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PRELIMINARY RESULTS OF THE OPTICAL CALIBRATION FOR THE STEREO CAMERA STC ONBOARD THE BEPICOLOMBO MISSION

V. Da Deppo[1,2], E. Martellato[3,2], E. Simioni[1], D. Borrelli[4], M. Dami[4], G. Aroldi[4], G. Naletto[5,1,2,6], I. Ficai Veltroni[4], G. Cremonese[2]

[1]*CNR-IFN UOS Padova LUXOR, Via Trasea 7, 35131 Padova, Italy tel +39-0499815639, fax +39-049774627, e-mail: vania.dadeppo@ifn.cnr.it*

[2]*INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy*

[3]*Department of Physics and Astronomy 'G. Galilei', University of Padova, Via Marzolo 8, 35131 Padova, Italy*

[4]*SELEX ES, Via A. Einstein 35, 50013 Campi di Bisenzio (FI), Italy*

[5]*Department of Information Engineering, Via Gradenigo 6/B, 35131 Padova, Italy*

[6]*CISAS, Via Venezia 15, 35131 Padova, Italy*

ABSTRACT

BepiColombo is one of the cornerstone missions of the European Space Agency dedicated to the exploration of the planet Mercury and it is expected to be launched in July 2016.

One of the BepiColombo instruments is the STereoscopic imaging Channel (STC), which is a channel of the Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem (SIMBIOSYS) suite: an integrated system for imaging and spectroscopic investigation of the Mercury surface. STC main aim is the 3D global mapping of the entire surface of the planet Mercury during the BepiColombo one year nominal mission.

The STC instrument consists in a novel concept of stereocamera: two identical cameras (sub-channels) looking at ±20° from nadir which share most of the optical components and the detector. Being the detector a 2D matrix, STC is able to adopt the push-frame acquisition technique instead of the much common push-broom one.

The camera has the capability of imaging in five different spectral bands: one panchromatic and four intermediate bands, in the range between 410 and 930 nm.

To avoid mechanisms, the technical solution chosen for the filters is the single substrate stripe-butted filter in which different glass pieces, with different transmission properties, are glued together and positioned just in front of the detector.

The useful field of view (FoV) of each sub-channel, though divided in 3 strips, is about 5.3° x 3.2°. The optical design, a modified Schmidt layout, is able to guarantee that over all the FoV the diffraction Ensquared Energy inside one pixel of the detector is of the order of 70-80%.

To effectively test and calibrate the overall STC channel, an *ad hoc* Optical Ground Support Equipment has been developed. Each of the sub-channels has to be separately calibrated, but also the data of one sub-channel have to be easily correlated with the other one.

In this paper, the experimental results obtained by the analysis of the data acquired during the preliminary on-ground optical calibration campaign on the STC Flight Model will be presented.

This analysis shows a good agreement between the theoretical expected performance and the experimental results.

I. INTRODUCTION

BepiColombo is the fifth cornerstone mission of the European Space Agency (ESA) foreseen to be launched in July 2016 with the aim of studying in great detail Mercury, the innermost planet of the Solar System [1].

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

The BepiColombo payload [2] consists of two modules: the Mercury Planet Orbiter (MPO) [3], realized in Europe, carrying remote sensing and radio science experiments, and the Mercury Magnetospheric Orbiter (MMO) [4], 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 tasks.

The MPO module carries instruments which are devoted to the close range study of the Mercury surface, investigation of the planet gravity field and 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 [5], dedicated to high accuracy measurements of the surface figure, morphology and topography.

The imaging and spectroscopic capability of the MPO module is 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 [6]. 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 stereo mode and color imaging in selected areas, high spatial resolution imaging (5 m/px scale factor at periherm) in panchromatic and broad-band filters, and imaging spectroscopy in the 400 - 2000 nm spectral range. This global performance is respectively reached using three independent channels: the STereoscopic imaging Channel, STC [7]; the High Resolution Imaging Channel, HRIC [8]; and the Visible and near-Infrared Hyperspectral Imager, VIHI [9].

