters, the Mercury Planetary Orbiter (MPO) from ESA and the Mercury Magnetospheric Orbiter (MMO) from JAXA, which are dedicated to the detailed study of the Mercury planet and of its magnetosphere. Together with the Mercury Transfer Module (MTM), which houses the electric and chemical propulsion systems for the transfer to Mercury, and the MMO Sunshield and Interface structure (MOSIF), which protects the MMO from Sun illumination until its deployment at Mercury, they form the Mercury Composite Spacecraft (MCS).

The launch of the MCS is planned on 18 October 2018 on an Ariane 5 launcher from Kourou. The transfer to Mercury is achieved using a combination of eight planetary swing-bys: the first on Earth, two of Venus and five around Mercury to decelerate and reach the nominal orbit. Solar electric and chemical propulsion are used for the interplanetary cruise, and for initial apogee raising and Mercury orbit injection, respectively.

Reached the target, in December 2025, the MPO and the MMO will separate and they will start their scientific investigations.

1.2 SIMBIO-SYS

Half of the data volume of the MPO is dedicated to the imaging system SIMBIO-SYS (Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem) [1] that will provide images and spectra in the visible and near infrared bands.

Three are the channels of SIMBIO-SYS (see Figure 1): a High Resolution Imaging Channel (HRIC) [2], a Visible and near Infrared Hyperspectral Imager (VIHI) [3] **Błąd! Nie można odnaleźć źródła odwołania.**, with imaging and spectroscopic capabilities in the range 400-2000 nm, and STC Stereo Imaging Channel [4], STC will provide the global mapping of all the planet surface in the panchromatic band (600-800 nm) and color images of specific regions in 4 selected wavelength bands in the range 420 and 920 nm.

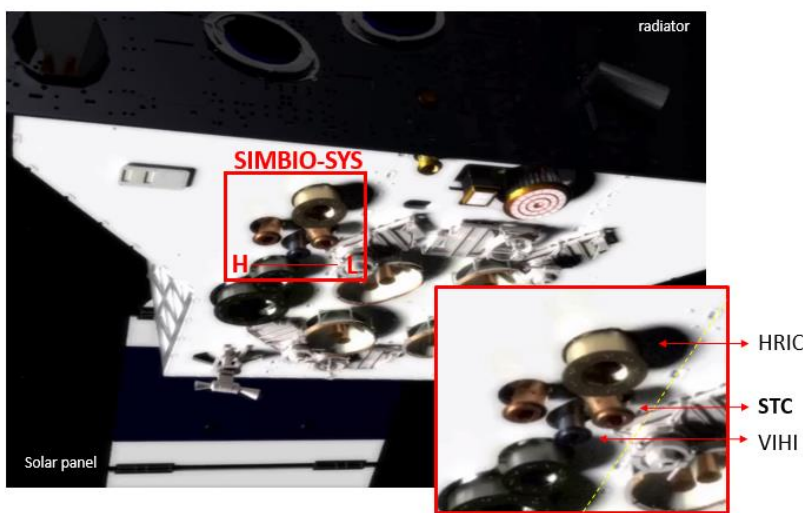


Figure 1 SIMBIO-SYS mounted on the MPO S/C. The three channel HRIC, STC and VIHI are shown in the inset (bottom-right) image. The red line connecting the two STC baffles, indicated with the letters L (Low) and H (high), identifies the along track direction.

Four are the planned phases of the BepiColombo mission:

- The Near Earth Commissioning Phase, right after the launch sequence when SIMBIO-SYS functionalities will be checked.
- The Cruise Phase. During this journey phase the SIMBIO-SYS instrument will be covered by the other S/C modules and only dark checks can be conducted. These performance checks will be done every 6 months to monitor the ageing of the instrument detector, to assess variations of instrument performances with respect to on-ground calibrations.

- Mercury Commissioning Phase. Just before starting the scientific operations, the SIMBIO-SYS full functionality and performance will be checked.
- Mercury Routine Phase, when SIMBIO-SYS will operate nominally for scientific observations and some regular calibration activities will be done.

1.3 The MPO Orbit

The Mercury Planetary Orbiter (MPO) spacecraft attitude is three-axis stabilized and nadir pointing. The foreseen orbit is polar, with the orbital plane perpendicular to the equator, and inertial, with the perihelion opposite to the Sun when Mercury is at perihelion (see Figure 2).

At the beginning of the mission, the perihelion and apohelion altitudes, with respect to the planet surface, will be respectively 480 km and 1500 km; the spacecraft altitude will reach 495 km at the equator at the ascending node, 782 km over the north pole, 1474 km above the equator at the descending node and finally 1058 km over the South pole.

Throughout the mission, the orbit perihelion will change in terms of latitude, longitude and altitude in the Mercury reference system. Its initial latitude is 16°N , then it will move the south pole reaching less than 40°S at the end of the mission. The height of the S/C from the surface will change during the mission bringing perihelion from a distance of 480 to 250 km and apohelion from 1500 to 1730 km. The semi-major axis of the orbit is 3430 km.

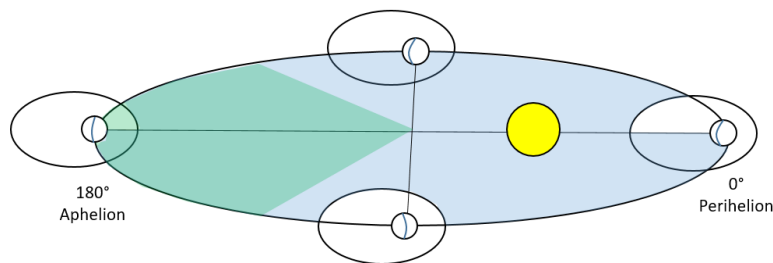


Figure 2. A simplified scheme of Mercury orbit and the schematic representation of the MPO orbit around Mercury.

