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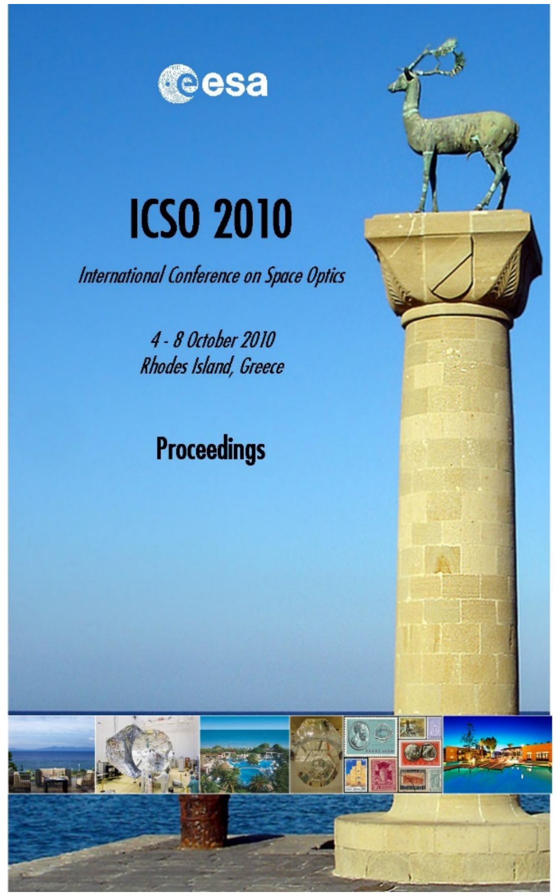

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OPTICAL DESIGN PERFORMANCE OF THE STEREO CHANNEL FOR SIMBIOSYS ONBOARD THE BEPICOLOMBO ESA MISSION

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ABSTRACT

In this paper the adopted optical design solution for the Stereo Channel of the imaging system SIMBIOSYS for the BepiColombo ESA mission to Mercury is presented.

The optical design of the camera together with its performance, expressed in terms of optical quality, tolerance and stray-light analysis, are fully described.

The main scientific camera objective is the tridimensional global mapping of the entire surface of Mercury with a scale factor of 50 m per pixel at periherm. Five different spectral bands are foreseen, a panchromatic and four intermediate bands, in the range between 410 and 930 nm.

The Stereo Channel consists of two sub-channels looking at ±20° from nadir direction, which share the detector and most of the optical components. The field of view of each channel is 4.8° × 5.3° with a scale factor of 22"/pixel.

The chosen modified Schmidt configuration guarantees an optimal aberration balancing over all the field of view and all the wavelength range; in addition the technical solution chosen for the filter manufacturing, i.e. single substrate with stripe-butted filters, allows to further optimize chromatic aberration.

For stray-light suppression, an efficient baffling system, able to well separate the two optical paths over the common optical elements, has been designed and an appropriate 'filter masking' has been foreseen to cope with ghosts and cross talk between adjacent filter stripes.

The tolerance analysis shows that manufacturing, alignment and stability tolerances are rather relaxed. Thus concluding, the analysis of the global optical performance of the camera assures that the scientific requirements are optimally fulfilled.

I. INTRODUCTION

BepiColombo is the fifth cornerstone mission of the European Space Agency (ESA) foreseen to be launched in August 2014 with the aim of studying in great detail Mercury, the innermost planet of the Solar System.

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, in its history it has been subjected to the most extreme environmental conditions, such as high temperature and large diurnal variation, rotational state changes due to Sun induced tidal deformation, surface alteration during the cooling phase, and chemical surface composition modification by bombardment in early history.

Mercury has been studied by the Mariner 10 spacecraft (S/C) in 1974-75 [1]-[3], when less than half of the planetary surface has been imaged at low resolution (scale factor of about 1-2 km/px) and its magnetic field and exosphere have been discovered. Since then, the only other satellite reaching Mercury is the NASA Messenger, that has very recently realized three flybys with the planet [4]; Messenger will be inserted in orbit around Mercury in March 2011.

