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The CaSSIS imaging system: optical performance overview

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ABSTRACT

The Colour and Stereo Surface Imaging System (CaSSIS) is the high-resolution scientific imager on board the European Space Agency's (ESA) ExoMars Trace Gas Orbiter (TGO) which was launched on 14th March 2016 to Mars.

CaSSIS will observe the Martian surface from an altitude of 400 km with an optical system based on a modified TMA telescope (Three Mirrors Anastigmatic configuration) with a 4th powered folding mirror. The camera EPD (Entrance Pupil Diameter) is 135 mm, and the expected focal length is 880 mm, giving an F# 6.5 in the wavelength range of 400-1100 nm with a distortion designed to be less than 2%.

CaSSIS will operate in a "push-frame" mode with a monolithic Filter Strip Assembly (FSA) produced by Optics Balzers Jena GmbH selecting 4 colour bands and integrated on the focal plane by Leonardo-Finmeccanica SpA (under TAS-I responsibility). The detector is a spare of the Simbio-Sys detector of the Italian Space Agency (ASI), developed by Raytheon Vision Systems. It is a 2kx2k hybrid Si-PIN array with a 10 µm pixel pitch.

A scale of 4.6 m/px from the nominal orbit is foreseen to produce frames of 9.4 km × 47 km on the Martian surface.

The University of Bern was in charge of the full instrument integration as well as the characterization of the focal plane and calibration of the entire instrument. The paper will present an overview of the CaSSIS telescope and FPA optical performance. The preliminary results of on-ground calibration and the first commissioning campaign (April 2016) will be described.

Keywords: space instrumentation, telescope, detector, calibration

1. INTRODUCTION

The Colour and Stereo Surface Imaging System (CaSSIS) is the scientific imaging system on board of the ExoMars 2016 Trace Gas Orbiter (TGO) mission launched on 14th March 2016 to Mars.

The main scientific objectives of the instrument are 1) to characterize sites which have been identified as potential sources of trace gases 2) to investigate dynamic surface processes (e.g. sublimation, erosional processes, volcanism) which may help to constrain the atmospheric gas inventory 3) to certify potential future landing sites by characterizing local (down to ~10 m) slopes.

To reach these scientific objectives, the main requirements on the instrument capabilities are:

- surface imaging at spatial resolution of < 5 m/px
- at least 3 broad-band colours optimized for Mars photometry
- quasi-simultaneous acquisition of stereo pairs over the full swath width to allow production of high resolution digital terrain models.
- a swath width >8 km

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These technical requirements combined with programmatic constraints have driven the instrument design.
Stereo: The TGO spacecraft design and its method for orienting its solar arrays led to the use of a rotation mechanism to orient the instrument so that the image rows are perpendicular to the orbital track, as Fig 1 shows. This mechanism allows acquisition of quasi-simultaneous stereo imaging by mounting the telescope pointing forward along-track from the nadir direction and rapidly rotating the telescope by 180° as the spacecraft flies over a target. The telescope off-nadir angle is 10° resulting in a stereo convergence angle of 22.4° considering the planetary curvature. The time between stereo points from the nominal orbit is 46.9 s and the 180° rotation is designed to be completed within ~15 s.

