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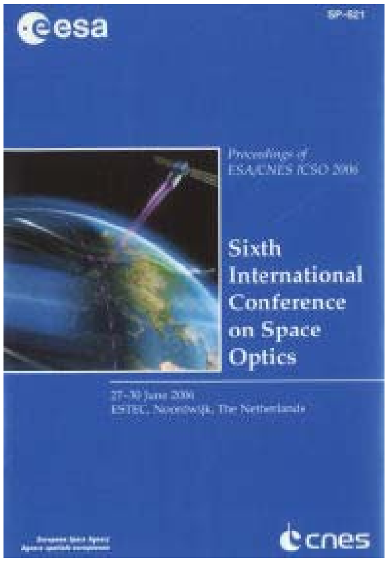

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PRELIMINARY OPTICAL DESIGN OF THE STEREO CHANNEL OF THE IMAGING SYSTEM SIMBIOSYS FOR THE BEPICOLOMBO ESA MISSION

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ABSTRACT

The paper describes the optical design and performance budget of a novel catadioptric instrument chosen as baseline for the Stereo Channel (STC) of the imaging system SIMBIOSYS for the BepiColombo ESA mission to Mercury.

The main scientific objective is the 3D global mapping of the entire surface of Mercury with a scale factor of 50 m per pixel at periherm in four different spectral bands.

The system consists of two twin cameras looking at ±20° from nadir and sharing some components, such as the relay element in front of the detector and the detector itself. The field of view of each channel is 4° x 4° with a scale factor of 23''/pixel. The system guarantees good optical performance with Ensquared Energy of the order of 80% in one pixel.

For the straylight suppression, an intermediate field stop is foreseen, which gives the possibility to design an efficient baffling system.

1. INTRODUCTION

Bepicolombo is a cornerstone mission of the European Space Agency (ESA) with the aim of studying in great detail the innermost of the solar system planet: Mercury.

Mercury is very important from the point of view of testing and constraining the dynamical and compositional theories of planetary system formation.

In fact, being in close proximity to the Sun it has been subjected to a rather peculiar environment, such as large temperature and high diurnal variation, rotational state changed by Sun induced tidal deformation, surface alteration during the cooling phase and chemical surface composition modification by bombardment in early history.

Mercury has been studied only by the Mariner 10 spacecraft (S/C) in 1974-75 [1,2,3], less than a half of the planetary surface has been imaged at low resolution rate (~ 1-2 km/px) and some measurements of the planet magnetic field has been done.

The BepiColombo payload, especially designed to fully characterized the planet, will consists of two modules: a Mercury Planet Orbiter (MPO) carrying remote sensing and radio science experiments, and a Mercury Magnetospheric Orbiter (MMO) [4], carrying field and particle science instrumentation. These two complementary packages will allow to map the entire surface of the planet, to study the geological evolution of the body and its inner structure, i.e. the main MPO task, and to study the magnetosphere and its relation with the surface, the exosphere and the interplanetary medium, i.e. MMO primary aim.

To achieve the mission objectives, the orbits of the two modules are rather different: MMO will be put in a highly elliptical polar orbit with periherm and apoherm altitudes of 400 and 12000 km, respectively; MPO will be in a slightly elliptical polar one with periherm and apoherm altitudes of 400 km and 1500 km and 2.3 hours orbital period.

The MPO orbital characteristics are determined both by the need to image the whole surface of Mercury at high resolution (~ 100 m/px) during the one year mission lifetime, and by the extremely challenging thermal constraints on the S/C. For a continuous observation of the planet surface during the mission, the S/C is 3-axis stabilized with the Z-axis, corresponding to payload boresight direction, pointing in the nadir direction.

The launch of the mission is foreseen in August 2013, and the S/C will reach Mercury in August 2019, after some Earth, Venus and Mercury gravity assists.