The BepiColombo payload, especially designed to fully characterize the planet, will consist of two modules: the Mercury Planet Orbiter (MPO), realized in Europe, carrying remote sensing and radio science experiments, and the Mercury Magnetospheric Orbiter (MMO) [5], realized by JAXA in Japan, 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 tasks, and to study the magnetosphere and its relation with the surface, the exosphere and the interplanetary medium, i.e. MMO targets.

The MPO orbital characteristics, i.e. elliptical polar orbit with periherm and apoherm altitudes of 400 km and 1500 km respectively, and 2.3 hours orbital period, are mainly determined by the need for the remote sensing instruments to have high spatial resolution not changing too much all over the surface during the one year nominal mission lifetime, and are extremely challenging due to the 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 to nadir.

A. 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 those of a laser altimeter, BELA [6], 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), an integrated system for imaging and spectroscopic investigation of the Mercury surface [7]. A highly integrated concept is adopted to maximize the scientific return while minimizing resources requirements, primarily mass and power.

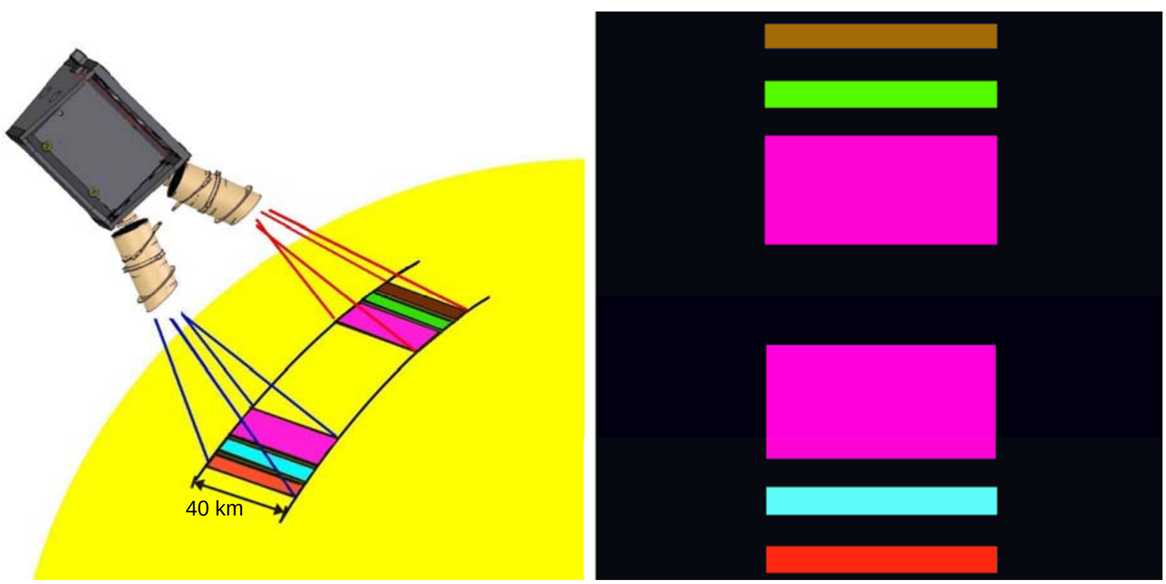
SIMBIOSYS incorporates capabilities to perform 50 - 200 m spatial resolution global mapping in both stereo mode and color imaging, high spatial resolution imaging (5 m/px scale factor at periherm) in panchromatic and broad-band filters, and imaging spectroscopy in the 400 - 2200 nm spectral range. This global performance is reached using three independent channels: the STereoscopic imaging Channel, STC [8]; the High Resolution Imaging Channel, HRIC [8]; and the Visible and near-Infrared Hyperspectral Imager, VIHI [10].

