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The Optical Design of the High Resolution Imaging Channel for the SIMBIO-SYS experiment on the BepiColombo Mission to Mercury

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Abstract. This paper deals with the optical design of the High Resolution Imaging Channel (HRIC) of the SIMBIO-SYS instrument, selected as part of the scientific payload for the ESA cornerstone BepiColombo mission to Mercury. Under the lead of Italy, the project is based on an international cooperation with Institutes from France and Switzerland. The HRIC design starts from the scientific requirement of 5 m ground pixel scale at 400 km from the planet surface and is based on a catadioptric Ritchey-Chretien configuration modified with a dedicated three lens corrector. The optimised configuration is convenient in terms of image quality, number of optical elements, total length and mass budget. The channel guarantees a corrected FoV of about 1.47° and allows the achievement of the required resolution with the selected APS hybrid detector of 2k x 2k pixels with a pixel size of 10 μm. The telescope is diffraction limited, thanks to its focal ratio (F/8), and shows an optimised radiometric flux within the operative spectral range (400 - 900 nm), which guarantees a good S/N. The channel is equipped with 1 panchromatic and 3 selective filters. The operation plan foresees the coverage of at least 20% of the Hermean surface with the HRIC.

Key words. BepiColombo mission, High spatial resolution imaging system

1. Introduction

HRIC is the High Resolution Imaging Channel of the instrument SIMBIO-SYS (Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem) instrument, selected by ESA, as part of the payload of the Mercury Planetary Orbiter (MPO) (Benkhoff 2007) of the BepiColombo mission, whose launch is foreseen in 2013. SIMBIO-SYS, is an in-

ternational project led by Italy, with main cooperation from France and Switzerland. The accommodation of the HRIC channel in the SIMBIO-SYS experiment (Capaccioni et al. 2004) is reported in Fig.1. The HRIC optical design has been developed at INAF Astronomical Observatory of Capodimonte, with the main objective of characterising relevant Mercury surface features at very high spatial resolution (pixel scale of about 5 m at 400 km from planet surface) in the visible (Marra et al. 2005). The characteristics of HRIC represent a challenge and an improvement of previous instruments observing Mercury. The high resolution images of selected regions will allow us to identify key surface features (e.g., craters, scarps, lava flows and plains) (Neukum et al. 2001; Watters et al. 2001) and to study their relation with internal processes, as well as the effect of external agents, such as meteor bombardment. In addition, HRIC images will be of paramount importance in support of experiments aiming to the identification of Mercury orbital parameters, such as the obliquity and the amplitude of the libration.
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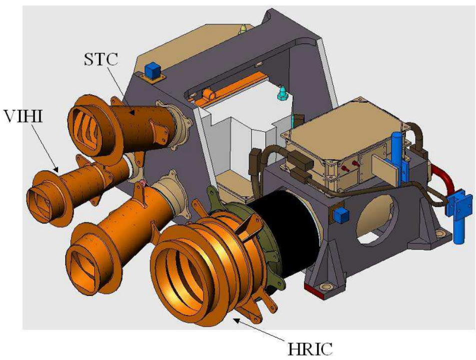

Fig. 1. SIMBIO-SYS instrument including the three integrated channels (the High Resolution Imaging Channel, HRIC, the STereoscopic imaging Channel, STC, and the Visual and Infrared Hyperspectral Imager channel, VIHI).

2. HRIC main objectives and scientific requirements

The main tasks of the HRIC are to provide high resolution images of selected Mercury surface features like craters, scarps, lava flows and plains with a panchromatic filter and to help in geo-mineralogical characterisation of local surface features by band-pass filters (Colangeli et al. 2006). The HRIC main scientific requirements are reported in Table 1.

Table 1. HRIC main scientific requirements.