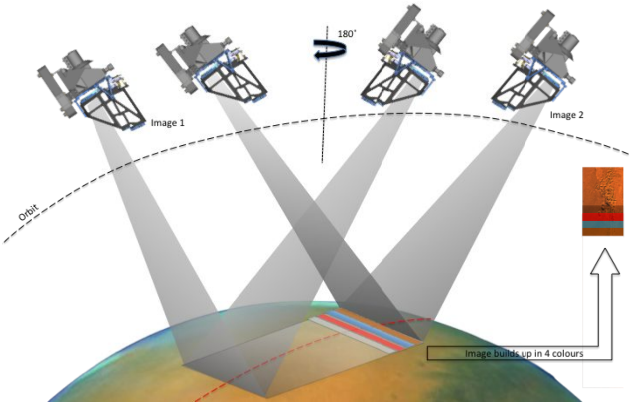

Figure 1 Cassis telescope stereo colour observation approach

Colours: The strategy to obtain colour images using the push-frame imaging approach follows the one used on SYMBIO-SYS and is based on the capability of the CMOS detector to acquire images in up to six user-defined windows simultaneously. An array of discrete coloured filters, the Filter Strip Assembly (FSA), is mounted in front of the detector (Ref. SPIE 9912-03). Four colour filter bands are oriented with their longer dimension perpendicular to the ground-track direction. Framelets are acquired from pixels exposed through each filter with a repetition rate synchronized to the ground track velocity and set to obtain sufficient overlap between successive framelets to permit accurate mosaicking. The FSA is fixed in front of the detector, parallel to its surface. Together, the detector and the FSA form the Focal Plane Assembly (FPA).The CaSSIS telescope is fixed onto a Camera Rotation Unit (CRU) with the optics and focal plane assembly to the one side of the main support, the Proximity Electronics (PE) within the rotation bearing and a cable management system on the other side. The central support has a honeycomb structure and consists of a sandwich panel with aluminium honeycomb core and near-zero thermal expansion coefficient Carbon Fibre Reinforced Polymer (CFRP) face sheets. In this configuration the focal plane electronics is remote from the telescope which simplifies the telescope and all internal interfaces. An Electronics Unit (ELU) with a power converter and a digital processing module (DPM) completes the system. Fig. 2 shows the structure of the CaSSIS instrument and Table 1 reports the main optical data.

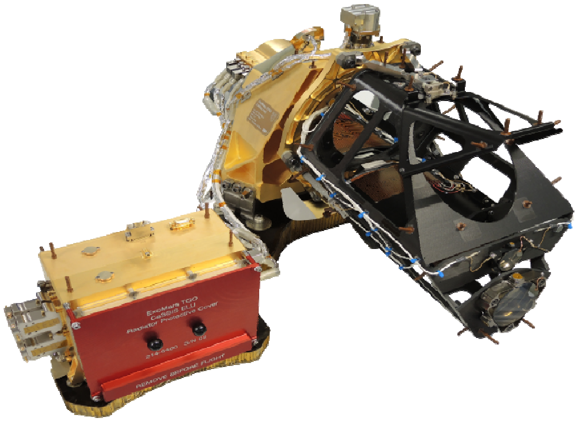

Figure 2 CaSSIS: CRU with telescope on right side and ELU with red cover on left side

Table 1 CaSSIS instrument main data

Orbit data	**Nominal Value**	**Measured Value (if available)**
Orbit type	Circular	Assumed
Orbit altitude	400 km	Assumed
Orbit inclination	74°	Assumed
Orbit period	1.966 h	Derived
Maximum ground track speed	3.012 km/s	Derived for 0 km ground elevation
Maximum change in true anomaly	0.0509 °/s	Derived
Optical data		
Focal length	880 (+/-50) mm	871.5 mm
Aperture diameter	135 mm	135 mm
Nominal F#	6.52	6.46
Pixel size (square)	10 µm	10 µm
Angular scale	11.36 µrad /px	11.47 µrad/px
Rotation axis-boresight angle	10.0 (+/- 0.2)°	9.89 (+/- 0.10)°
Stereo angle from 400 km altitude	22.39°	22.14°
Rotation time (180° rotation)	15 s	
Nominal slant distance to surface	406.92 km	406.76 km
Scale at slant angle	4.62 m/px	4.67 m/px
Time between stereo points along track	46.91 s	46.38 s
Detector and Images data		
Bits per pixel	14 (returned as 2 byte integers)	14
Maximum dwell time (1 px of smear)	1.51 ms	1.52 ms
Detector size	2048 x 2048 px	2048 x 2048 px
Image size	2048 x 256 px	2048 x 280 px (PAN) 2048 x 256 px (colours)
# of images returned per exposure	4	3-6 (small windows used as dark current/bias validation)
Detector area used	2048 x 1350	2048 x 1291
FOV of used area	1.33° x 0.88°	1.35° x 0.85°
Nominal image overlap	10%	5%
Filters (effective wavelength/equivalent bandwidth)		
PAN	675 nm / 250 nm	675.0 nm/229.4 nm
BLU	485 nm / 165 nm	499.9 nm/118.0 nm
RED	840 nm / 100 nm	836.2 nm/94.3 nm
NIR	985 nm / 220 nm	936.7 nm/113.7 nm