In this paper the final optical design for the STC and its theoretical performance are presented. The optical design of STC has been frozen in October 2009; the structural and thermal model (STM) is now experiencing environmental tests and will be delivered to ESA in September 2010. The Flight Model (FM) is going to be built and tested during next months and will be delivered to ESA in January 2012.

The adopted catadioptric design is original, optimally aberration balanced and able to satisfy all the scientific and technical requirements imposed by that particular space mission.

II. STC OPTICAL DESIGN

STC is a double wide angle camera designed to image each portion of the Mercury surface from two different perspectives, providing panchromatic stereo image pairs required for reconstructing the Digital Terrain Model (DTM) of the planet surface. In addition, it has the capability of imaging some portion of the planet in four different spectral bands (see Fig. 1)



(a) **(b)**

Fig. 1. In (a) STC Stereo concept. In (b) position and size of useful filter strips images on the detector area (in black). Note that not illuminated gaps are present between each filter image.

A. STC Stereo Design Concept

The proposed stereo design is composed of two "sub-channels" looking at the desired stereo angles, that share the majority of the optical elements and the detector (see Fig. 2). With respect to classical two- or single-camera designs, this solution allows to reach good stereo performance with general compactness, saving of mass, volume and power resources.

In general, in the space missions in which the satellite has a polar orbit around the observed planet, stereo cameras adopt a push-broom acquisition mode: the detector is a linear array and the full bidimensional image is reconstructed placing side by side each of the lines successively acquired at a suitable rate determined by the spacecraft velocity. For STC, instead, a push-frame mode has been chosen, in this case the detector is a CMOS Active Pixel Sensor (APS) bidimensional array, so actual 2D images of the planet surface are acquired, then buffered and read while the spacecraft moves. Only when the image on the detector has shifted along track by an amount corresponding to the FoV of each filter, another image is acquired.

The selected APS device has the snapshot option, that is substantially an electronic shutter; for this reason, no mechanical shutter has been foreseen for this instrument. The push-frame acquisition method allows to have some overlap of the imaged regions in the along-track direction, increasing the image matching accuracy and taking into account possible small drifts of the satellite pointing.

B. Optical layout

The first proposed optical design for the stereo camera dated back to 2002; since then the configuration has changed many times to adapt to the evolution of the scientific and technical requirements [8],[11],[12]. The philosophy followed in the design definition has been that of having a compact layout in which the images of the two sub-channels were formed on the same detector.

The STC optical solution (see Fig. 2) chosen to be flown on the BepiColombo mission is an original design, which can be thought to be composed by two independent elements: a fore-optics, consisting of two folding mirrors per each channel, and a common telescope unit, which is an off-axis portion of a modified Schmidt design.

The scientific requirements and characteristics of the design are summarized respectively in Tab. 1(a) and Tab. 1(b). The main characteristics of the optical system can be described following the optical path shown in Fig. 2. First, the couple of folding mirrors redirects the ±20° (with respect to nadir) incoming beam chief rays to much smaller ±3.75° ones. Then, a doublet, with an essentially null optical power, corrects the residual aberrations of the primary mirror. It has been positioned about half distance between the spherical mirror M1 and its center of curvature, replacing the classical Schmidt correcting plate (placed in the curvature center), and thus reducing the length by about a factor two with respect to the classical solution. Given that the doublet optical power is near to zero, the residual chromatic aberration in terms of primary and secondary colors is negligible over the whole 410-930 nm spectral range.

Tab. 1. (a): STC scientific requirements; (b): STC optical characteristics.