The main scientific objective of STC is the global mapping of the entire surface of Mercury in 3D with a maximum spatial resolution of 50 m per pixel. It will allow to generate the Digital Terrain Model (DTM) of the entire surface in the panchromatic band improving the interpretation of morphological features at different scales and topographic relationships.

In this paper we will describe very briefly the main characteristics of the STC optical design and we will report about the preliminary results obtained by the analysis of the performance of the camera Flight Model (FM).

II. STC OPTICAL DESIGN AND THEORETICAL PERFORMANCE

A. STC stereo concept

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 DTM of the planet surface. In addition, it has the capability of imaging some portions of the planet in four different spectral bands [10].

The selected stereo design is composed of two “sub-channels” looking at the desired stereo angles, which share the majority of the optical elements and the detector. 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, 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. 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.

B. Optical layout

The STC optical solution (see Fig. 1) chosen for 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. 1. 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.

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). 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. 1(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.

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

In conclusion, since portions of the incoming beam are blocked and gaps are present between each filtered useful images on the detector, the entire FoV is not actually recorded. For each sub-channel 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.

The selected detector is a 2k x 2k hybrid APS Si_PIN device: this type of detector was preferred to the more classical CCD because of its radiation hardness, a very critical point given the hostile Mercury environment. Moreover 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 the Mercury surface.

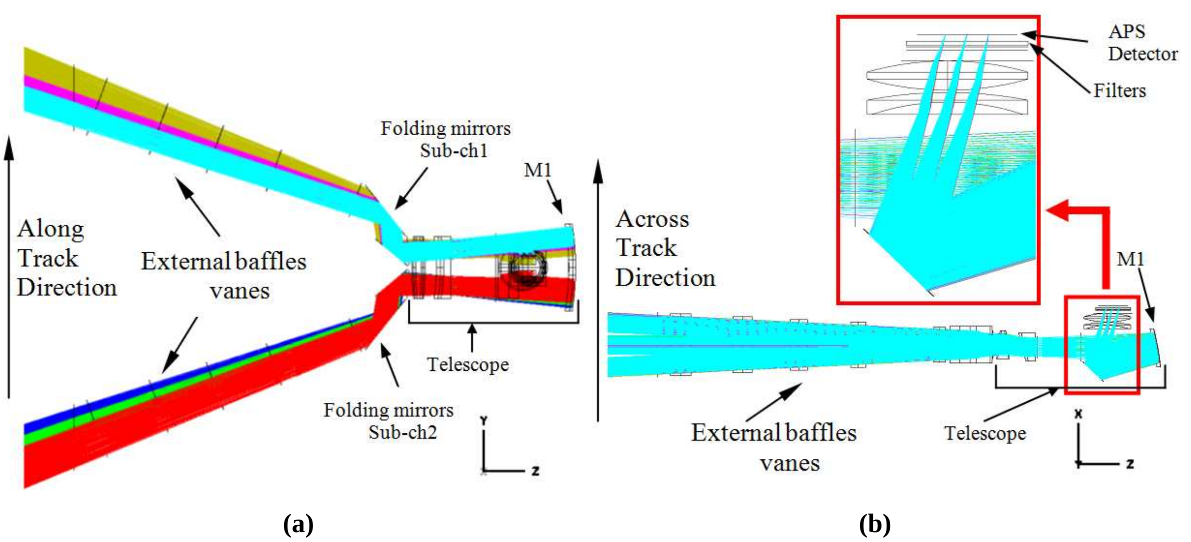
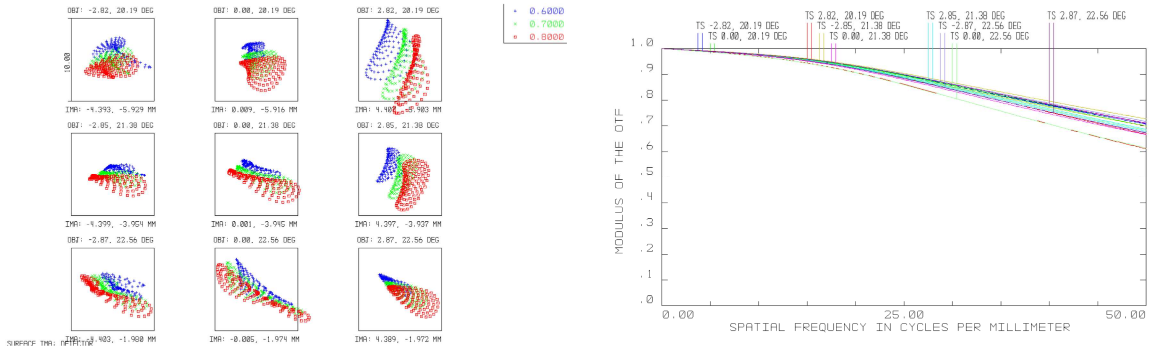