2. OPTICAL SYSTEM OVERVIEW

2.1 Optical system design

The optical system consists of a ø135 mm, f=880mm, F/6.5 off-axis 4× reflective telescope with a field of view (FoV) of 0.878° in the plane of symmetry and 1.336° in the cross-track direction. The initial baseline considered a Three-Mirror-Anastigmatic configuration (TMA) with an intermediate focal surface and an additional flat folding mirror to compact the structure.

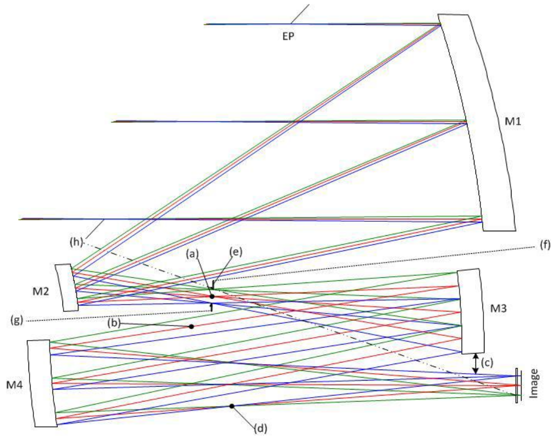

Figure 3 Ray tracing via CodeV software design of the CaSSIS optical system. The configuration has an intermediate focal plane (a) and two intermediate walls (f and g) which subdivide the telescope into an upper compartment with M1 and M2 and a lower compartment with M3 and M4 separated with baffles to avoid direct light in to the detector through the field stop. The powered mirror M4 allows maintaining compact design

The optimization of the optical system is driven to reduce the optical element sizes. Iterations were made with a system with 3 ideal lenses, keeping the focal length and overall length constrained and taking the element sizes as performance merits. The only optical performance metric involved was the Petzval correction (the sum of the element powers to be zero). The first order design had foreseen an accessible exit pupil to support straylight suppression. This pupil still exists (d), but there was insufficient clearance. The remaining options for straylight baffling were the placement of a field stop (e) at the intermediate image (a) and two intermediate walls (f and g) which subdivide the telescope into an upper compartment with M1 and M2 and a lower compartment with M3 and M4. The optical design has further taken care to prevent direct sky view from the detector through the field stop into object space, line (h). The 4 aspheric mirrors are made of ZERODUR® Expansion Class 0 and coated with protected silver.

2.2 Optical system structure

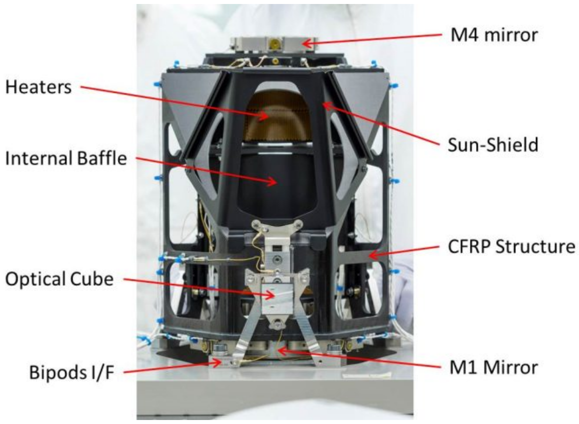

Figure 4 CaSSIS telescope CFRP structure with baffles and the optical cube alignment before the detector integration

A carbon-fiber reinforced polymer (CFRP) material, using a RUAG Space proprietary process, has been used in the design of the structure to increase its stiffness and its ability to withstand the random vibration loads. The tube structure, which has a wall thickness of 4.8mm, was manufactured as one piece. Inserts were then added to the tube allowing it to be ready for receiving walls and other metallic structural components. The structure has internal baffles made of aluminium and located adjacent to the field stop allowing them to block the optical path from the entrance aperture to the focal plane assembly (FPA), and radiatively and conductively transferring heat to the telescope assembly from a series of electrical heaters. INVAR® mirror mounts are attached to the CFRP tube and maintain the mirrors in place throughout the environmental changes and allowing testing in 1g gravity without significant degradation to the image.
(The interface between the telescope assembly and the rotation drive mechanism uses three titanium bipods, as Figure 4 shows)