Parameter	Value
Pixel scale	5m/pixel at periherm (400 km from Mercury surface)
Pixel resolution	12.5 rad/pixel (with pixel of 10 μm)
Spectral range	400-900 nm
Image quality	Diffraction limited at 400 nm
Filters	1 panchromatic (650 nm central wavelength, 500 nm bandwith), 3 band-pass (550 nm, 700 nm, 880 nm, 40 nm bandwith)

3. Optical design

The HRIC optical design has been optimised in order to satisfy not only scientific requirements and nominal optical performance but also dimensional requirements and mechanics constraints of compactness and low mass required for space applications. The optical design is based on a catadioptric concept, with optimisation of a Ritchey-Chretien configuration by a dedicated corrector (Fig. 2). The instrument has a focal length of 800 mm and is equipped with a dedicated refractive camera, in order to correct the field of view covered by a detector of 2k x 2k pixels, with a pixel size of 10 μm. The focal ratio of the instrument is F/8, in order to be diffraction limited at 400 nm and to optimise radiometric flux and overall mechanical dimensions. The main HRIC optical characteristics are reported in Table 2 (Marra et al. 2006). The combined (reflective + refractive) solution guarantees a good balance of achieved optical performances and optimisation of resources (mainly volume and mass). The curvature of the lenses is spherical, in order to simplify manufacturing. The quality of the optical design has been optimised and checked by analysis with the Zemax code. The adopted configuration corrects and transmits well over the whole band of observation (400 900 nm). A relative obscuration ratio of 0.3 (between primary and secondary mirror diameters) has been achieved in order to provide a good energy transfer to the telescope exit pupil. The optical design presented in this paper takes also into account the foreseen filters and detector package, in which the detector window acts also as filter.

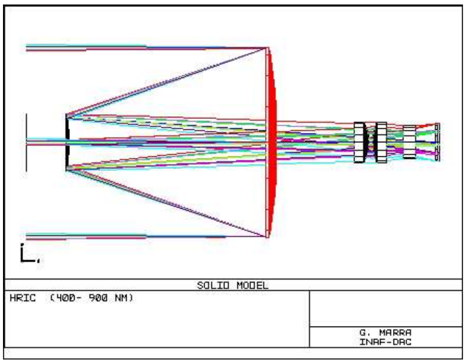

Fig. 2. HRIC optical layout.

Table 2. HRIC Main optical characteristics.

Parameter	Value
Optical configuration	Catadioptric: Ritchey - Chretien modified with a dedicated corrector
Aperture	100 mm
Angular field of view	1.47
F-number	8
Focal length	800 mm
Image scale	12.5 μrad/pxl
Focal Plane detector	2048 x 2048 (CMOS APS)
Detector pixel size	10 μm x 10 μm

4. HRIC main optical performances

Since the system is diffraction limited, the fraction of diffraction Encircled Energy (EE) curves enclosed in one pixel and the diffraction Modulation Transfer Function (MTF) until the Nyquist frequency have been considered in order to evaluate the image quality. For both diffraction EE and MTF, central obscuration has been included. In addition, RMS spot radius on the image plane and field curvature and distortion have been evaluated. The field corrector has been optimised in order that images in different filter bands can be compared without distortion and field curvature. Thus the image quality is high over the whole field of view. The main optical performances are reported in Table 3.

Table 3. HRIC main optical performances.

Parameter	Value
Polychromatic Diffraction EE in one pixel	70%
Polychromatic MTF at Nyquist frequency	59%
Polychromatic RMS spot diameter (geometric)	0.8 μm
Field curvature	12 μm
Distortion	0.05%

The curves of fraction of polychromatic EE enclosed in one pixel, for different fields of view from the centre to the edge are shown in Fig. 3. The fraction of polychromatic EE over the whole field of view is greater than 70%. The worst case condition for EE refers to the edge of the field. Polychromatic diffraction modulation transfer function (MTF) curves up to the Nyquist frequency of 50 cycles/mm of the system are shown in Fig. 4. The MTF is greater than 59% at the Nyquist frequency over the whole field of view. The spot diagrams on the image plane, for different angular distances from the centre to the edge of the field, are shown in Fig. 5. The RMS spot diameter is less than 1.6 μm over the full field, so it is well enclosed in the Airy disk of 7.8 μm. The curves of field curvature and percent distortion versus field of view are shown in Fig. 6. The focal plane is flat and it is located in the origin of the field curvature diagram, between tangential and sagittal curves. The field curvature is less than 12 μm and the maximum distortion is 0.05%.