1.1 SIMBIOSYS

The MPO module is carrying instruments which are devoted to the close range study of Mercury surface, to the investigation of the planet gravity field and to fundamental science and magnetometry. Imaging and spectral analysis are performed in the IR, visible and UV range. These optical observations are complemented by those of gamma-ray, X-ray and neutron spectrometers, which yield additional data about the elemental composition of the surface, and by

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those of a laser altimeter, BELA [5], dedicated to high accuracy measurements of the surface figure, morphology and topography.

The imaging and spectroscopic capability of the MPO modulus will be exploited by the Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem (SIMBIOSYS), that is an integrated system for imaging and spectroscopic investigation of the Mercury surface. A highly integrated concept is adopted to maximize the scientific return while minimizing resources requirements, primarily mass and power [6].

SIMBIOSYS incorporates capabilities to perform 50-200 m spatial resolution global mapping in both stereo mode and colour imaging filters, high spatial resolution imaging (5 m/px scale factor at periherm) in panchromatic and broad-band filters, and imaging spectroscopy in the spectral range 400-2000 nm. This global performance is reached using three channels: STC [7], the STereoscopic imaging Channel; HRIC, the High Resolution Imaging Channel [8]; and VIHI, the Visible and near-Infrared Hyperspectral Imager [9].

2. THE STEREOSCOPIC IMAGING CHANNEL (STC)

STC is a double wide angle camera designed to image each portion of the Mercury surface from two different perspectives, providing colour and panchromatic stereo image pairs required for reconstructing the Digital Terrain Model (DTM) of the planet surface (see Fig. 1).

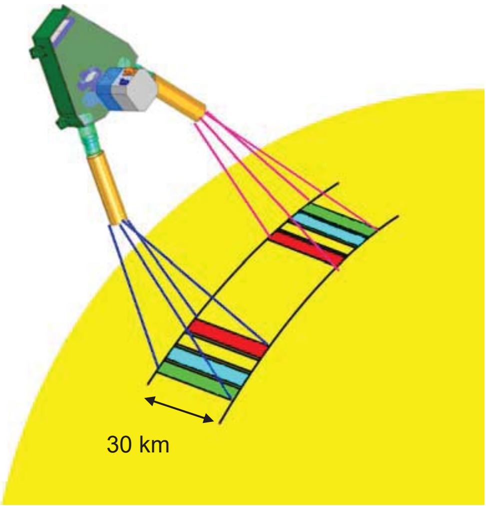

Fig. 1 STC concept.

2.1 STC scientific requirement

The main scientific requirement for the STC is to provide the global color coverage of the surface with a mean scale of 110 m/px (minimum of 50 m/pixel at the equator), with the aim of studying surface composition and defining the main geological units, large scale tectonic features, impact crater population and, if present, volcanic edifices. The STC stereo channel will be a useful tool to define with high detail the topography, which is a critical measurement for tectonic features characterization, geological units lateral boundaries definition and for measuring important geophysical parameters. The STC will also provide the context for the HRIC investigation.

A stereo imaging system has to satisfy a series of scientific requirements linked not only to common optical performance definition, but also to the additional constraints imposed by photogrammetric tasks.

The overall camera requirements are reported in Tab. 1. The scale and the swath at periherm have been defined to map the whole Mercury surface during the mission lifetime. For reaching high DTM accuracy in elevation measurement, 80 m vertical accuracy, a rather classical solution [10,11], with the two channels looking at +20° and –20° from nadir, has been chosen. Optical performance required are expressed in terms of Ensquared Energy (EE) inside one pixel of the detector or alternatively as Modulation Transfer Function (MTF) at the detector Nyquist frequency. The selected wavelength coverage guarantees the possibility to study surface composition, in one panchromatic and three colour filter wavelength bands.

Tab. 1 STC scientific requirements.

Scale factor	50 m/px at periherm
Swath	30 km at periherm
Stereoscopic properties	±20° stereo angle wrt nadir direction both images on only one detector
Vertical accuracy	80 m
EE MTF	> 70% inside 1 px > 60% at Nyquist frequency
Wavelength coverage	540-890 nm (4 filters)
Filters	panchromatic (700 ± 100 nm) 550 ± 10 nm 700 ± 10 nm 880 ± 10 nm

2.2 STC optical design

The design of the camera has been driven not only by the just described scientific requirements but also by the aim of saving mass and power. In this attempt an optical solution with common detector and some optical elements has been studied for the two channels. The design has been kept as short as possible, compatibly with the need of having an intermediate focus position to cope with straylight problems due to the common path choice.