2.3 Focal Plane Assembly (FPA)

CaSSIS re-uses the Focal Plane Assembly (FPA) of the Simbio-Sys instrument for ESA's Bepi Colombo mission to match the schedule deadline [2]). The detector is a Raytheon Osprey 2k hybrid CMOS and it is based on Hybrid Silicon PIN (Si PIN) CMOS technology. The Si PIN diodes, being backside illuminated, have a 100% fill factor and very high quantum efficiency up to near-IR wavelengths, ranging from 4% at 400nm up to 91% at 800nm at 293 K by taking advantage of the Raytheon anti-reflection coating. The FPA array is composed by 2048x2048 pixels with 10µmx10µm pixel pitch. The CMOS process provides a full well capacity of about 90000 electrons. This technology allows the snapshot acquisition and windowing. The window size can vary from 1 to 2048 in the row direction (foreseen as cross-track) with the resolution of one row and from 128 to 2048 with 64 columns resolution (along-track). The read-out integrated circuit (ROIC) allows a read-out speed of 5Mbps with a clock frequency of 2.5MHz. The detector can be read-out extremely quickly with 14 bit digital resolution and it is enclosed in a dedicated package which provides the necessary electrical, mechanical and thermal interfaces to the device, including the optical window. The FPA is shown in Figure 5.

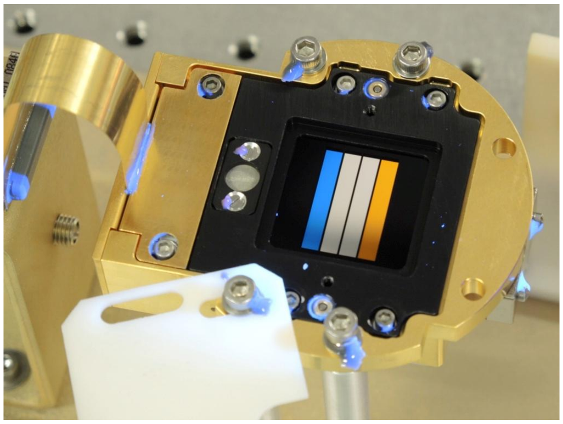

Figure 5 Picture of the filter assembly integrated on the FPA. The FPA was illuminated by UV light to check for contamination by dust. The filter on the left of the picture is PAN, reflecting blue light and the filter on the right is BLU reflecting red and orange light. In between, the RED and NIR filters both reflect all visible light and appear like mirrors.

An array of discrete multilayer dielectric passband colour filters stripes is deposited in front of the detector window, with their long-axes perpendicular to the ground-track direction. Optics Balzers Jena GmbH produced the CaSSIS filters using an innovative photolithography technique to deposit thin-film passband optical filters and black masks made of low reflective chromium (LRC) on a single fused silica monolithic substrate [5]. The wavelength bands for the four colour filters of CaSSIS were derived from the ones used on the HiRISE/MRO instrument. The bands, BLU and PAN correspond closely to the first two bands used by HiRISE ("BG" and "RED", respectively) ensuring consistency between the CaSSIS and HiRISE datasets. The two other CaSSIS filters, RED and NIR, split the third filter of HiRISE ("IR") in two. Table 1 shows the filters bands and the optical performances are fully described [3]

2.4 Optical system performances

The overall imaging performance achieves a Modulation Transfer Function MTF of >0.3 at the detector Nyquist Frequency of 50 lines/mm (44 lines/mrad in object space) @λ=632nm over almost the whole FoV, thus making optimal use of the detector (i.e. the MTF should also not be much greater than 0.3 at the Nyquist Frequency to avoid aliasing effects.