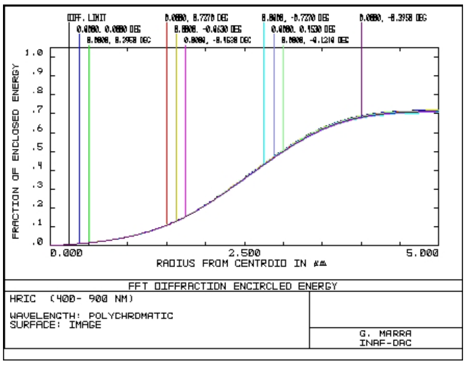

Fig. 3. HRIC Encircled Energy curves.

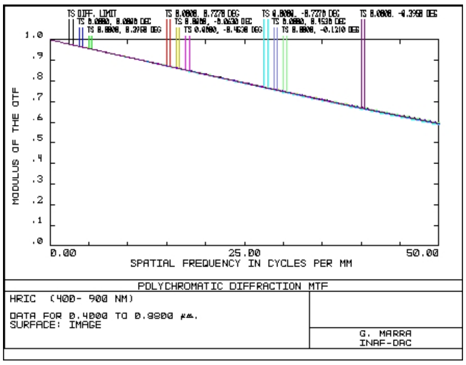

Fig. 4. HRIC Modulation Transfer Function curves.

5. HRIC design analysis

A trade-off design analysis has been performed in order to achieve the optical configuration shown in this paper. An off-axis optical configuration seems to be disadvantageous, with respect to the centred proposed configuration, due the increment in mass and volume and the complexity increase in terms of lenses and mirror manufacturing.

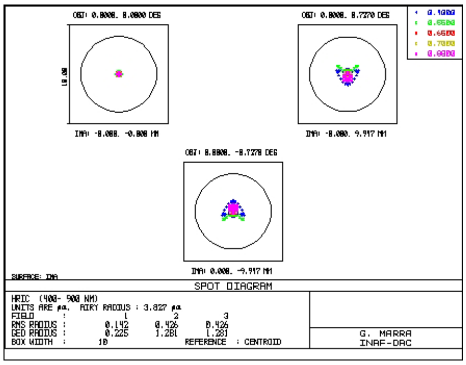

Fig. 5. HRIC spot diagrams on image plane.

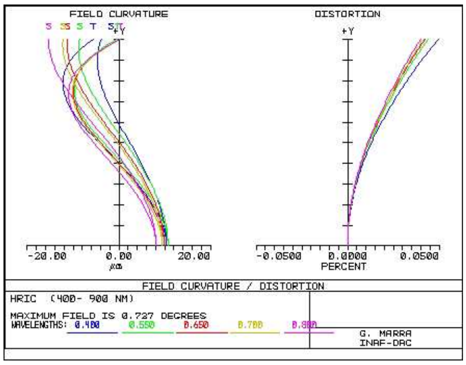

Fig. 6. HRIC Field curvature and distortion on the image plane.

A trade off-analysis has been performed also by varying the pupil diameter and analysing the image quality and pixel scale degradation (Table 4). In order to achieve the required spatial resolution of 5m/pixel, the pupil diameter cannot be less than 80mm. For a complete trade-off analysis, optical evaluations must be combined with other factors, such as thermal flux during operation at Mercury. In this sense, the minimal pupil size still compatible with optical and image quality performances is desirable.

MTF is a parameter suitable for the characterisation of the spatial resolution of the instrument. In particular, the MTF gives information on scene contrast as viewed by the instrument, describing the loss of modulation amplitude for every spatial frequency, which is determined by the imaging system. The image

Table 4. HRIC image quality analysis in terms of MTF (%) at Nyquist frequency and EE (%) in one pixel with an obscuration ratio of 30%, varying pupil diameter and pixel scale at 400 Km of altitude.