The data acquired near the aphelion (see the green area in Figure 2) will be the most important ones for the imaging systems and in particular for STC. In this arc of the Mercury orbit, the observation conditions for MPO are optimal, at perihelion the surface is illuminated by the Sun with phase angle in the range 0° - 60° . On the opposite near perihelion, the Mercury hemisphere with the best spatial resolution will be in eclipse.

2. STC- STEREO CHANNEL

2.1 The STC instrument

STC represents the first push frame stereo camera of ESA. Based on a new concept, STC integrates the compactness of a single detector telescope with the photogrammetric capabilities of a two direction camera.

Two separate incoming optical paths $\pm 20^{\circ}$ oriented with respect to nadir allow the instrument to acquire images of the same surface region with a different viewing angle in two different moments, taking advantage of the along track movement of the S/C.

Historically different solutions have been proposed for stereo cameras in planetary missions. The most common solution was the use of push-broom linear array telescope such as Lunar Reconnaissance Orbiter Camera (LROC) [5] or NASA instruments CTX [6] and HiRISE [7]. These telescopes acquire stereo images in different orbits. The idea of acquiring the stereo couple during the same orbit using multiple optical paths along two or more directions was adopted by Chang E1 Stereo Camera [8], Mars Express HRSC [9] and Kaguya TC [10] but they use always the push-broom mode without fully exploiting the information detectable by a bidimensional detector.

A stereo frame device is CaSSIS [11] (ExoMars 2016) which presents a common telescope configuration (oriented 10° respect to nadir) but takes advantage of a rotational unit to acquire images in the backward and forward directions.

STC, providing two different optical sub-channels and a single telescope with a unique detector, represents a new concept of instrument. The same configuration, even if with a more basic optical design, will be adopted by the Luna-Resurs-1 orbiter mission [12].

The STC camera has a focal length of 95.2 mm and is equipped with some filters to acquire images in specific wavelength ranges. STC will provide the global mapping of all the Mercury surface and color images of selected targets. The mapping will allow the generation of a Digital Terrain Model of the entire surface, improving the interpretation of morphological features at different scales and topographic relationships with the aim of defining geological units, large to middle scale tectonic features, impact crater population and, if present, volcanic edifices and lava flows.

2.2 Optical design

STC [13] allows the acquisition of three quasi-continuous surface regions for each sub-channel. These regions correspond to four broadband and two panchromatic filters having specific wavelength bands in the range between 400-940 nm. Filters names, spectral bands, and dimensions and Field of View (FoV) in the along track (AT) and cross track (CT) directions are reported in Table 1. The filters are listed in the order they appear on the detector from top to bottom (see Figure 4).

Table 1. STC filters definition and main parameters.

Name	Spectral Band	Filter size on detector	FoV (CT×AT)	Boresight AT	Boresight CT	Mean IT [ms]	Max IT [ms]
920	920 ± 20 nm	64×896 pxls	0.38°×5.38°	-17.9660°	-0.0460°	6.5	40.0
550	550 ± 20 nm	64×896 pxls	0.38°×5.38°	-19.2135°	-0.0345°	6.8	40.3
PANL	700 ± 100 nm	384×896 pxls	2.31°×5.38°	-21.3605°	-0.0205°	0.8	5.2
PANH	700 ± 100 nm	384×896 pxls	2.31°×5.38°	21.5740°	-0.0085°	0.8	5.2
420	420 ± 20 nm	64×896 pxls	0.38°×5.38°	19.4275°	-0.0105°	9.4	43.0
750	750 ± 20 nm	64×896 pxls	0.38°×5.38°	18.1810°	-0.0145°	5.3	37.8

Table 1 reports also the mean and maximum integration time predicted by the STC radiometric model [14] and the angular direction of each boresight respect the nadir direction [21]. The AT boresight direction of the panchromatic filters is about ±21° while those of the broad-band (BB) filters are about ±18° and ±19°; thus the panchromatic images refer to on-ground regions that are further from nadir direction with respect to the BB ones.

The STC camera features two sub-channels, named High (H) and Low (L) with respect to the mounting interface on the S/C (yellow dotted line on Figure 1). Some of the optical elements are specific to each sub-channel, but the core optical unit is in common.

The STC optical design is basically composed by two principal units:

- a fore-optics module, one for each sub-channel;
- a common telescope unit.

Each of the fore-optics unit consists in a couple of plane folding mirrors that are able to redirect the light beams coming from the planet (respectively at -20° and +20° for each sub-channel) to the second common unit (see Figure 3).

The common unit is a modified Schmidt telescope with a focal length of 95 mm. A correcting doublet lens replaces the classical Schmidt plate. This design results compact and light with a length reduced by about a factor 2 with respect to the classical Schmidt design.