The desired 50 m/px scale factor at periherm is reached with a 90 mm system effective focal length, considering the choice of a 10 microns pixel size CMOS APS as detector. This kind of detector is particularly useful both in terms of radiation hardness, given the hostile Mercury environment, and for the capability of snapshot image acquisition, which is less demanding in terms of S/C pointing and stability.

Each channel consists of an achromatic 'air-spaced' doublet, giving an intermediate focus, coupled to a relay system that brings the image on the detector via a folding mirror (see Fig. 2). The doublet and the folding mirror are specific for each channel, the rest of the optical train is instead common to both channels.

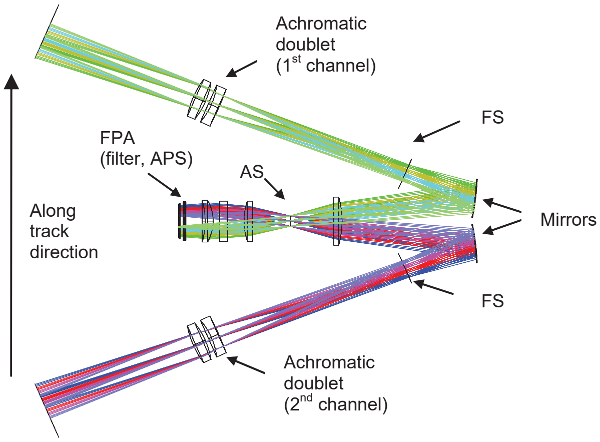

Fig. 2 STC overall optical design layout.

At the intermediate focus, a Field Stop (FS) is foreseen; the FS has been suitably sized to let only the light rays coming from the useful FoV to impinge and enter the system. Additionally, given the clear separation between the optical path of the two channels, an *ad hoc* baffling system is foreseen and will be studied in detail in the next future.

The global FoV of each channel is 4° x 4°, subdivided in 4 strips, one for each filter, covering four quasi-contiguous strip on Mercury surface (see Fig. 1); at periherm, each strip corresponds to an area of about 30 x 5 km^2.

Simulation and optimization of the camera design has been done by means of the raytracing software Zemax.

The design has been chosen to satisfy the desired optical performance for all the filters in the whole FoV of each filter. Being the wavelength range rather extended, the on-axis and lateral chromatic aberrations tend to be the worst offenders in the optimization of the system. Unfortunately the choice of the glasses are restricted to rad-hard glasses, due to the hazardous environment in which the S/C will be operating, and, more specifically, to the rad-hard glasses the optics manufacturer has available in house. So only BK7G19, LAK9G15, SF6G05 and fused silica have been considered.

The Aperture Stop (AS) position, approximately in the middle of the relay system, has been chosen to allow a good aberration balancing over all the FoV; in this way the AS is also common to both channels.

The whole design has been conceived to be light weight and as simple as possible from a manufacturing and assembling point of view. The overall length has been kept as short as possible and the smallest number of optical elements has been used; only pure spherical surface are used, except a slightly cylindrical lens necessary to reduce the chromatic aberration at the edges of the FoV.

To avoid mechanical movable parts, the filter concept is to use four different filtering strips deposited contiguously (side by side) on the same substrate. This window will be placed in the converging light beam near the APS detector. To avoid wavelength shifting due to non orthogonal incidence of the beam on the filter itself, the camera design has been envisaged to be as telecentric as possible.

The complete system consists of two identical cameras placed in the "along track" plane (see Fig. 2). The forward and the backward channels are nominally oriented at +20° and –20°, respectively (actually the optical axes of the two achromatic doublets are ±24° from nadir, and the system is working off-axis). The stereoscopic angle for the different filters will be different depending on the off- axis field portion used; the stereoscopic angle varies from 18° to 21.6°.

