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Alignment procedure for detector integration and characterization of the CaSSIS instrument onboard the TGO mission

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ABSTRACT

The Colour and Stereo Surface Imaging System (CaSSIS) is a high-resolution camera for the ESA ExoMars Trace Gas Orbiter mission launched in March 2016. CaSSIS is capable of acquiring color stereo images of features on the surface of Mars to better understand the processes related to trace gas emission.

The optical configuration of CaSSIS is based on a three-mirror anastigmatic off-axis imager with a relay mirror; to attain telecentric features and to maintain compact the design, the relay mirror has power.

The University of Bern had the task of detector integration and characterization of CaSSIS focal plane. An OGSE (Optical Ground Support Equipment) characterization facility was set up for this purpose. A pinhole, imaged through an off-axis paraboloidal mirror, is used to produce a collimated beam.

In this work, the procedures to align the OGSE and to link together the positions of each optical element will be presented. A global Reference System (RS) has been defined using an optical cube placed on the optical bench (OB) and linked to gravity through its X component; this global RS is used to correlate the alignment of the optical components.

The main steps to characterize the position of the object to that of the CaSSIS focal plane have been repeated to guide and to verify the operations performed during the alignment procedures. A calculation system has been designed to work on the optical setup and on the detector simultaneously, and to compute online the new position of the focus plane with respect to the detector.

Final results will be shown and discussed.

Keywords: space instrumentation, telescope, alignment and integration, FPA assembly, theodolites, direction cosines

1. INTRODUCTION

The Assembly Integration and Verification (AIV) phase is both the core and one of the most critical phases in the preparation of a space mission. The results affect both the final performance of the instrument and its preliminary characterization. All the required operations and subsequent measurements are also necessary to create background knowledge of the instrument that will be then used to interpret the data acquired during the mission.

Moreover, the preparation of space instrumentation must conform to many constraints, involving state-of-the-art technical setups and checks, in order to guarantee the quality of the outcome; a careful coordination management and registration of all interventions are needed. So, high precision in the alignment of the components, their subsequent fastening, as well as time schedule, budget and communications with ESA, are all problems to be tackled during the complete work.

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From this point of view, the CaSSIS telescope is a special instrument. It has been finally approved in 2013 and launched in 2016. This has led to a really tight schedule (almost half time of a standard instrument) driving some of the adopted solutions.

CaSSIS [1] is the Colour and Stereo Surface Imaging System onboard the ESA ExoMars Trace Gas Orbiter (EMTGO). ExoMars2016 was launched in March 2016 and will arrive at Mars in October 2016. EMTGO main objectives are the detection of a broad suite of atmospheric trace gases, the characterization of their spatial and temporal variation and localization of the sources of the key trace gases.

CaSSIS is intended to acquire moderately high resolution, color and stereo images of the Mars surface from a circular orbit 400 km above the surface. The CaSSIS telescope assembly has been designed to support acquisition of both single images and stereo image pairs. The telescope assembly comprises optical elements for focusing the beam, mechanical mounts for supporting the optical elements, structures to support the optical elements and mounts, internal baffles and field stops, mounting structures for interfacing to the rotation drive and to the Focal Plane Assembly (FPA) [2] (see Figure 1a). The FPA is equipped with 4 filters in the wavelength range from 400-1100 nm [3]. The main characteristics of the CaSSIS instrument are summarized in Table 1.

Table 1. CaSSIS instrument main data.

Optical data	**Nominal Value**	**Measured Value (if available)**
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 (colors)
# of images returned per exposure	4	3-6 (small windows used as dark current/bias validation)
Detector area used	2048 x 1350 px	2048 x 1291 px
FOV of used area	1.33° x 0.88°	1.35° x 0.85°
Nominal image overlap	10%	5%
Filters		
PAN (central wavelength/ bandwidth)	675 nm/ 250 nm	675 nm/ 250 nm
BLU (central wavelength/ bandwidth)	485 nm/ 165 nm	485 nm/ 165 nm
RED (central wavelength/ bandwidth)	840 nm/ 100 nm	835.5 nm/ 100 nm
NIR (cut-on wavelength)	876 nm	867 nm