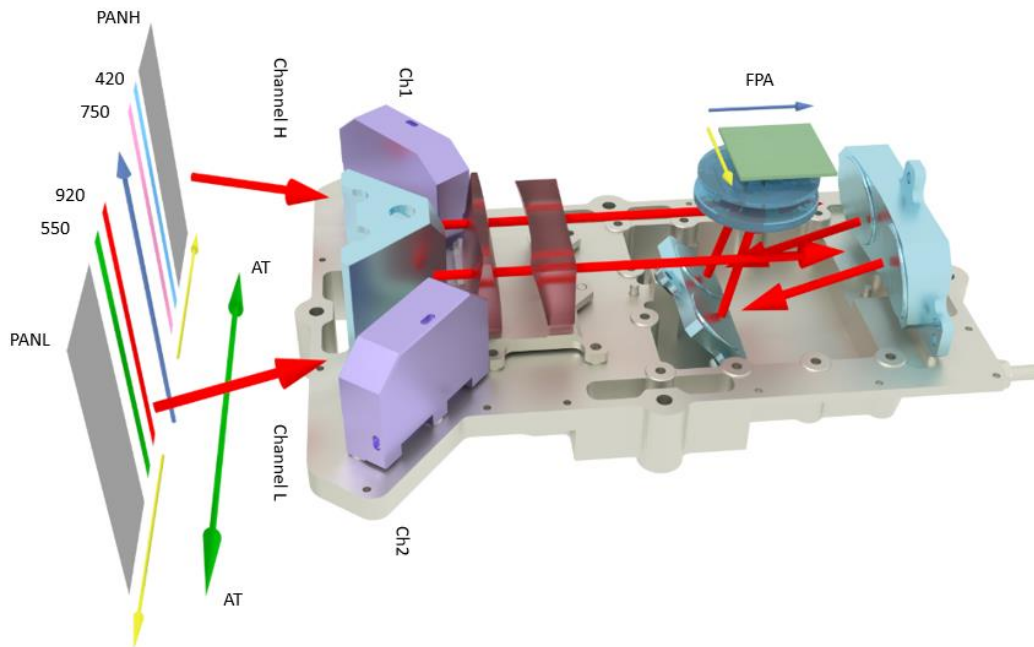


Figure 3. STC schematic optical layout. In green the along-track direction. In red the optical path. On the left side, the figure shows the on ground FoV for all the filter-frames and the projected directions of the detector rows and columns. The versus of the along-track (AT) direction changes 2 times every Mercury year as described in Section 1.3.

The incoming light beams are focused by the spherical mirrors on a 10 μm pixel size SiPIN hybrid CMOS detector (green in Figure 3). Before reaching the detector, the light rays are folded by a plane mirror and pass through a field-correcting doublet and the filter assembly.

The system is an off-axis configuration (both in the AT and CT directions). The absence of central obstruction and support structures (i.e. spiders) allows to obtain an optical MTF of the order of 0.65-0.69 and a PSF of 1.36/1.45 pxls (including detector sampling).

The main instrument parameters are reported in Table 2.

Table 2. Main optical and digital parameters of STC.

Optical concept	off-axis modified Schmidt, unobstructed	Optical MTF	0.65-0.69
Strategy	Stereo-push frame	PSF (FWHM)	1.36/1.45 pxls (including detector sampling)
Maximum FoV (Cross Track)	5.38°	Pupil size	15 mm \varnothing
IFoV	21.7°	Detector type	SiPIN CMOS
Mean focal length	95.2 mm	Pixel size	10 μm
Focal ratio	F/6.3	Dynamic range	14 bit
Optical distortion	<0.3%		

2.3 Focal Plane Assembly

Due to its orbit in close proximity to the Sun, the BepiColombo payload will work in a harsh environment characterized by a high radiation dose. Thus, thanks to its intrinsic radiation hardness, a CMOS has been chosen as detector for STC.

The STC detector allows the snapshot image acquisition with a minimum exposure times around 400 ns and assures a linearity region for the acquisition with the PAN filter to an upper bound of 0.26 ms of integration time considering the present assumed radiometric model of Mercury [14].

For CMOS APS detectors the readout of the charge from each pixel is done by a readout electronics integrated into the pixel itself. Moreover, its capability to direct download only specific pixels of the whole FPA allows to select six specific windows, corresponding to the areas of each filter. The filter windows definition is shown in Figure 4.

This also permits to acquire a small area outside the illuminated part (bottom left part of the detector) called Window X. The Window X will be used as a dark current monitor [15]; its position and dimension are defined to reduce the readout time and the dimensions of the buffer/data storage unit.

Finally, the fast readout allows both to avoid the presence of mechanical shutters, thanks to ITR (Integrate Then Read) strategy, and to achieve the short exposure times that are necessary for Mercury observations.

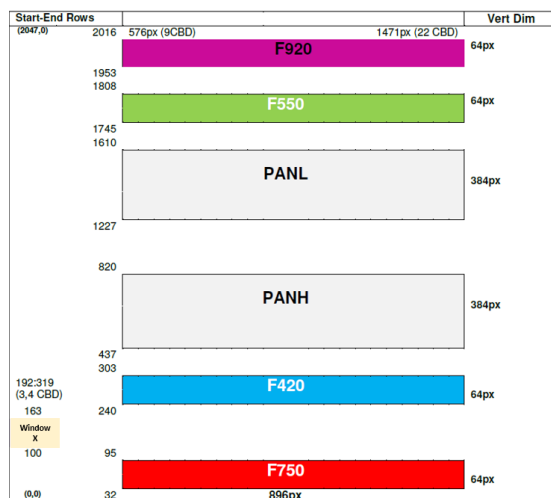


Figure 4. Focal Plane Assembly of STC.

The detector was developed by Raytheon Vision Systems (RVS) that has produced a custom visible sensor based on a 2048 × 2048 format with a 10 μm pitch unit cell [16]. The same device has been selected also for the SIMBIO-SYS HRIC [2] and for the Colour and Stereo Surface Imaging System (CaSSIS) for the ExoMars mission [11].

The sensor was designed to achieve high sensitivity as well as low read out noise (<100 e⁻) for space-based, low light conditions. It also must maintain its performance in a total ionizing dose environment up to 70 kRad (Si) as well as immunity to Single Event Effects, such as latch up and single event upset.

3. STRATEGY

Following nowadays plan, STC will work in the range of Mercury true anomalies between 138° and 222° (i.e. around aphelion). The performance of the instrument will depend on illumination conditions as a compromise between the high SNR at aphelion and the better incidence angle configuration at bounds orbits where grazing illumination will rescue most performant and contrasted images.

During its mission STC will change its swath and pixel on ground. A summary of the on ground parameters for the panchromatic acquisitions is reported on Table 3.

Table 3 Main on ground parameters for the first aphelion MPO orbit around Mercury. The periherm case is considered with a sub-nadir point of lat. 16° N latitude while the south pole case is considered with a sub-nadir point of lat. 83° S latitude.