(a)

Scale factor	50 m/px at periherm
Swath	40 km at periherm
Stereoscopic properties	±21.4° stereo angle with respect to nadir; both images on the same detector
Vertical accuracy	80 m
EE MTF	> 70% inside 1 pixel > 60% at Nyquist frequency
Wavelength coverage	410-930 nm (5 filters)
Filters	panchromatic (700 ± 100 nm) 420 ± 10 nm 550 ± 10 nm 750 ± 10 nm 920 ± 10 nm

(b)

Optical concept	Catadrioptic: modified Schmidt telescope plus folding mirrors fore-optics
Stereo solution (concept)	2 identical optical channels; detector and most of the optical elements common to both channels
Focal length (on-axis)	95 mm
Pupil size (diameter)	15 mm
Focal ratio	*f*/6.3
Mean image scale	21.7 arcsec/px (105 µrad/px)
FoV (cross track)	5.3°
FoV (along track)	2.4° panchromatic 0.4° color filters
Detector	Si_PIN (format: 2048 × 2048; 10 µm squared pixel); 14 bits dynamic range

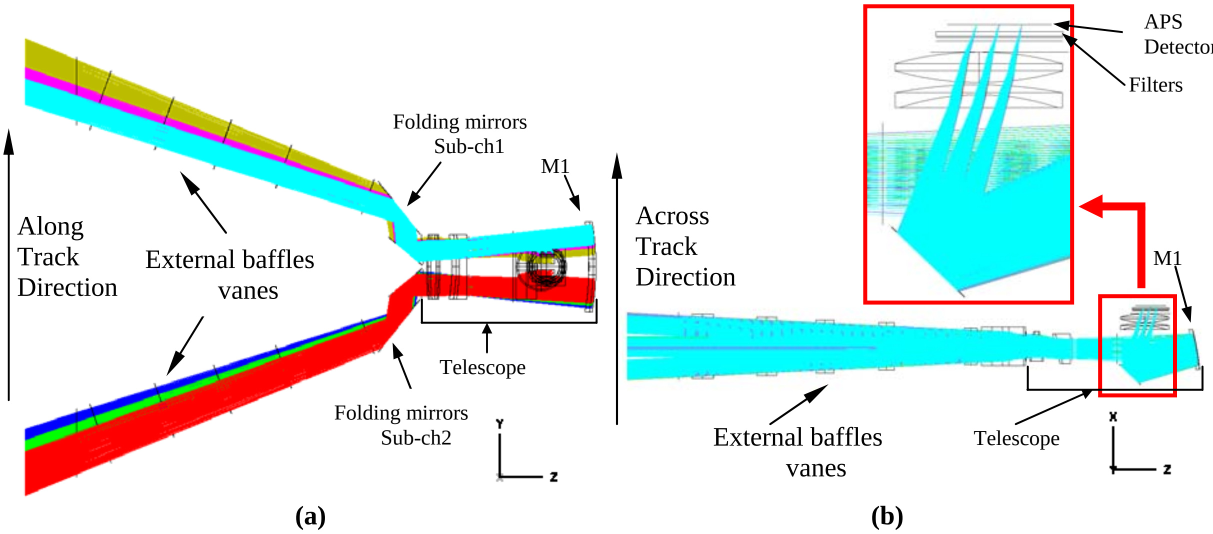


Fig. 2. Final overall STC optical layout. The whole STC optical design is shown: in (a) the configuration is viewed in the plane defined by the along track and nadir directions; in (b) the projection in the orthogonal plane, the one including across track and nadir directions, is given. In the inset, an enlarged view of the focal plane region helps to better follow the rays which are focalized on the APS detector.

The aperture stop position, placed in the front focal plane of the M1 mirror, just after the correcting doublet, has been chosen to allow a good balancing of the aberrations over all the FoV and to guarantee the telecentricity of the design for preventing wavelength shift at the filter strip assembly (FSA). The telescope mirror is off-axis because of the need to have a free back focal length sufficient to easily integrate the Focal Plane Assembly (FPA), maintaining at the same time the required optical performance. To cope with the field dependent aberrations (i.e field curvature, lateral color, ..), a two-lens field corrector has been placed in front of the detector. Finally, to reduce the volume of the instrument, the beam exiting M1 has been folded by a plane mirror (see the inset of Fig. 2(b)) and, for easiness of mounting, the FSA and the detector surfaces are lying in planes parallel to the one including the along track direction and nadir one.

