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FIRST LIGHT OF CASSIS - THE STEREO SURFACE IMAGING SYSTEM ONBOARD THE EXOMARS TGO

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ABSTRACT

The Colour and Stereo Surface Imaging System (CaSSIS) camera was launched on 14 March 2016 onboard the ExoMars Trace Gas Orbiter (TGO) and it is currently in cruise to Mars.
The CaSSIS high resolution optical system is based on a TMA telescope (Three Mirrors Anastigmatic configuration) with a 4th powered folding mirror compacting the CFRP (Carbon Fiber Reinforced Polymer) structure. The camera EPD (Entrance Pupil Diameter) is 135 mm and the focal length is 880 mm, giving an F# 6.5 system; the wavelength range covered by the instrument is 400-1100 nm. The optical system is designed to have distortion of less than 2%, and a worst case Modulation Transfer Function (MTF) of 0.3 at the detector Nyquist spatial frequency (i.e. 50 lp/mm).
The Focal Plane Assembly (FPA), including the detector, is a spare from the Simbio-Sys instrument of the Italian Space Agency (ASI). Simbio-Sys will fly on ESA's BepiColombo mission to Mercury in 2018. The detector, developed by Raytheon Vision Systems, is a 2k×2k hybrid Si-PIN array with 10 μm-pixel pitch. The detector allows snap shot operation at a read-out rate of 5 Mpx/s with 14-bit resolution. CaSSIS will operate in a push-frame mode with a Filter Strip Assembly (FSA), placed directly above the detector sensitive area, selecting 4 colour bands. The scale at a slant angle of 4.6 m/px from the nominal orbit is foreseen to produce frames of 9.4 km × 6.3 km on the Martian surface, and covering a Field of View (FoV) of 1.33° cross track × 0.88° along track. The University of Bern was in charge of the full instrument integration as well as the characterisation of the focal plane of CaSSIS. The paper will present an overview of CaSSIS and the optical performance of the telescope and the FPA. The preliminary results of the on-ground calibration campaign and the first light obtained during the commissioning and pointing campaign (April 2016) will be described in detail. The instrument is acquiring images with an average Point Spread Function at Full-Width-Half-Maximum (PSF FWHM) of < 1.5 px, as expected.

Keywords: space instrumentation, push-frame technique, telescope, focal plane, filter

I. 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. These technical requirements combined with programmatic constraints have driven the instrument design.
CASSIS OBSERVATION APPROACH: 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, as sown in Fig. 1. The strategy to obtain colour images using the push-frame imaging approach also follows the one used on Simbio-Sys and is based on the capability of the CMOS detector to acquire framelets in up to six user-defined windows simultaneously [1].

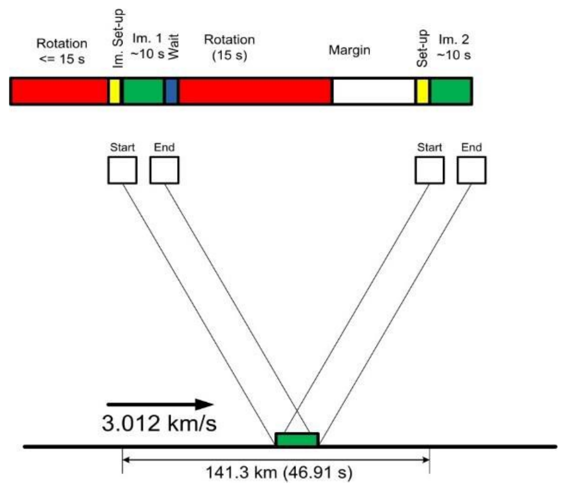


Fig. 1 Cassis telescope stereo colour observation approach

An array of discrete stripe colour filters, the Filter Strip Assembly (FSA), is thus installed in front of the detector, with their long-axes perpendicular to the ground-track direction. Framelets are acquired from pixels exposed by 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, .