		Periherm	Poles
S/C Height	[km]	480	966.7

Pixel On-ground	[m]	58	121.8
Swath CT	[km]	48.3	100.96
	[°]	1.19	7.9
Swath AT	[km]	23.3	52.5
	[°]	0.55	1.2

The on ground pixel size for the other filters can be considered equal to the panchromatic one. Figure 5 reports the on ground pixel size for all the STC filters; the minimum value is reached at periherm, when the subnadir point is at 16°N of latitude. It has to be considered that the decreasing of the periherm altitude during the mission will improve the instrument performance.

The STC ability to generate high-resolution Digital Elevation Models with a spatial resolution of 58 m at the equator and 121 m at the poles, will provide the possibility to understand both the global morphological framework of Mercury, as well as specific geological processes that occurred or are still occurring on its surface.

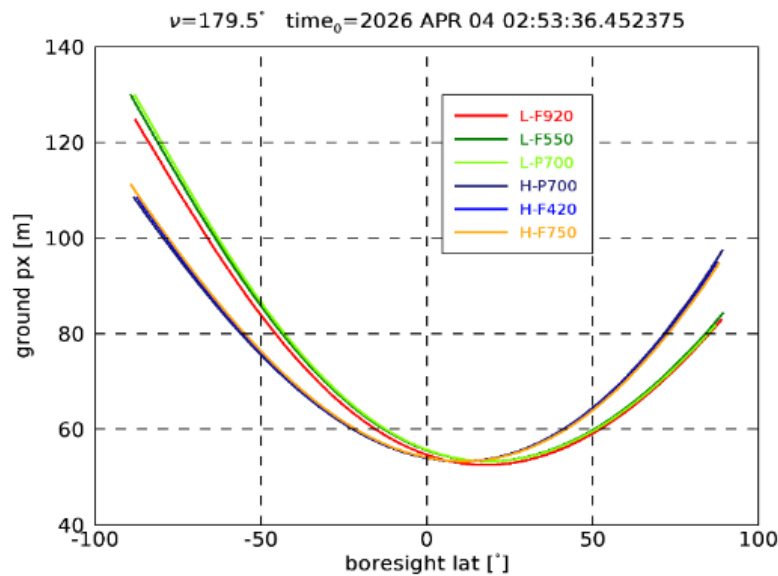


Figure 5 STC along track on ground px size calculated for all the filters and as a function of the boresight latitude at the indicated orbit.

Three possible operative sub-modes are foreseen during the mission: i) Stereo Mapping ii) Color Mapping iii) Target Stereo Mapping (see Figure 6).

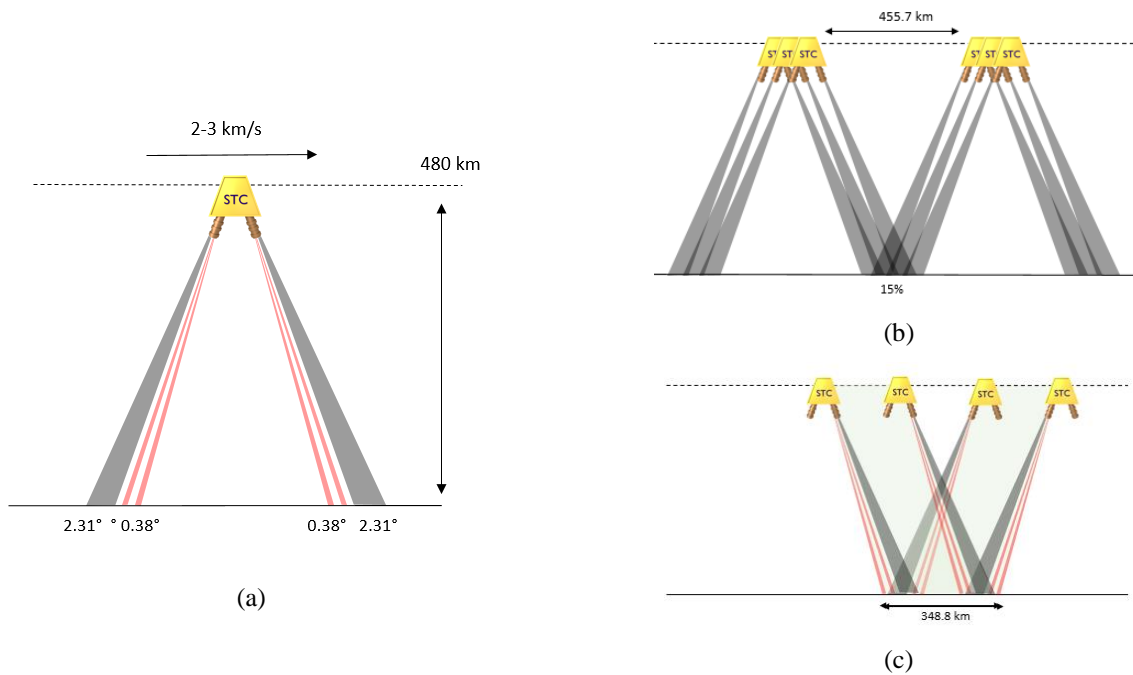


Figure 6 Principal acquisition strategies of STC. In (a) the nominal on ground FoV with external Panchromatic filters and internal BB filters. In (b) a schematic representation of the Stereo Mapping operative sub mode adopted for Global Mapping. In (c) a schematic representation of the Color Mode or Target Stereo Mapping.

3.1 Stereo Mapping

During the first operative sub-mode (which will be used for half the nominal mission for the so called Global Mapping phased) the STC will work continuously (see Figure 6b), to cover with both panchromatic filters the whole surface of the planet.

L and H sub-channels will be acquired simultaneously until reaching a latitude limit (83°N at first orbit) in which one of the sub-channel will start to acquire images on the dark side. After this limit (both on south and north pole) only one of the sub-channels will be acquired.

Considering the first perihelion and the angle with respect to the nadir direction, the baseline of the stereo acquisition block will be 455.7 km providing a vertical accuracy of 80 m assuming a conservative 1 pixel accuracy in image matching.