The FSA is mounted just over the detector surface at about 1 mm from it. The FSA is composed by 5 different glass pieces, each with the desired transmission band characteristics, glued together side by side. This solution has the advantage of avoiding the use of cumbersome movable part as a filter wheel; but despite its compactness, it has the drawback that the portions of the filter strips close to the glued edges cannot be used and have to be masked. This masking is anyway useful to cope with the ghosts, both internal and narcissus, which are created by the reflection of the beam inside the filter strip or by multiple reflections on the detector and filter surfaces.

In conclusion, not all the possible FoV is actually recorded, since portions of the incoming beam are blocked and gaps are present between each filtered useful images on the detector (see Fig. 1(b)). Thus for each sub-channel, it is possible to acquire simultaneously three quasi-contiguous areas of Mercury surface in different colors and without using movable elements; however, while the nominal FoV of each sub-channel is 5.3° × 4.8°, including gaps, the scientific useful FoV is actually smaller, i.e. 5.3° × 3.2°, and it is divided in three portions (5.3° × 2.4°, 5.3° × 0.4°, 5.3° × 0.4°). At periherm, each panchromatic strip corresponds to an area of about 40 × 19 km^2 on the Mercury surface and each colored strip to an area of about 40 × 3 km^2.

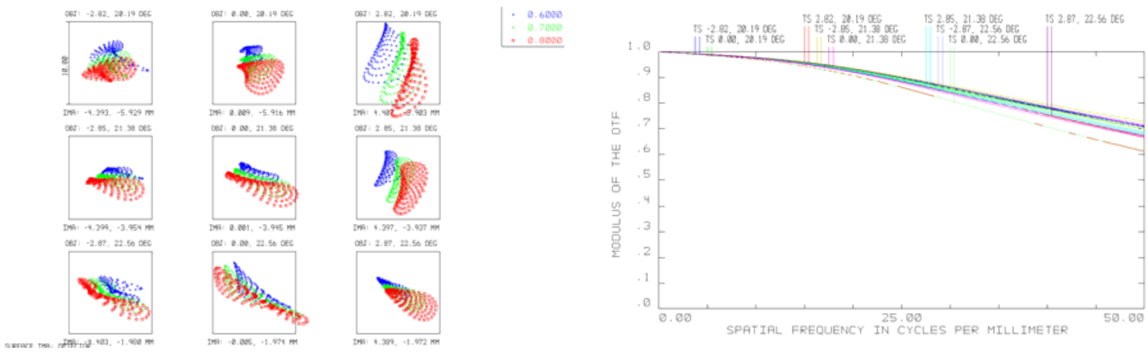
Considering that the two sub-channels are projecting their images side by side on the same plane, the useful area on the system focal plane has a rectangular shape, which would obviously be optimally coupled with a rectangular sensor array. However, due to programmatic reasons, a squared 2048 × 2048 pixel array had to be adopted, so that large part of the detector will not be used. In Fig. 1(b) the filter strip image positions on the 2k × 2k detector are schematically represented. The selected detector is a hybrid APS Si_PIN device: this type of detector has been preferred to the more classical CCD because of its radiation hardness, a very critical point given the hostile Mercury environment. Moreover, as already mentioned, its capability of snapshot image acquisition allows both to avoid the use of a mechanical shutter, and to easily obtain the millisecond exposure times that are necessary to avoid possible image smearing due to the relative motion of the S/C with respect to Mercury surface.

The optical paths of the two sub-channels are well separated; to avoid any interference between the beams, each sub-channel has its own aperture stop, thus obtaining a system with two independent side by side cameras with common optical elements. This solution has the advantage of avoiding the need for an intermediate focus for crosstalk prevention: in fact the stray-light level can be optimally controlled through an ad hoc external baffling system and, since the two sub-channels are kept well apart, by inserting internal separating vanes.