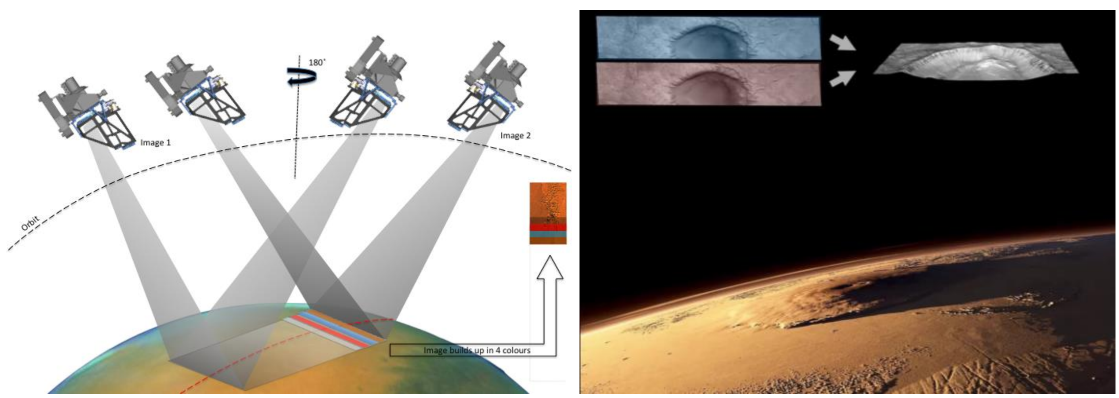


Fig. 2 Cassis telescope stereo colour observation approach

The overall dimensions of FSA from Symbio-sys have been conserved but the number, dimensions and positioning of the filters within the window have been modified to reflect the differences in imaging operation, optical design, and scientific aims of the Symbio-Sys and CaSSIS instruments. The field-of-view of CaSSIS, the ground-track velocity of TGO, the signal-to-noise budget and internal bottlenecks in the data transmission rate result in an optimal use of the detector area with four different colour filters and the simultaneous acquisition of up to three framelets with a maximum size of 2048x280 pixels, at a repetition rate of 367 ms. A broad transmission filter, PAN, was selected to provide the highest signal and will be used for stereo reconstruction. In our baseline configuration, 280px-high framelets will be acquired through this filter in order to have a 15% overlap between successive acquisitions. The framelets acquired through the three other colour filters will be 256px high, resulting in a 5% overlap. Data through the PAN filter are acquired on both observations in a stereo run to provide the stereo pair. 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. 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. 3 shows the structure of the CaSSIS instrument and Table 1 reports the main optical data.

Tab 1 CaSSIS Optical data

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

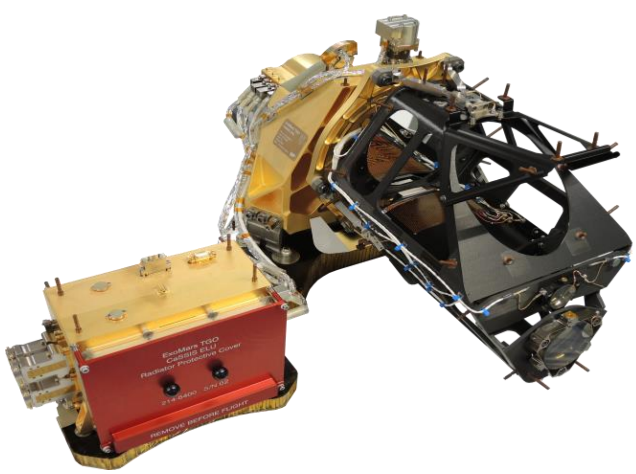
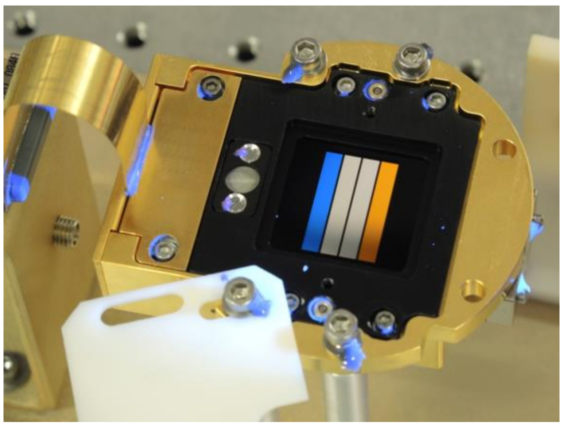