Fig. 1. Final overall STC optical layout. In (a) the configuration is viewed in the plane defined by the along track and nadir directions; in (b) the projection in the orthogonal plane, the one including across track and nadir directions, is given. In the inset, an enlarged view of the focal plane region helps to better follow the rays which are focalized on the APS detector.



(a) **(b)**

Fig. 2. STC optical performance: (a) spot diagrams; (b) MTF for the panchromatic filter.

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.

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, calculated 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. 2(a). This shows that the spots are completely enclosed within a 10 µm square box, which represents the detector pixel size. A small lateral color residual, less than one third of a pixel, is present in one corner of the field.

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. 2(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 tolerance 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.

The results of the preliminary tolerance analysis 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 of the detector position during the alignment.

III. EXPERIMENTAL SET-UP

In order to verify the optical performance of the STC FM, and also to carry out the full calibration activities, an *ad hoc* Optical Ground Support Equipment (OGSE) has been conceived and tested in a cleanroom environment at Selex ES premises.

A schematic of the optical bench set-up is shown in Fig. 3.

The OGSE is composed by a collimator unit that can be used with different targets (pinholes, diffuser, etc.) illuminated by different sources (QTH, monochromator, integrating sphere). The collimator is a custom made dioptric element chromatically corrected over the STC working wavelength range. It has a focal length of about 750 mm.

This collimator assembly is rigidly mounted on an optical bench and it is fixed. In order to span each STC sub-channel FoV, the beam exiting the collimator is folded via a plane mirror, which is able to rotate in two directions (Azimuth and Elevation) around the Azimuth position 45°. The stability performance of the OGSE is guaranteed by the high repeatability of the rotator stages which is less than 1 arcsec. This high repeatability allows also to assure a good level of accuracy through a careful calibration of the stages done with a theodolite.

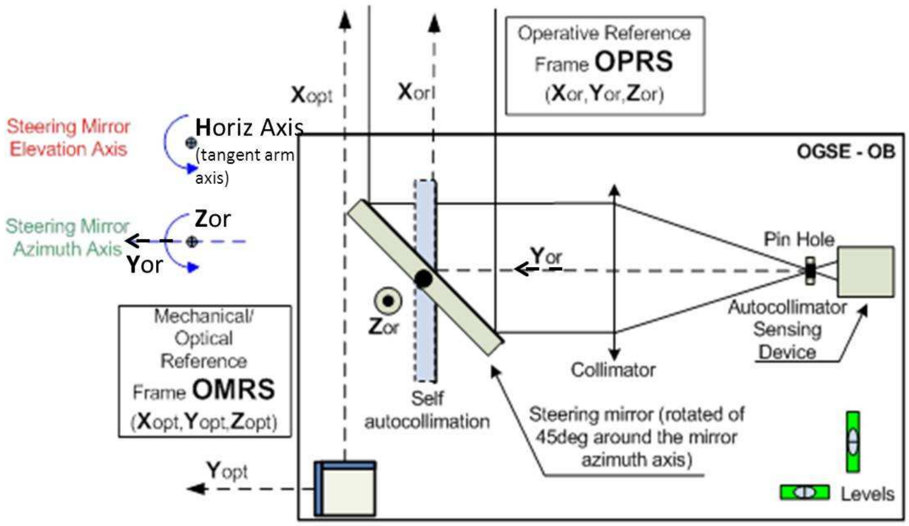


Fig. 3 OGSE schematic diagram and reference system definition.