In this phase STC will acquire images with a compression factor of 7 (bit rate of 2 bit/px). During each orbit, STC will cover a meridian arc and the polar stabilized orbit will guarantee to STC the possibility to take advantage of the rotation of the planet to acquire images of all the surface.

For each MPO orbit (2.3 h), Mercury rotates CT by 0.595° which corresponds to 25.3 km; thus a minimum field-of-view of 3.6° is required to obtain two successive camera swaths with no gaps at the equator. Since STC has a maximal FoV of 5.38° , the whole planet surface will be covered without gaps.

Orbit geometric definition has an impact on the three principal acquisition parameters (defined as depicted in Section 10 in the Flight Operation Procedures): i) Cross Track windows dimensions ii) Integration times iii) Repetition time.

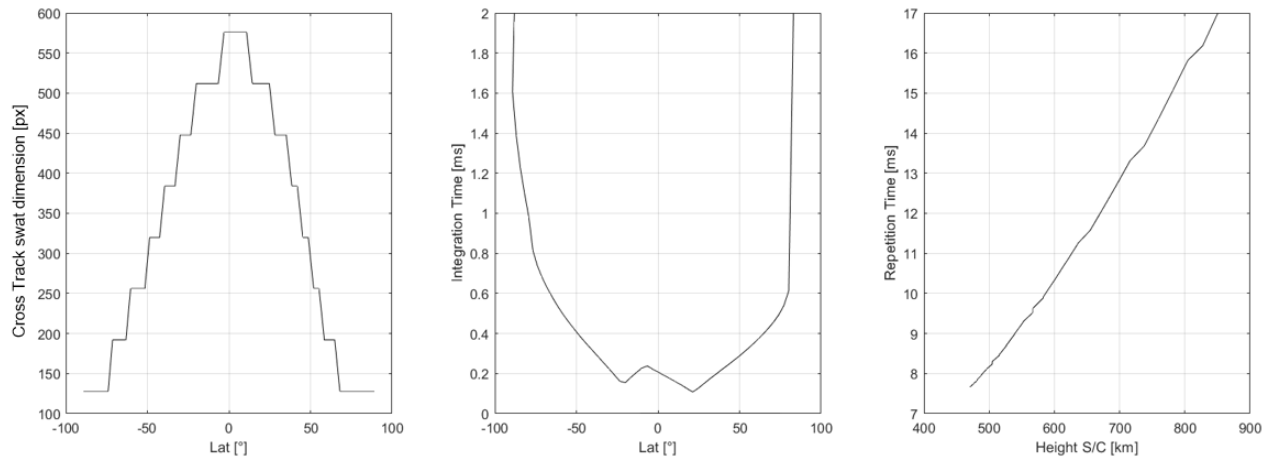


Figure 7 Principal parameters of the Stereo Mode at first orbit as function of the first dependence. The Cross Track swath dimension has been represented as function of Latitude and Repetition Time as a function of the S/C height

As shown in Figure 7, the first two parameters are more dependent on latitude than the acquisition; the Repetition Time is instead more dependent on S/C height.

In particular, cross track windows dimension defines the on ground cross track swath that, if maintained at maximal value will bring to a total overlap at poles. For this reason, the STC orbit is divided in segments with a Cross Track window dimension increasing toward poles and decreasing toward perihelion.

The Integration Times (IT) that maximizes the SNR is different for the two sub-channels because of the different phase condition. The synchronous acquisition of the two sub-channels forces to acquire with the same ITs which is defined on the dynamical range of sub-channel L or H in dependence on the framed hemisphere.

The SNR, whose difference between the two sub-channels is on average around 10% and reaches the maximum value (50%) near the perihelion at the aphelion, results always greater than 160 and can reach 245 as maximal value.

Considering the reflectance model of the instrument and the gain of the detector, no smearing will affect the panchromatic observations.

Unlike the other two formal parameters, RT is more dependent on S/C altitude than latitude. It is defined to maintain the overlapping along track at 10% and, as the other parameters, will be different for each sub-section of the orbit arc between 7.5 s (at perihelion) and 15 s.

3.2 Color Mapping

The color mapping will provide target-oriented acquisitions of multiband images with the four broadband filters. To limit the loss of data volume, STC will acquire images with a channel at the time, maintaining the overlapping between two consecutive acquisitions between 10% and 15%. The images (corrected for phase angle) will provide mosaicked multiband cubes for clustering or spectrophotometric analysis.

This operational mode will limit the image size to 348.8 km along track.

As for Stereo Mapping mode, also Color Mapping operations will be defined by latitude and height. In this case the limited FoV of the filters will reduce the RTs to a range 0.5-4 s.

Color Mapping will utilize 42.6 Gbit (considering a compression factor of 3.75) of Data Volume covering 15% of the Mercury surface.

For the entire mission, the SNR of most of all the broad band filters apart from the F420 (more sensible) spans from about 100 (near poles) to 165 (near the equatorial plane).

3.3 Target Stereo Mapping

Once STC will finish the global mapping of the planet, detailed target oriented stereo mode could be used. In this strategy mode STC will obtain on selected targets a stereo reconstruction, and hence a DTM, with a higher accuracy than during the global mapping.

For the detailed stereo mapping, we will be working on small targets in a mode similar to Color Mapping (see Figure 6c) but acquiring the Panchromatic filters with different acquisition parameters .

This strategy is in definition and it will be adopted only for limited target or if more data volume will be available at mission level.

4. ON BOARD SOFTWARE AND CONTROL SYSTEMS

4.1 Compression

The compression algorithm 0 that is used in the Main Electronics (ME) of SIMBIO-SYS remote sensing suite (including STC) allows to obtain the bit packing, reversible (lossless) and irreversible (lossy) compressions. The algorithm adopts a wavelet approach and is controlled by the parameter IBR, defined as 16 times the bit-rate, that can assume the values from 0 to 63.