The optical characteristics of the camera are summarized in Tab. 2.

Tab. 2 STC optical characteristics.

Optical concept	telecentric catadioptric design; air spaced doublet objective plus a relay; off-axis FoV
Stereo solution (concept)	2 identical optical channels; detector and some optical elements common to both channels
Focal length on-axis	90 mm
Pupil size (diameter)	15 mm
Focal ratio	*f*/6
Mean image scale	23.5"/px (114 µrad/px)
FoV (cross track)	4°
FoV (along track)	0.7° (per each filter)
Detector	APS (2048 x 2048 squared pixel; 10 µm size)

2.3 STC performance

The performance of the camera has been calculated for all the filters in all the FoV; spot diagrams and EE have been considered. The EE including diffraction effects is of the order of 80% all over the FoV of each filter (4° x 0.7°); it is slightly smaller at 700 nm, where some chromatic focal shift is present, and at 880 nm, where the diffraction effect starts to be significant.

The spot diagrams and the relative EE for the panchromatic filter are shown respectively in Fig. 3 and Fig. 4. It can be seen that at 600 nm and 800 nm, the spots are well within the overlaid box having the 10 µm x 10 µm pixel size of the foreseen APS detector; the spots are slightly larger than that for the central 700 nm wavelength.

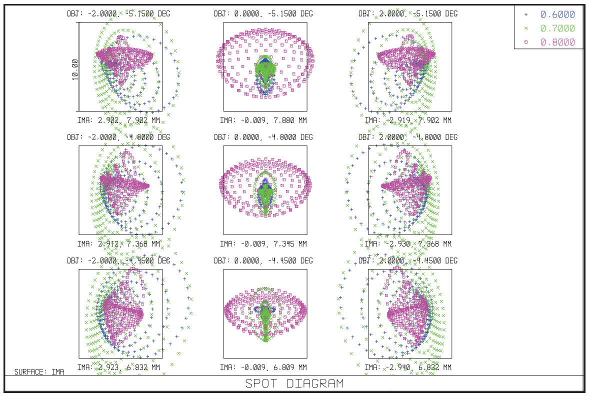

Fig. 3 Spot diagram for the panchromatic filter. Spot at the center, corners and edges of the FoV are shown for minimum (600 nm), center (700 nm) and maximum (800 nm) wavelength in filter band.

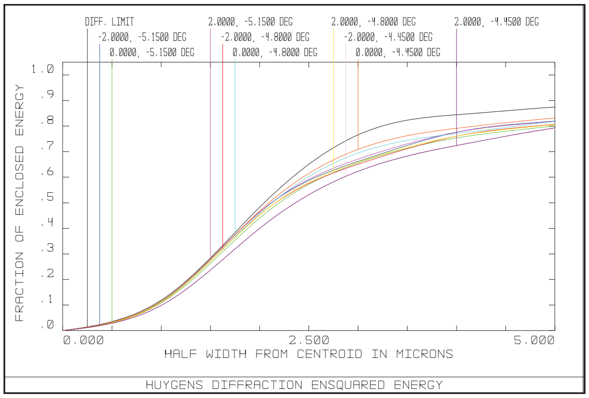

Fig. 4 EE for the panchromatic filter. Different lines correspond to different points in the FoV (center, edges, corners). The values are a mean over the wavelength band of the filter.

The mean diffraction EE has been calculated over all the FoV of each filter and over the wavelength band of the filter itself. As an example the correspondent EE for the panchromatic filter is reported in Fig. 4. As clearly visible, the mean EE is of the order of 80% or more all over the FoV.

Also the MTF of the optical system has been derived for all the filters in the whole FoV. The mean MTF, at the Nyquist frequency of 50 cycle/mm, is of the order of 60-70%. The mean MTF for the panchromatic filter is shown in Fig. 5.

Considering that a reasonable value for the detector MTF is 50-60%, the global MTF of the system, including detector sampling, is of the order of 30 %.