Fig. 3 CaSSIS: CRU with telescope on right side and ELU with red cover on left side

II. THE CASSIS FOCAL PLANE ASSEMBLY

CaSSIS Focal Plane Assembly (FPA) reuses the FPA of the Simbio-Sys instrument for ESA's BepiColombo mission. 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 the 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 optical window incorporates the broad-band optical filters and represents the FSA. The FPA as shown in Fig 4.



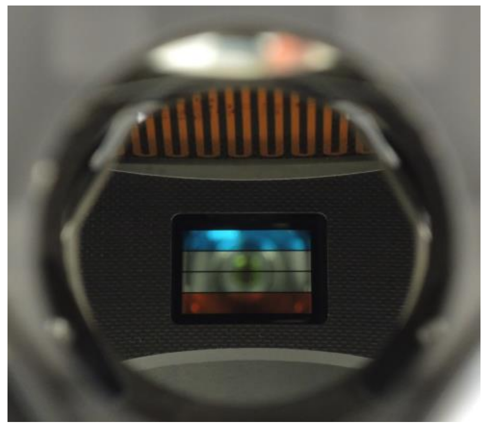


Fig 4 Picture of the filter assembly integrated on the FPA. The FPA was illuminated by UV light to check for contamination by dust. The filter on the left of the picture is PAN, reflecting blue light and the filter on the right is BLU reflecting red and orange light. In between, the RED and NIR filters both reflect all visible light and appear like mirrors. In right side how the filters of the FPA appear through the Entrance pupil of the telescope

The 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, were produced by Balzers (Optics Balzers Jena GmbH) 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 [2].
The filters bands are in Fig. 5 shown and the optical performances are fully described on the paper [3]

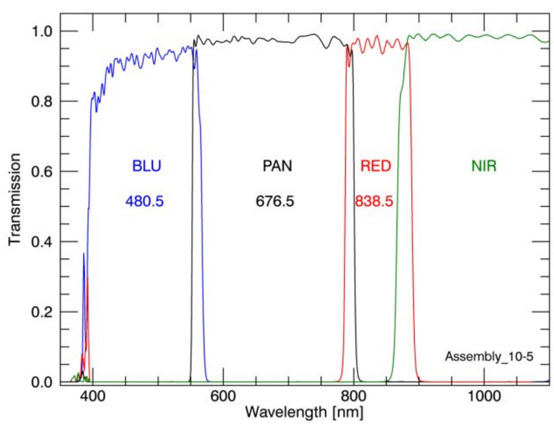


Fig. 5Measured transmission curves through the centres of each of the bandpass filters of assembly 10_5, which was then integrated on CaSSIS PFM. These measurements were performed by Balzers (Optics Balzers Jena GmbH) prior to shipment of the filters to the University of Bern. The numbers shown below the filters names for BLU, PAN and RED are the central wavelengths for these three filters, calculated from the filters edges, defined here by 50% of transmission. This number is not defined for the NIR filter as the long wavelength edge was not measured.

The wavelength bands for the four colour filters of CaSSIS were derived from the ones used on the HiRISE/MRO instrument. The two first 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. This additional colour is designed to improve the discrimination between expected surface minerals, particularly Fe-bearing phases, as electronic transitions and crystal field effects are responsible for strong and diagnostic absorptions in the 0.7-1.1µm range by minerals containing ferrous iron $Fe2+$ (mafic minerals olivine and pyroxene) and ferric iron $Fe3+$ (hematite, goethite…). The wing of the saturated UV absorption band caused by the Fe charge-transfer also strongly affects the spectrum at shorter wavelength, which will affect the BLU/PAN ratios. As the reflectivity of the Martian surface at blue and green wavelengths is very low, the BLU filter provides an extremely high sensitivity to fog and surface frost.