In the nominal mission, the observation strategy foresees an IBR=32 for Global Mapping phase and IBR=63 for Color Mode corresponding respectively to a Bit Rate of 2 and 3.9375 bit/px.

The higher compression factor for GM phase was justified during the calibration on ground by analyzing the effect of the compression algorithm on the actual images STC. An IBR=32 guarantees a degradation on the DTMs reconstruction limited to the 7% independently on illumination condition [17].

4.2 Temperature

The orbit environment foresees no temperature variation during a MPO orbit. On the other side Mercury orbit will impact on temperature environment with a variation (considering uncertainties) of 6% (18°) on the instrument interface with the MPO between aphelion (TA=180°) and the bound limits of the operation orbits range of STC (TA≈135°).

A TEC (ThermoElectric Cooler) will maintain the sensor temperature limited, allowing the best performance of the instrument by limiting the thermic exponential dependency of the dark by this parameters.

Two are the main sensors which will monitor the thermal internal ambient of the camera: TFPA1 and TChannel-Bw; the first is mounted on the Focal Plane Assembly (FPA), the latter on the backside of the Low Channel folding mirror to measure the STC optical bench temperature. Nominal safe temperature range are considered 268±60 K for the FPA, and 284±21 K for the Optical Bench. An additional sensor is mounted on the Proximity Electronic (temperature range 281.5±21.5 K). As explained in Section 0 specific Flight Operation Procedures are defined to manage and react safety to the temperature changes.

4.3 Operations

During all operative phases the SIMBIO-SYS instrument will be commanded through proper sequence of commands which are sent to the spacecraft (S/C) using Flight Operation Procedures (FOPs). These can be grouped into 4 distinct types depending on the application context:

- Flight Control Procedure (FCP): to be used for the scientific usage of the channel
- ENGINEERING procedure (ENG): to be used for SW update, memory check and HK management
- CRITICAL Procedure (CRP): to be used for safety command the instrument
- TeST procedure (TST): to be used during the commissioning phases

If ENG, CRP and TST represent particular complex timeline, FCP represents the base language of the telemetry. Most of the important parameters that can be defined in timelines are commanded in the Flight Operation Procedures (FOPs), part of the FCPs. The most important ones have been described in Table 4.

Table 4 Main parameters for the science acquisition which can be defined in FOPs.

FOPs parameters		
Name	Description	Limits
Nacq	number of acquisitions	Nacq < 65535
Nw	number of windows	0 < Nw < 7
Wc	windows coordinates	filters depending
CT	cross track window dimension	CT > 128, multiple of CBD
CBD	compression box dim.	64×64 or 64×128
IT	integration time	(400 ns < IT < 10s)
IBR	inverse bit rate	0/1 lossless, 1 < IBR < 64 lossy
RT	repetition time	RT > 150 ms
Priority	number of high priority acquisitions	P < 255

Each acquisition can be defined by the Integration Time, adopted by ITR method, and the Repetition Time (RT) defined to guarantee the overlapping between the acquisition for surface acquisition. STC can operate defining the number of consecutive acquisitions or in continuous mode; until a following TM would be reached by ME. The continuous mode will be adopted in all of the orbit sub-segments (see Section 3.1) of the global mapping to guarantee the absence of gaps between two sub-segment acquisitions.

IBR and CBD parameters define the compression strategy for each acquisition allowing bit-packing (IBR=0) or lossless (IBR=1) or lossy compression (IBR>1).

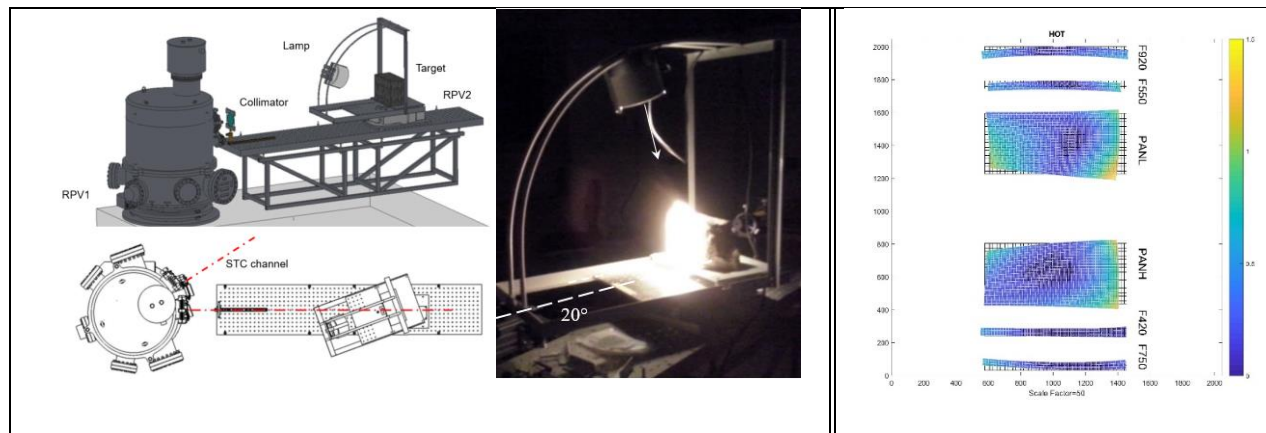
Scientific priority defines the antenna used for data transmission (X-Band or Ka-Band) and how the S/C manages the science data: standard science is being stored into the S/C solid state memory for later download, while the high priority science is being immediately transmitted to ground together with HK data.

5. CALIBRATION

The on ground calibration campaign has been performed in order to derive the optical, geometric and radiometric calibration of the STC proto-flight-model (PFM).

These calibrations were performed at Leonardo S.p.A facilities, and a dedicated Optical Ground Support Equipment (OGSE) was developed.