Pixel [m]	**Pupil ⊘** [mm]	**F**	**FOV** [deg]	**MTF**	**EE**
5	100	8	1.47	59	70
5	90	8.9	1.47	48	61
5	80	10	1.47	41	52
10	50	8	2.93	47	63
8	60	8.83	2.34	↓	↓
5.7	70	10	1.67	↓	↓

quality of HRIC system has been evaluated in terms of optical and average (across and along track) system MTF, which includes the degradation factors for detector, optic, image motion and jitter. The values obtained for selected filters are listed in Table 5.

Table 5. Image quality of HRIC in terms of Optical and average system MTF for the different filters with pupil diameter of 100 mm and 80 mm.

Pupil ⊘ [mm]	**Optical MTF**	**Avg. System MTF**
	Filter 550	
100	0.60	0.27
80	0.51	0.23
	Filter 650	
100	0.54	0.24
80	0.44	0.2
	Filter 700	
100	0.51	0.22
80	0.41	0.18
	Filter 880	
100	0.41	0.18
80	0.35	0.15

The HRIC channel has been modelled, in order to simulate effects such as degradation of optics, detector characteristics and noise on the image quality, by varying the optical aperture from 100 to 80 mm. The MTF is not the only parameter that describes the image quality. Root Mean Square (RMS), Relative Edge Response (RER) and Signal to Noise Ratio (SNR) dependent on spatial frequency are used to complete the characterisation. The RMS gives the root mean square error between intensities of reference and HRIC images. The RER provides the normalised response of the imaging system to an edge, estimating effective slope of the imaging system's edge response. The SNR(u,ν), the Spatial Frequency-Dependent Signal-to-Noise Ratio, is a generalised measure of the image quality. This function includes the three main image quality parameters, i.e. spatial resolution, object contrast, and noise (Bernhardt et al. 2005).It describes the ratio between the signal and the noise detected in the image dependent on the two dimensional spatial frequencies u and ν. Since the detectability of a feature is not accounted for by the MTF (Moy 2000), for the image quality evaluation it is necessary to consider how the SNR varies with spatial frequencies. In particular SNR decreases versus spatial frequencies, since it is modulated by the MTF following the relation:

$$SNR(u,\nu) = SNR(0,0) \cdot MTF(u,\nu) \cdot |F(u,\nu)|$$

where SNR(0,0) is the ordinary SNR and F(u,ν) is the Fourier Transform of the input signal. So the SNR curve versus spatial frequency, is the MTF curve scaled of the SNR factor and the input signal's Fourier modulus (Hans–Martin 1995).

6. Conclusions

The optical design of the High Resolution Imaging Channel of the SIMBIO-SYS experiment for the ESA BepiColombo mission to Mercury, has been developed in order to satisfy at the same time scientific requirements of high resolution and image quality for Mercury key features recognition and mechanics constraints of compactness and low mass. The optical layout takes in into account the foreseen detector and filters package, in which the detector window acts also as filter. An analysis of the optical design has been performed which shows that the obtained centred optical configuration is more advantageous with respect to an off-axis configuration, in terms of reduced mass and volume and complexity in terms of lenses and mirrors manufacturing. HRIC image quality has been analysed for a pupil diameter of 100 mm and 80 mm, also in terms of system MTF, including the detector ideal MTF, image motion and jitter and degradation factors for detector and optics. In order to evaluate the HRIC system image quality degradation factors, the RMS, RER, parameters and SNR dependent on spatial frequencies are foreseen to be used in addition to MTF. This analysis will let us estimate the way image degrades varying the pupil aperture size in the range of 100 to 80 mm, and how this would influence the capacity of Mercury surface feature characterisation. This study will give us information about the minimum pupil size desirable for reduction of the thermal flux entering the instrument, still compatible with the optical and image quality required performances.

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