III. THE OPTICAL SYSTEM

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 main optical data in Tab 1 are reported. 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.

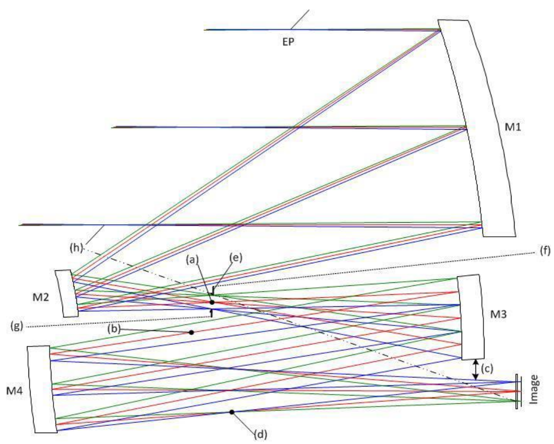


Figure 6 Ray tracing via ZEMAX code of the CaSSIS 135 optical system. The TMA configuration has an intermediate focal plane (a) and two intermediate walls (f and g) which subdivide the telescope into an upper compartment with M1 and M2 and a lower compartment with M3 and M4 separated with baffles to avoid direct light in to the detector through the field stop. The powered folding mirror M4 allows maintaining compact design and telecentric system.

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. The overall imaging performance achieves a Modulation Transfer Function (MTF) >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 . Fig. 7 shows the simulated polychromatic MTF at different FoV in the wavelengths range 400-1000 nm and a simulated through focus at 632 nm on the focal plane wrt the best focus in Fig.8 is reported:.
University of Bern was responsible for the integration of the detector on the telescope. The Optical Ground Segment Equipment (OGSE) used to integrate the detector and to test the optical performances of CaSSIS is 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 and the Full Entrance Pupil diameter (EPD) of the telescope covered by the collimated beam, as Fig. 9 shows. The pre-alignment of the CaSSIS telescope with the OAP optical axis was achieved using a theodolite alignment technique [4].

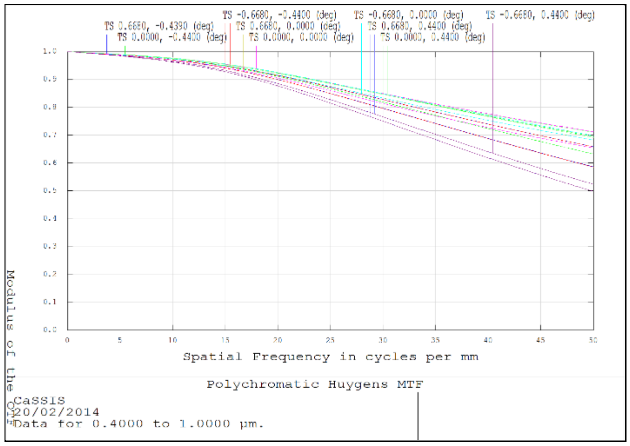


Fig. 7 Simulated (Zemax code) polychromatic MTF (range 400-1000nm) over the full CaSSIS FoV (1.336°x0.887°) corresponding to a 20.48 mm x 13.56 mm area on the image plane of the detector.