Figure 8 (a) shows the calibration setup. On the right side there is the optical bench, including the collimator and the rotation stage with the light source and a rock sample; on the left side there is the thermo-vacuum chamber with one of its channel aligned to the collimator optical axis. The right image was acquired during calibration activities, and shows the simulated illumination condition of the sample with the light in maximal phase angle configuration. In (b) the images show the distortion modelled by RFMs (see section 5.4) on the six frames of STC. The color map refers to the absolute value of the distortion.



(a)

(b)

Figure 8 Some images of the calibration process. In (a) schematics of the lay-out of the SVS (Stereo Validation Setup) and a picture of illuminated target sample. In (b) an example of geometric distortion results.

5.1 Optical parameters

The PSF of the telescope has been measured by means of a dithering technique using a 50 μm diameter pinhole. The pinhole has been moved at subpixel level on a 18×18 grid with step of 0.1 px. The derived PSF calculated for the center of the PAN-L filter is slightly elliptical with FWHM of 1.38 and 1.49 pixels, including diffraction effects.

The measured mean optical MTF is 0.64 (@50 lp/mm). It achieves a minimum value of 0.57 on the 550 nm filter and a maximum value of 0.74 on the 750 nm one. The MTF for the whole instrument, including the detector sampling, can be considered as the product of measured optical MTF and the MTF detector value (assumed to be 0.509).

5.2 Dark calibration

The dark current was measured at 7 different temperatures around the nominal one (268±5 K) covering the ITs between 400 ns and 19.5 s (the longer integration times are foreseen to be used for the stellar calibration). Readout noise (RON) is limited to 70 e⁻ RMS (10 Digital Numbers, DN) for low ITs and reaches 170 e⁻ (25 DN) for the highest one. Fixed Pattern Noise (FPN) is limited to 135 DN for low ITs.

Table 5. Principal characteristics of the dark images. All the parameters are defined, for uniformity, in DN on a dynamic of 14 bit. Principal typical conversion parameters are reported.

Temperature		263K	268K	273K
FPN	(IT<10 ms)	<133.7 DN	<135 DN	<134.42 DN
	(IT>10 ms)	<360 DN	<400 DN	<440 DN
RON	(IT<10 s)	7 DN	10 DN	15 DN
	(IT>10 s)	17 DN	23 DN	25 DN
Operability		99.63%	99.70%	99.88%
Conversion Factor		21 μV/e ⁻ typical		
Saturation Charge Capacity		<100.000 e ⁻		
Average Inverse Gain		7e ⁻ /DN		

5.3 Radiometric Calibration

The radiometric calibration allows to derive the image in physical quantities starting from the raw images in DN. For this, a Labsphere ISS-2000-C integrating sphere (IS) with four halogen lamps, one of which equipped with a shutter, has been

used. Using the IS, it is possible to derive the relation between the signal in digital number (DN) detected by the CMOS and the signal in physical units. Figure 9 shows the radiance function obtained for the central px of each detector filter. The relation has been obtained for each px of the illuminated regions of the CMOS.

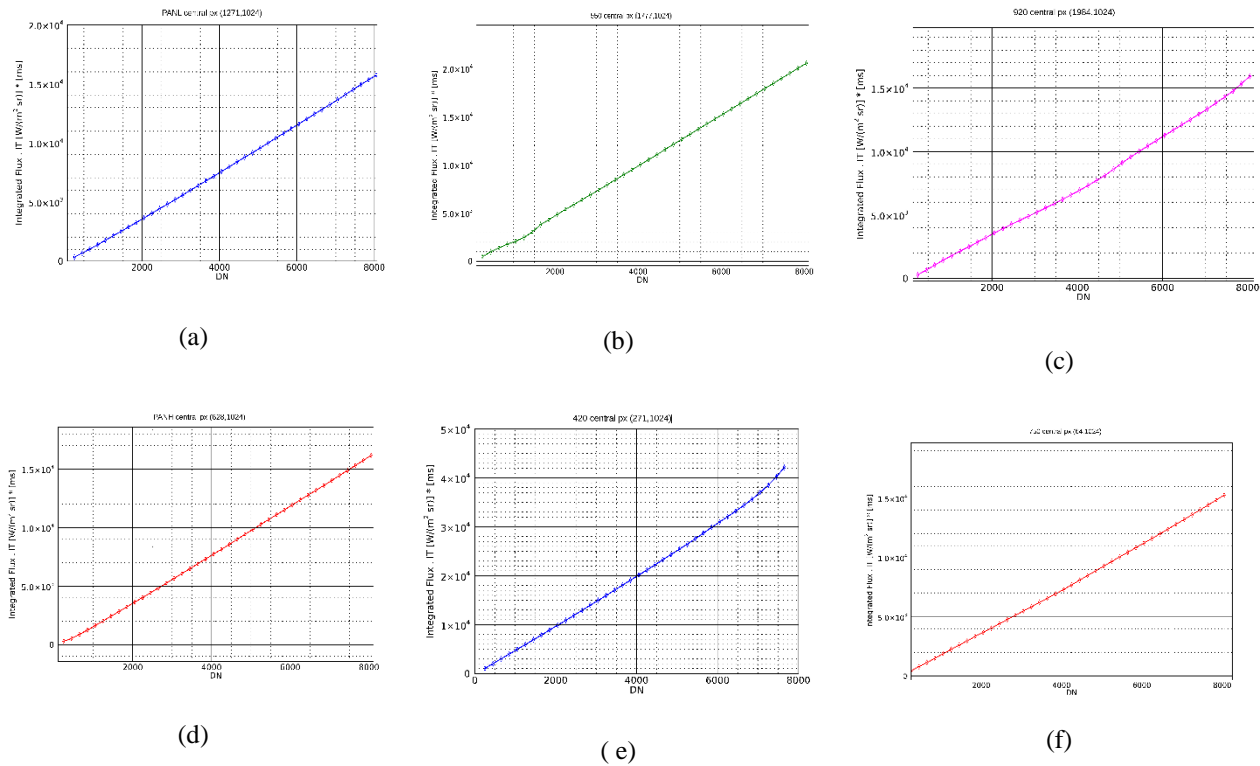


Figure 9. Radiance relation for the central pixel of each filter.