The STC camera is placed in a thermal-vacuum chamber (TVC), which is mounted on a rotation stage in order to place one or the other of the STC sub-channels in front of the OGSE.

IV. STC FM OPTICAL PERFORMANCE

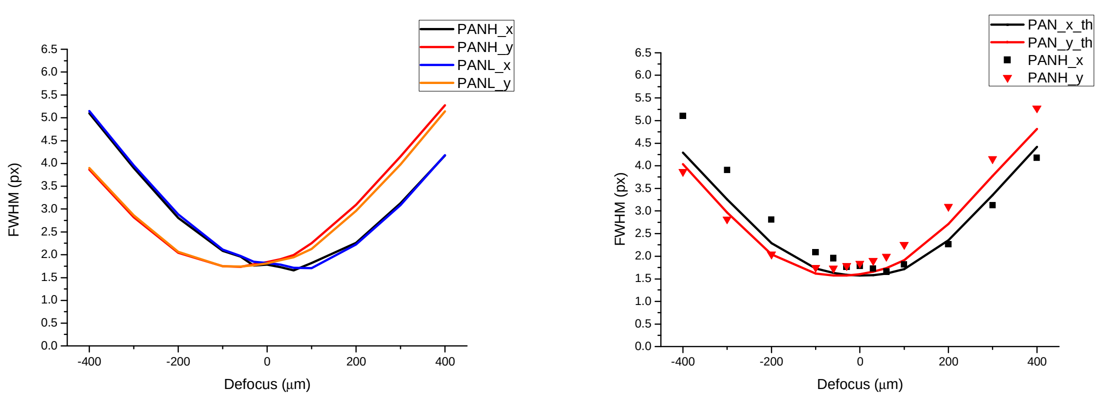
A. Focus check

In order to asses if the camera is correctly aligned, a pinhole has been moved back and forth from the focal plane of the collimator. Given the focal length of the collimator and that of the camera, there is a factor of 50:1 from the shift of the pinhole along the collimator optical axis and the corresponding shift of the focal plane of the camera. The pinhole used has a diameter of 150 µm corresponding to approximately 19 µm image size on the STC focal plane. The through-focus performance of the camera has been checked at the center of the FOV for each of the filters.

The X direction corresponds to the along track direction and it is parallel to the rows of the detector, whereas the Y direction is the across track direction and it is parallel to the direction of the columns of the detector. The FWHMs in x and y of the image of the pinhole onto the focal plane for the different positions of the pinhole have been measured. In Fig. 4 a) the FWHMs for both the PAN filters have been reported; the FWHMs are almost the same for the panchromatic filter of the two sub-channels (called high H and low L).

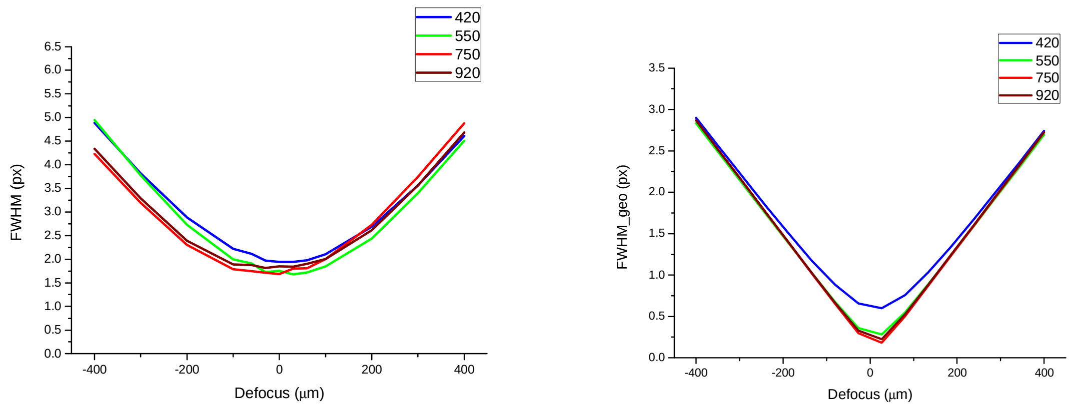
A comparison between the expected values of the FWHM and the measured ones are reported in Fig. 4 b). The theoretical values have been obtained through the convolution of the dimension of the pinhole with the PSF for each particular position. In fact the dimension of the pinhole cannot be discarded with respect to the PSF size.