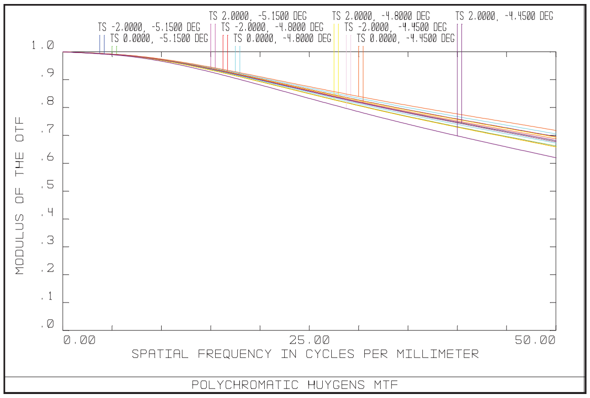

Fig. 5 MTF for the panchromatic filter. Different lines correspond to different points in the FoV (center, edges, corners). The values are a mean over the wavelength band of the filter.

A preliminary analysis of the camera distortion has been done, because of the off-axis design the distortion is mainly anamorphic (i.e. the system has two different focal lengths in the sagittal and tangential planes). As an example, in Fig. 6 this distortion effect is shown for the panchromatic filter: to clearly see the deformation pattern, the differences between predicted (underlying grid) and real ('x') positions of the chief rays have been multiplied by a factor of two; for the considered FoV of the filter (4° x 0.7°) corresponding to about 6 mm x 1 mm on the detector, the distortion is about 4.4%. After correcting for the anamorphic contribution, it can be seen that the residual distortion is less than 0.85% per each filter strip.

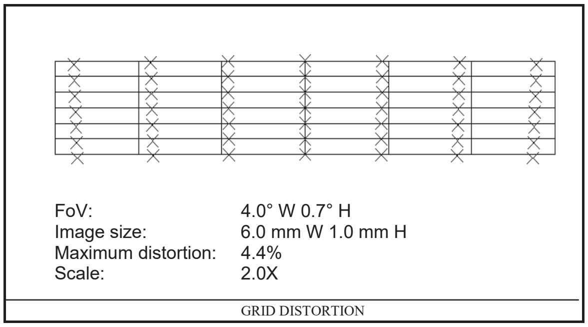

Fig. 6 Grid distortion for the panchromatic filter. Note that real chief ray displacements from theoretical values are multiplied by a factor of two to make the distortion effects clearly visible.

2.4 Exposure time

The choice of the exposure time for the images will be derived not only by the intensity of the scene the system will be looking at, but also by the need to prevent the smearing of the image on the pixel due to S/C motion during the acquisition time. Actually, the acquisition philosophy is that of quasi-pushbroom, or matrix scanner, imaging, in which the composite surface image projected on the detector will be firstly acquired, then buffered and read while the S/C moves; only when the image on the detector has been shifted along track by an amount corresponding to the FoV of each filter, another composite image will be acquired.

Since the S/C velocity at periherm is about 2.2 km/s, this implies that the exposure time has to be less than 5 ms to assure that the image is not smeared, (during 5 ms the surface, imaged on the detector, shifts of about one fifth of a pixel); the repetition time is of the order of 2-5 seconds depending on the position of the S/C during the orbit.

Computation of the expected flux from Mercury surface and of the relative convenient exposure time has been done [12]. Assuming a mean planetary albedo of 0.12 [13], an optics throughput of 0.8, a filter transmission of 0.9, a detector efficiency of 0.44, and an exposure time of 2 ms, the expected flux reaching each pixel is about 4 x 10^4 photons for the colour filters, with a signal to noise ratio of 200, and 4 x 10^5 photons for the panchromatic one. Being the foreseen full well capacity of the detector of the order of 10^5 photo-electrons, to avoid saturation in the panchromatic band, a neutral density filter, with a reduction factor of the order of 90%, has to be considered. If the insertion of a neutral density filter will be proven to be impossible, the integration time for the panchromatic filter has to be opportunely tuned; however for all the filters it will be important to have the capability of tuning the exposure time taking into account the position of the S/C, its altitude from the surface and its position with respect to the Sun.