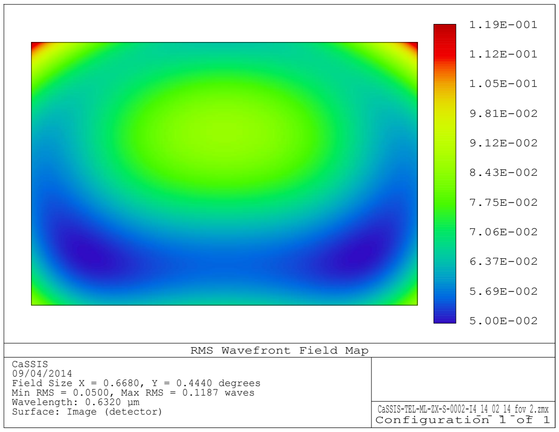

Figure 6 Simulated (via Zemax code) wavefront error (WFE) at 632 nm over the full CaSSIS FoV (1.336° x 0.887°) corresponding to a 20.48 mm x 13.56 mm area on the image plane of the detector.

The wavefront error (WFE) was measured at 13selected positions of the CaSSIS detector, sampling its entire FoV, with an interferometer setup. The distance between the WFE and the plane of the detector is then calculated. Table 2 shows the obtained values of PSF simulated via Code V software at the 13 reference mechanical positions.

Table 2 CaSSIS MTF obtained on filters position on focal plane

Position on detector filters	**Position on focal surface**	**MTF**	**Distance wrt best WFE (µm)**
Middle	1	0.41	-45.3
BLU	2	0.48	+12.6
PAN	3	0.53	+8.0
NIR	4	0.44	-15.5
RED	5	0.51	-18.6
BLU	6	0.32	+97.0
Middle	7	0.47	+7.6
PAN	8	0.48	+33.4
NIR	9	0.53	-15.4
RED	10	0.48	-18.7
BLU	11	0.21	+98.1
Middle	12	0.51	+7.5
PAN	13	0.49	+34.2

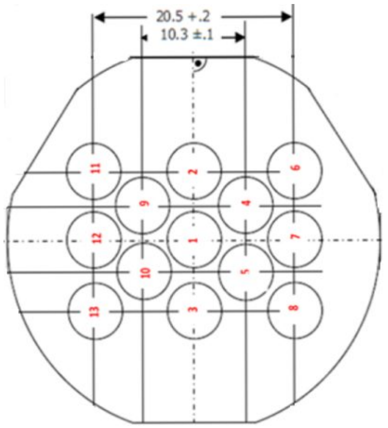

Figure 7 Wave Front Error (WFE) at 632 nm is measured at 13 different detector positions on the detector

3. DETECTOR INTEGRATION AND FOCUSING

The University of Bern was responsible for the mounting of the detector to the telescope. The Optical Ground Segment Equipment (OGSE) used to integrate the detector and to test the optical performance of CaSSIS was based on a collimated beam obtained with an 147 mm-diameter Off Axis Parabola (OAP) and a 10 µm pinhole which can be illuminated with either white (Quartz Tungsten Halogen) or monochromatic (10 nm FWHM bandpass) light. The CaSSIS telescope was placed on a granite tower with the optical axis vertical to mitigate the effects of Earth gravity on the defocusing and the Full Entrance Pupil diameter (EPD) of the telescope covered by the collimated beam.

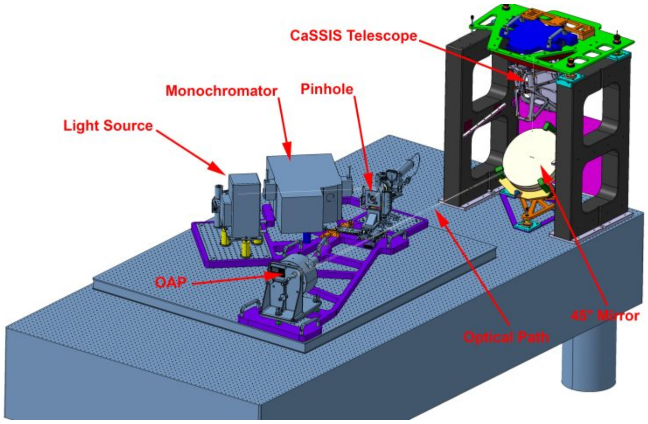

Figure 8 OGSE used to integrate the detector and to test the optical performances of CaSSIS. The collimated beam obtained with an 147 mm-diameter Off Axis Parabola (OAP) and a 10 µm pinhole and illuminated with either white (Quartz Tungsten Halogen) or monochromatic (10 nm FWHM bandpass) light. The CaSSIS telescope optical axis vertical via the 45 deg mirror to mitigate the effects of Earth gravity