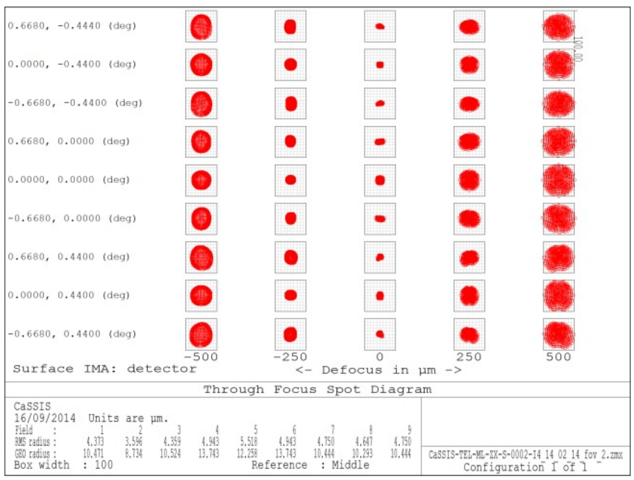


Fig. 8 Simulated Through focus ± 250 micron at 632 nm on detector image wrt the best focus position. (via Zemax code) and the obtained RMS spot diagrams over the full CaSSIS FoV (1.336°x0.887°) corresponding to a 20.48 mm x 13.56 mm area on the image plane of the detector. The focused spot is collected in 2x2 pixel (20 micron x 20 micron)

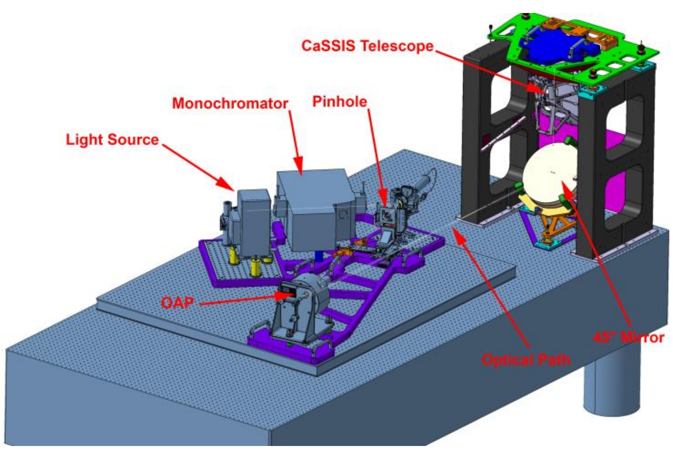


Fig. 9 OGSE used to integrate the detector and to test the optical performances of CaSSIS. The collimated beam obtained with an 147 mm-diameter Off Axis Parabola (OAP) and a 10 µm pinhole and illuminated with either white (Quartz Tungsten Halogen) or monochromatic (10 nm FWHM bandpass) light. The CaSSIS telescope optical axis vertical via the 45 deg mirror to mitigate the effects of Earth gravity.

The 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 20µm. 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, ratio of the respective focal lengths of the OAP and CaSSIS telescope was then applied to calculate the defocus distance of the CaSSIS detector [5]. This 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-mechanic 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 lamba/40) to provide a perfectly collimated beam and changing the size of the detector shims to obtain images at various through-focus positions.

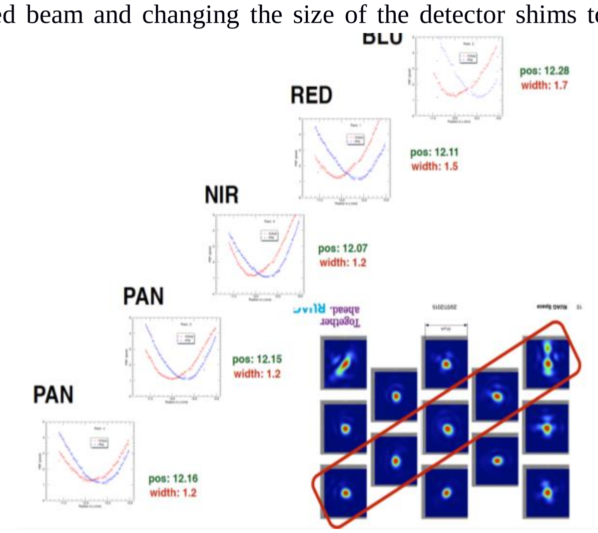


Fig. 10 PSF FWHM obtained in the position on the diagonal red line.