5.4 Distortion

Thanks to the Schmidt design and to the positioning of the aperture stop, the optical distortion contribution is very limited. The maximum value, measured during the geometric calibration phase, is around 0.3% at the field of view boundary [20][21]. Considering the purpose of the instrument and the selected STC off-axis configuration, a distortion map model based on RFM (rational function model) has been developed. In contrast to other existing models, which admit linear estimates, RFM is not referred to specific lens geometry, but it is general enough to model a variety of distortions.

The adopted setup take advantage of a pinhole, a collimator lens with a focal length of 750 mm chromatically corrected over the visible spectral range, a rotating plane folding mirror, which can rotate in 2 direction to cover the field of view of the instrument, a thermal vacuum chamber (TVC) mounted on a rotational stage (to align the OGSE with one or the other sub-channel).

The purpose of the calibration campaigns is to acquire a grid of point source images for each filter to define the main optical parameters, and measure the distortion and the variability of these data with temperature.

RFM was used to define the geometrical distortion of all the STC filters, for different optical bench temperatures (275-295 K). The model guarantees residuals uniformly distributed on the FPA (see Figure 8b as an example) with a mean value of 0.096 px and a standard deviation of 0.06 px (with a repeatability of the setup less than 2 arcsec).

5.5 Validation

STC is based on a new and innovative stereo camera concept, an original optical design, and for the stereo acquisition mode, it is based on the push frame mode. This is the reason why a stereo validation on ground was required to verify the capability of providing stereo pairs and the consequent generation of the Digital Terrain Model (DTM).

The validation process definition engages three principal issues:

- suppling an independent 3D reconstruction of the target to be used as a reference measurement and to be compared with the DTM derived with STC.
- adapting the instrument acquisition to the clean room environment.
- defining the approach to supply two different views of the target surface and, at the same time, providing the measurement of the geometry of the system.

The stereo validation was realized in laboratory with a specific setup [22]. The SVS is a combination of optical and mechanical components that allows the indoor reproduction of the instrument observing conditions: the same object area is imaged first by the H channel and then by the L channel. The indoor simulation of the spacecraft trajectory (for simplicity only the periherm has been considered) is provided by two rotation stages; furthermore a light source is mounted over a curve rail system conceived to rotate together with the target support plate maintaining a constant illumination condition. The support was designed reproducing some of the possible light incidence angles (10°, 30°, 50° and 70°) referring to the possible Sun ray's incidence angles to the Mercury surface when the spacecraft is at periherm.

A series of stereo-pairs of an anorthosite stone sample (good analogue of the hermean surface) and of a modelled piece of concrete, acquired in clean room by means of a STC laboratory model, have been processed in the photogrammetric pipeline using image correlation for the 3D model generation. The stereo reconstruction validation has been performed by comparing the STC DTMs to a high-resolution laser scanning 3D model of the stone samples as reference data. The latter had a much higher precision than the expected in-lab STC DTM (20 µm vs 190 µm). Processing parameters have been variated in order to test their influence on the DTM generation accuracy. The tests suggest that the range of illumination angles (from 50° up to 70°) provides better accuracy and coverage of the 3D products. The obtained RMS error values are all well below the 190 µm, which represents the requirement for STC at the breadboard scale (the best results obtained in the tests are 63 micrometers and the worst 93 micrometers). The same results can be converted at the Mercury scale providing a consistent indication of the estimated accuracy in the determination of the planet topography. The vertical accuracy can be expected to stay between 30 m and 54 m considering a pixel on ground of about 55 m computed at 400 km from the surface (pericentre).

5.6 Inflight Calibration

Different calibration measurements are foreseen during BepiColombo mission. Considering the variability of the environment due to Mercury and MPO orbit, most of the test will be performed periodically during the SIMBIO-SYS life. The in-flight calibrations can be divided in two classes: internal calibrations, that are all the calibrations of single channels realized without any involvement of the S/C; external calibrations, which need the involvement of S/C resources.

For the internal ones:

- Detector performance: it includes dark count rate, cosmic ray damages, readout noise, thermal effects verification, FPN, spurious charge, and all the blind tests that will be performed every 6 months during the cruise phase and at Mercury in specifics orbit taking advantages of the dark side of the planet.
- PSF and radiometric calibrations will be performed on stellar fields. For the Photo Response Non Uniformity measurement, two different strategies are considered: sum of multiple acquisition of Hermean surface images or a quasi-dithering reduction method proposed for LEO satellites [23] provided for hi-variability IR-CCD.

For the external ones:

- Absolute calibration will be performed on stellar fields. Together with the geometric calibration it will be performed in the commissioning phase pointing available calibration standards stars.
- Geometric calibration will be performed on stellar fields. As for the absolute calibration, multiple and periodic calibrations will refine the uncertainty introduced by aging and thermal variation of the optical bench.

The external calibration will also be performed after commissioning. In fact, the instrument thermal conditions will vary during the mission. The contribution due to thermo-elastic effects (temperature transients) corresponds to distortions between the Star TRackers (STRs) line-of-sights and the payload line-of-sight. This forces the mission control to foresee different calibration phases for each orbit (aphelion, perihelion, TA=45.135°) to cross-verify the SIMBIO-SYS imaging channel orientations with respect to the STRs.

6. CONCLUSIONS

In mid-October, the STC of SIMBIO-SYS, on board of BepiColombo, will leave the Earth on an Ariane 5 from Kourou. The journey will return the first Mercury images in late 2025. BepiColombo will endure temperatures in excess of 350°C and gather data during its one year nominal mission, with a possible 1-year extension. The on-ground calibration of the instrument was performed at Leonardo S.p.A. and the team is preparing for the journey and for the definition of the observation strategy. The instrument is ready for launch.

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