The pre-alignment of the CaSSIS telescope with the OAP optical axis was achieved using a theodolite alignment technique [4]. The accurate positioning of the detector was performed mechanically via shimming using a criterion consisting in minimizing the Point Spread Function (PSF) Full Width at Half Maximum (FWHM) on the detector for the PAN, RED and NIR filters. The PSF FWHM was calculated by fitting a 2D Gaussian function onto the pinhole images. Because of the absence of a focusing system on the detector side, the "through focus" analysis was performed by moving the pinhole along the OAP optical axis, as preliminary identified during OGSE calibration. Images were acquired for many positions of the pinhole, typically 20 images acquired with steps of 20 µm. Each of these pinhole images was independently fitted by a 2D Gaussian function to extract the FWHM in the x- and y- direction, from which the average

FWHM was derived. The average FHWM from all images were then plotted as a function of the pinhole position. A 2nd order polynomial function was fitted to these data and the best position identified at the minimum of the fitted function. A magnification factor, the ratio of the respective focal lengths of the OAP and CaSSIS telescope was then applied to calculate the defocus distance of the CaSSIS detector [6]. That procedure was repeated for many positions in the FoV and results compared to the interferometric measurements performed by RUAG Space. A pre-compensation for the expected effect on the focus position of moisture release in flight (modelled by RUAG Space) has also been introduced.

Since the very first series of measurements performed with the OAP, we have noticed a significant astigmatism attributed to an incorrect mounting of the setup. In addition, we have observed a significant variability of the behaviour of the setup over time which points to a higher than expected instability in the opto-mechanical mount of the OAP itself and the pinhole positioning mechanism. The uncertainties caused by these issues and the resulting unacceptable risk for the focusing of the instrument lead us to improvise a second independent procedure to identify the best focus. A cross check was thus performed by using a laser interferometer (Zygo, 100 mm EPD, Model: MK-II-02, Fizeau plane lambda/40) to provide a perfectly collimated beam and changing the size of the detector shims to obtain images at various through-focus positions. These images were treated as the pinhole images acquired through the OPA, by fitting 2D Gaussian functions and finally plotting the average FWHM as a function of the detector position to identify the best focus. The difficulty here was that the beam from the interferometer was much too bright for the CaSSIS system and had to be attenuated using neutral density filters. Because this solution was improvised, we did not have the time to procure a large enough filter to cover the entire 10 cm beam of the interferometer and had to work with a 5x5 cm neutral density filters. This filter was placed in 6 successive positions in the beam (centre, left, right, bottom, top, centre again). Images acquired in the left, right, top and bottom positions were then stacked before being fitted.

Examples of PSF FWHM vs. pinhole position curves obtained with the OAP setups through the different filters and the fit of the measurements using second order polynomial laws are shown in Figure 9. A comparison with the PSF of the telescope alone measured by RUAG Space with an interferometric setup is also shown for comparison. The obtained PSF FWHM is 1.7 px at the position of the BLU filter and smaller (1.2 px) in PAN and RED (as planned) to obtain the highest resolution data for the main stereo channel. A similar trend is observed in the telescope data provided by RUAG Space.