2.5 Tolerance analysis

In the analysis of an optical design, the tolerance budgeting is of primary importance. The tolerancing of a stereo camera is a challenging task: in fact not only the desired performance has to be reached and maintained separately for each channel, but also the combination of the two channels and their mutual orientations have to be kept as fixed as possible during all the mission lifetime; in addition, all the optical parameters relative to the DTM reconstruction accuracy have to be fully taken into account. Having in mind these considerations, a preliminary assessment of both manufacturing, alignment and stability tolerance has been undertaken.

The philosophy in tolerancing the system follows directly from the clear subdivision of the system in a objective plus mirror unit, different for each channel, and a relay unit, which is common to the two optical paths (see Fig. 2). Moreover it can be noticed that the system is nominally symmetric, with respect to the nadir pointing direction. This implies that possible asymmetries in the actual system can only arise by asymmetries in the realization/mounting of the two achromatic doublets on one side and of the relay unit lenses on the other. Given that optical shop machines usually work spherical surface in symmetric way, the primary reasons for possible asymmetries in the system will be a different realization of the two objective lenses and/or a different relative mounting of the objectives, and a not-axial mount of the relay unit components.

For what concerns manufacturing and alignment tolerances, the two objective plus mirror units and the relay system unit have to be toleranced separately with the aim of compensating the error/misalignment of the each part only by adjusting internal parameters. The compensation for the first units is accomplished quite well: in fact, possible defocusing can be easily compensated by changing distances at the FS level, where there is the intermediate focus, and residual tilts and decenterings by a simple re-orientation of the folding mirror. For what concerns the relay unit, we have verified that it is extremely tolerant, and that standard manufacturing and alignment allow the system to reach the desired level of performance.

Summarizing the preliminary obtained results, the most critical *manufacturing* tolerances for the radius of curvature of the lenses and mirrors are ±0.05 mm, corresponding to 0.1-0.2% in the case of the achromatic doublet; the others are much more relaxed, of the order of 1-2%. For what concerns the *alignment* tolerances, we have verified that the required allowable motions of the various elements for aberration compensation are of the order of ±0.2 mm for decentering and ±0.2° for tilt. For the *stability* tolerances, the analysis has shown that the relay part is so stable that deformations changing the curvature radius of about 0.2% and causing a shift or expansion of the element of ±0.1 mm are totally acceptable. On the other hand, tolerances on the first achromatic doublets are really stringent: only 0.05% variation on curvature radius and 10-20 μm shift of the single optical element are allowed. Factors affecting boresight direction have also been preliminary analyzed, showing some criticality: optical element shifts of the order of 10 μm or tilt of about 20” would lead to half of a pixel variation in pointing direction of each channel.

3. CONCLUSIONS

The characteristics and foreseen performance of the Stereoscopic Imaging Channel (STC) for the BepiColombo mission have been presented. The adopted solution, two channels sharing some optical elements and the detector, is innovative for a planetary stereo camera, considering that classical stereoscopic designs typically consist of two completely independent twin cameras oriented at the desired stereo angle.

The optical design of each channel is a slightly off-axis solution, composed by six lenses plus a folding and focusing mirror; all the surfaces are spherical except one cylindrical. In designing the STC, only rad-hard glasses have been used, combined in a suitable way to compensate for chromatic aberration in the range 540-890 nm all over the camera FoV of about 4° x 4°. This FoV is subdivided in four strips (0.7° each), each one with its proper wavelength selection.

The optical performance of the camera assures that it will meet the required scientific constraint. Moreover, a preliminary tolerance analysis has shown that manufacturing and alignment tolerances are rather relaxed, while stability tolerances are more stringent. In particular, the most critical elements are the two achromatic doublets and the folding mirrors, which are those most exposed to thermal flux coming from Mercury surface and indirectly from the Sun. So, an accurate thermal model analysis is needed to fully assess the camera behavior in Mercury environment.

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