The measurements have proven that the system is in good focus for the PAN filter, whereas the residual astigmatism, which is present in the camera, is slightly bigger than the one theoretically foreseen.



(a) **(b)**

Fig. 4 In a) the measured FWHMs for the two panchromatic filters (PANH and PANL) are shown. In b) the measured FWHMs are compared with the theoretical ones.



(a) **(b)**

Fig. 5 In a) the measured FWHMs for the filters are shown. In b) the expected FWHMs for the filters from geometrical raytracing are depicted.

Also the through-focus measurements done for the other filters are in good agreement with the expected ones, with the F420 nm filter having slightly worse performance wrt the other filters (see Fig. 5).

B. PSF measurements

Using the dithering technique [12] the PSF at subpixel level has been measured. The pinhole in the focal plane of the collimator has been moved in steps corresponding to 0.1 px on a 15x15 grid. The interpolated results of the PSF reconstruction are shown in Fig. 6.

The profile is almost a Gaussian function with a FWHM of 2 pixels corresponding to the expected dimension of the pinhole image including the diffraction effects.

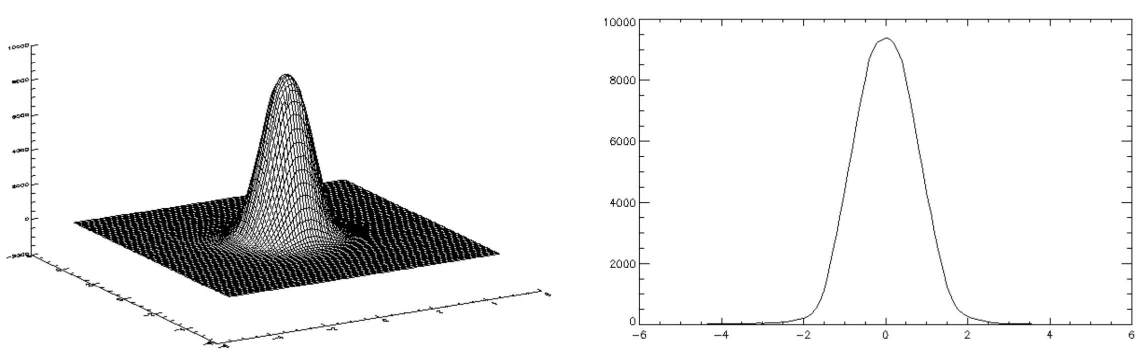
The measured MTF of the instrument, though accomplished with the EM detector, has shown a good agreement between the expected theoretical data and the measured ones [13].

V. CONCLUSION

In this paper a brief description of the optical concept of the stereocamera STC of the SIMBIOSYS instrument for the BepiColombo mission and a summary of the raytracing simulation results have been given. The preliminary results of the calibration measurement realized on the FM of this camera have been reported. They show that the actual performance of the system is extremely close to the nominal one. It has been verified that the camera is in perfect focus.

Unfortunately, the PSF measurements were done with a pinhole too large to measure the actual PSF of the instrument. Nevertheless, the obtained results for the PSF reconstruction show that the OGSE system implemented for this type of measurement is appropriate (i.e. very good system stability) and the adopted elaboration technique is suitable for this kind of analysis.

The final optical calibration of the instrument will be done in the next months adopting a much suitable pinhole size.



(a) **(b)**

Fig. 6 In a) the interpolated measured 3D dithering PSF for the PAN filter is shown. In b) a cross section plot of this PSF is given. X and Y are in pixel unit, intensity in DN.

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