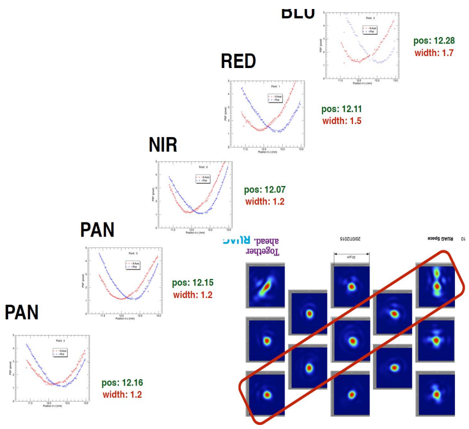

Figure 9 PSF FWHM obtained in the position on the diagonal red line, corresponding to the positions 6, 4, 1, 10, 13 on the detector identified as in Fig

The resulting Effective Focal Length (EFL) of the telescope has been estimated by plotting the position of the pinhole image on the detector as a function of the actual position of the pinhole in the plane perpendicular to the optical axis. The obtained EFL is 879.0 mm (Figure 10). This result is closer to the nominal one EFL than the average of measurements (871.5 mm) at the focal plane made by RUAG (Table 1).

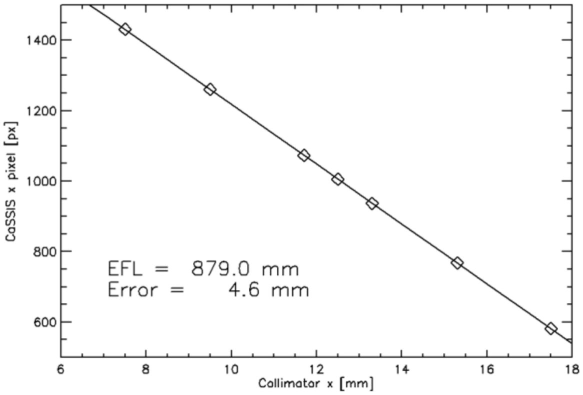

Figure 10 Effective Focal Length with respect to the pinhole position in OGSE system

3.1 PSF Focusing results

Because of all the difficulties mentioned in section 3, we could not fully characterize in the laboratory the PSF of the instrument pre-flight. However, the observed consistency between the best focus position provided by the OAP setup and the interferometer setup at the time of the integration and verified again toward the end of the calibration phase, gave us confidence that the detector had been mounted very close to the optimal position. The set of measurements performed with the interferometer at the end of the calibration campaign showed a relatively symmetric PSF with an average FWHM of 1.7 pixels (Fig. 10). It is very likely however that this is an upper value for the real PSF of the instrument. Indeed, we had observed that vibrations of the setup, due to the vacuum and thermal regulation systems of the chamber in which the instrument was installed, resulted in significant movement of the spot image on the detector. This causes a blurring of the final image obtained by stacking the images acquired at different positions in the beam. We thus concluded from all our laboratory characterizations that the PSF of the CaSSIS instrument would be smaller than 1.7 pixels in the centre of the field of view, and therefore an upper limit.

Figure 11 Best focus during on ground calibration gives PSF FWHM 1.7 px

4. FIRST LIGHT IN FLIGHT

4.1 First light: preliminary focus results

CaSSIS obtained its first light images on the 7th of April 2016 during Near Earth Commissioning of TGO's instruments. More than 40 stars could be identified in the first images, thanks to small motions of the telescope that helped us distinguishing real stars from cosmic rays (Figure 12). We could fit all the star images to obtain characterizations of the PSF over the entire field of view of the instrument. The result reveal that once the telescope reaches its operational temperature, the measured PSF are very symmetric and narrow (Figure 11) with average FWHM of the order of 1.2 to 1.3 pixels through the PAN, RED and NIR filter, increasing to 1.4 – 1.5 pixels in the BLU filter (Figure 12).

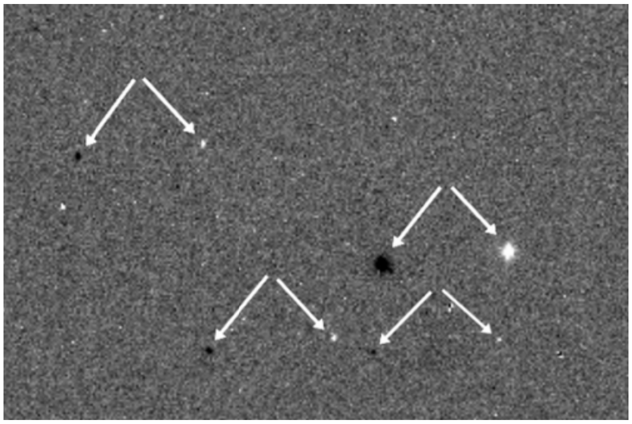

Figure 12 During the first commissioning in April 2016 to test the rotational system a stars field has been acquired and PSF FWHM obtained.(explanation in the text of the figure)