C. Optical performance

Simulation and camera design optimization have been done by means of Zemax ray-tracing software, trying to satisfy the desired optical performance for all the filters over each corresponding FoV and taking care to better optimize the optical performance in the panchromatic band. In addition to having a single detector common to the two sub-channels, the main drivers of the design have been the use of spherical optics only, for easiness of realization, and of using fused silica only as rad-hard glass, for easiness of procurement. Notwithstanding these extremely critical constraints, an optical configuration which allows to satisfy all the optical requirements has been obtained.

The mean diffraction ensquared energy (EE) has been calculated over all the FoV of each filter, and over the wavelength bands of the filters themselves. The EE including diffraction effects is of the order of 80% all over the FoV of each filter, with the exception of the filter centered at 420 nm where it is just below 80% because of some chromatic focal shift. As an example of the quality of the STC optical performance, the spot diagrams for the panchromatic filter are depicted in Fig. 3(a). It can be seen that the spots are well within the overlaid box having the 10 μm square size of the foreseen detector pixel; a small lateral color residual is present in one corner of the field, but it has been verified to be less than a tolerable value of one third of a pixel.



(a) (b)

Fig. 3. STC optical performance: (a) spot diagrams; (b) MTF for the panchromatic filter.

Also the MTF of the optical system has been derived for all the filters over the whole FoV. The mean MTF, at the Nyquist frequency of 50 cycles/mm, is of the order of 60-70%. As an example, the mean MTF for the panchromatic filter is shown in Fig. 3(b). 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 30-40 %.

In the analysis of this optical design, the study of the tolerances budgeting has also been performed. 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 sub-channel, but also the combination of the two sub-channels and their mutual orientations have to be kept as fixed as possible during all the mission lifetime. Having in mind these considerations, an assessment of both manufacturing, alignment and stability tolerances has been undertaken. This will provide an idea about the amount of work necessary to align the system and at the same time about the sensitivity and stiffness of the optical bench over which the optics have to be mounted. The criteria assumed in this analysis are that the image spot should not degrade by more than 30% its rms radius and that it should not be displaced more than half of a pixel.

The preliminary tolerance analysis results show that the achievable standard manufacturing tolerances of the optical shops for lenses and mirrors, (0.1-0.2% on curvature radius, 1 arcmin on surface parallelism, 10^{-3} on refractive index, ..), can be easily compensated by small adjustments during the camera alignment. More critical are instead the tolerances for maintaining the system in-flight performance. Two different subsets of stability tolerances have been considered: the short term tolerances, which have to be satisfied during the interval time needed for the acquisition of two stereoscopic image pair, and the long term ones, that have to be maintained during the whole mission. The former are relative to simple displacements of the boresight direction for each sub-channel, which are very sensitive to displacements and rotations of the spherical M1 mirror and to the rotations of the folding mirrors; the latter implies a degradation of the optical quality, which depends primarily on M1 movements and deformations, since almost all the power of the instrument is on that mirror.

Actually, the time interval between two stereo acquisitions of the same area is less than two minutes at the periherm (where most of the images will be acquired), so the mechanical design has to guarantee 2-3 μm mirror stability during this time interval, and alignment stability through the mission of the order of tens of microns.

III. CONCLUSIONS

The characteristics and foreseen performance of the Stereoscopic imaging Channel for the BepiColombo mission have been presented. The adopted solution, two sub-channels sharing most of the 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 layout is composed by a fore-optics, one for each sub-channel, followed by a common telescope, which is an off-axis portion of a modified Schmidt design. The telescope is composed by four lenses, two quasi-afocal doublets, plus two mirrors, a focusing and a folding one. All the surfaces of the optical elements are simple spherical or planar surfaces and only the fused silica rad-hard glass has been used.

The aberrations are well compensated all-over the camera FoV of about $5° \times 5°$ and in the wavelength range between 410 nm and 930 nm, where all the five spectral bands, a panchromatic and four broadbands, are foreseen.

Finally, the tolerance analysis has shown that manufacturing, alignment and stability tolerances are rather relaxed. Thus concluding, the analysis of the global optical performance of the camera assures that it will meet the required scientific constraint.

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