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 Fig. 10. 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 on the telescope data provided by RUAG Space. Because of all the difficulties mentioned in section X, 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 integrations 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, without being able to provide any estimate of the actual width.

IV. FIRST LIGHT IN FLIGHT

CaSSIS obtained its First light with the preliminary focus results images on the 7th of April 2016 during Near Earth Commissioning of TGO's instruments. All the star images are fitted to obtain characterizations of the PSF through the 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 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 (Fig. 11). Best focus for the first light acquired during the first commissioning gives PSF FWHM of about 1.2 px. 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, as Fig. 12 shows. 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.

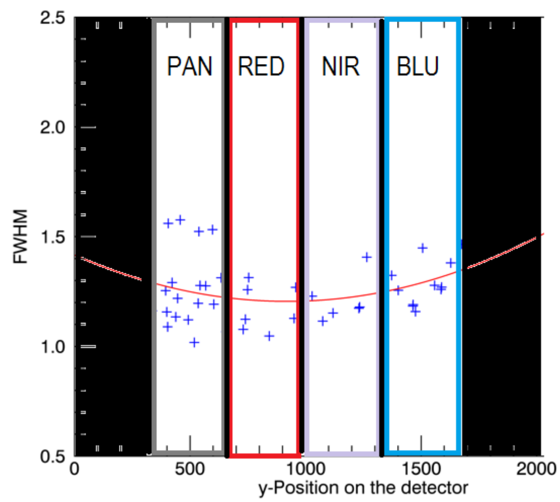


Fig. 11 The image shows the average FWHM of the PSF as a function of the y-axis (along track) position on the detector. The filters are PAN, RED, NIR and BLU from left to right. The FWHM PSF in the different filters band is confirmed as predicted.

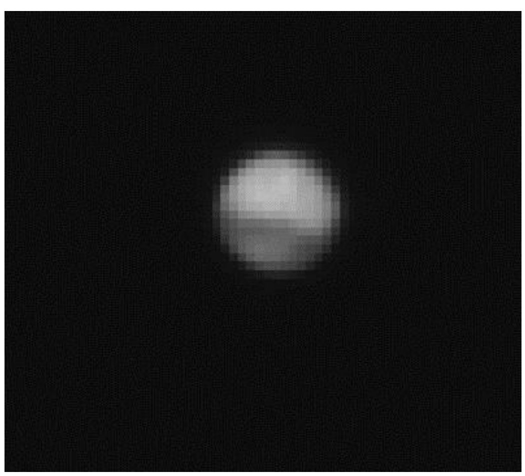


Fig. 12First Image of Mars acquired during the Mid cruise check in 13 June 2016 (41 Milions kilometers from Mars). The image confirms in base of the pixel scale that from this distance Mars appears around 15 pixels (11.36 arcsec/pixel)

V. 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.

VI. AKNOWLEDGMENT

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VII. REFERENCES

[1] Flamini et a. “SIMBIO-SYS: the Spectrometers and Imagers Integrated Observatory SYStem for BepiColombo Orbiter”,*Plan. Space Sci*., 58, 125 (2010).
[2] Bauer, T., H. Thome, and T. Eisenhammer, “Bandpass filter arrays patterned by photolithography for multispectral remote sensing”, Proc. SPIE 9241, (2014)
[3] L. Gambicorti et al. “Thin-film optical pass band filters based on new photo-lithographic process for CaSSIS FPA detector on Exomars TGO mission: development, integration and test “ Proc SPIE 9912, (2016)
[4] A. De Sio et al. "Alignment procedure for detector integration and characterization of the CaSSIS instrument on board the TGO mission”, Proc. SPIE 9904, (2016)
[5] Tubiana C.et al. “Calibration of OSIRIS images”, Astronomy &Astrophysics (2015)