Analysis of the first stars imaged during Near Earth Commissioning shows indeed that the average FWHM of the PSF is of the order of 1.2-1.3 pixels for the PAN, RED and NIR filters and 1.4-1.5 pixels for the BLU filter. An example of resulting PSF obtained in the RED is in Fig. 13 shown.

Figure 13 Best focus for the first light acquired during the first commissioning gives PSF FWHM of about 1.2 px

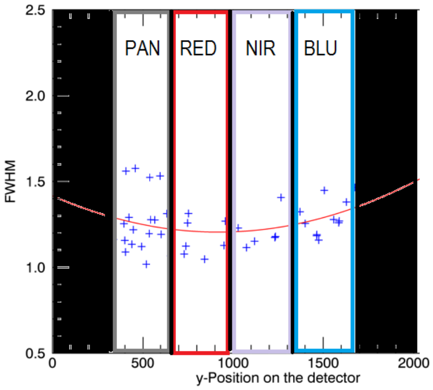

Figure 14 The image shows the average FWHM of the PSF as a function of the y-axis (along track) position on the detector. The filters are PAN, RED, NIR and BLU from left to right. The FWHM PSF in the different filters band is confirmed as predicted.

CaSSIS acquired its first image of Mars on 13 June 2016 as part of its extensive instrument commissioning en route to the Red Planet. The line-of-sight distance to Mars on 13 June was 41 million kilometers, giving an image resolution of 460 km/pixel. The planet is roughly 34 arcseconds in diameter at this distance. The Elysium region of Mars, home to the planet's largest volcanoes, faces the spacecraft in this view.

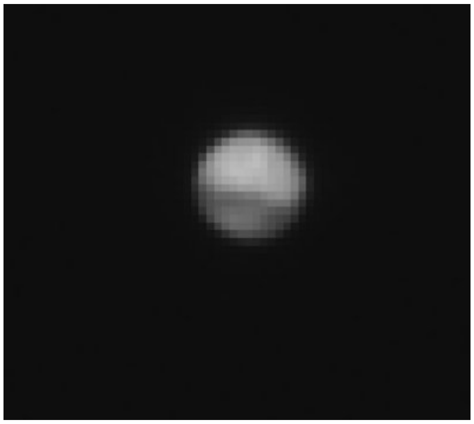

Figure 15 First Image of Mars acquired during the Mid cruise check in 13 June 2016 (41 Milions kilometers from Mars). The image confirms in base of the pixel scale that from this distance Mars appears around 15 pixels (11.36 arcsec/pixel)

5. CONCLUSION

The design of the CaSSIS instrument is based on a modified Three Mirror Anastigmat (TMA) off-axis telescope with a fourth powered mirror, a 2048x2048 pixels hybrid CMOS detector with a pixel pitch of 10 µm, a monolithic filter strip with four colour bandpass filter and a telescope rotation mechanism to provide low distortion and high SNR 4-colour and stereo images of the surface of Mars using the push-frame technique. In this paper, we have detailed the procedure used to integrate the detector at the best focus position and reported on the performances of the system in terms of focus, as characterized in the laboratory and in flight. Because of unforeseen technical difficulties with the ground optical setup, the PSF could not be characterized in details pre-flight. However, the use of two independent techniques to find the best focus position, one based on the use of an off-axis parabola the other on the use of a laser interferometer, gave us confidence that the detector had been positioned correctly and that the instrument should have a PSF < 1.7 px (average FWHM). Analysis of the first stars imaged during Near Earth Commissioning shows indeed that the average FWHM of the PSF is of the order of 1.2-1.3 pixels for the PAN, RED and NIR filters and 1.4-1.5 pixels for the BLU filter.

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