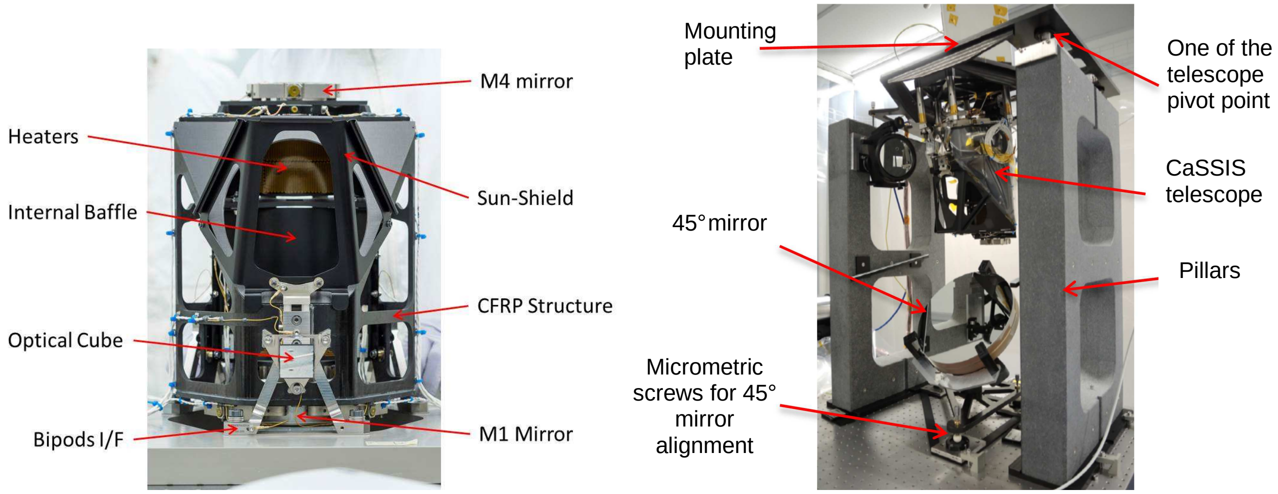
In this paper all the alignment procedures carried out in the AIV to integrate the detector on the focal plane of the CaSSIS telescope will be described, including a discussion on the motivations and drivers that have influenced each operative step.

The main aim of the paper is, then, to describe the Optical Ground Support Equipment (OGSE) and to link together all the positions of its optical components. The procedures necessary to characterize and to align the OGSE will be described. This process requires the definition of a Reference System (RS) common to all components, that can be easily checked and that allows to verify the OGSE stability and reliability. Such a RS allows to define the mutual positions of all optical components of the OGSE.

After that the references, on the CaSSIS telescope, will be characterized in the same RS allowing calculation of the mismatch between the direction of the collimated beam generated by the OGSE and the optical axis of the telescope.

CaSSIS has a field of view (FoV) of 1.33° × 0.88° and it is provided with a Raytheon Vision System 2k x 2k pixels Si PIN hybrid CMOS detector [4]. Each pixel has a FoV of 11.36 µrad that corresponds to 2.34”. In principle, a precision of 13 pixels is required for the positioning of the central field, this corresponds to a precision of 30” in the alignment between the OGSE and the CaSSIS optical axis.

To reach such a challenging precision, a feedback loop of operations has been developed in order to minimize the contribution of instrumental errors. We have performed the final steps by introducing, in the alignment feedback loop, the detector itself and correlating the adjustment also with the shape and movement of the PSF on the focal plane of the telescope.



(a) (b)

Figure 1. (a) CaSSIS telescope main components including the RUAG reference cube. (b) CaSSIS telescope mounted in the cleanroom area over the optical bench. The different parts of the mechanical support structure and the 45° mirror are highlighted.

2. THE EXPERIMENTAL SETUPS

In this section the laboratory setup, the instrumentation available for the alignment and the optical setup will be described.

2.1 Laboratory environment

In order to maintain a low contamination level of the components, all the operations have been carried out in a 25 m^2 laminar flow ISO5 clean room. The clean zone is surrounded by a grey zone, designed to host the electronic support equipment and the technical personnel that are non-directly involved in the instrumentation handling but that are needed to communicate and to operate during the alignment integration phases.

In the ISO5 zone a stabilized 1.5 x 3 m^2 optical bench has been used as reference plane for the calibration setup and for the telescope. The telescope has been placed down-faced, with the optical axis parallel to the gravity, connected on a support fabricated with two monolithic granite pillars and a metal interface plate to host the telescope itself. The telescope can be moved, with respect to the interface plate, on three pivots in order to change its orientation with respect to the vertical direction (see Figure 1b).

2.2 Optical setup

The aligning optical setup has been studied in order to provide a collimated beam simulating a point-like object source placed at infinity. In particular, a 10 µm pinhole, placed in the focus position of an off-axis paraboloidal mirror, has been used to produce the collimated beam. The off-axis paraboloidal (OAP) mirror has 1035 mm effective focal length and a 14.7 cm clear aperture.

The generated collimated beam is parallel with respect to the surface of the optical bench and perpendicular to the CaSSIS optical axis. The collimated beam is then reflected in the upwards direction by a 30 cm diameter $\lambda/4$ flat mirror. The angle of the mirror with the beam is nominally 45°, but can be adjusted, with micrometric screws, to allow the alignment with the optical axis of the telescope (see Figure 2).

The OAP focal plane is conjugated with the CaSSIS focal plane and the magnification (i.e. the ratio between the focal length of CaSSIS and the one of the OAP) is about 0.9.

In order to explore the CaSSIS FoV, the pinhole can be moved, with micrometric precision, in the focal plane of the off-axis parabola. The pinhole can also be moved back and forth from the focal plane, intra and extra-focus, thus allowing to change the distance of the object (simulated star). A through-focus scan at the telescope level can then be implemented.

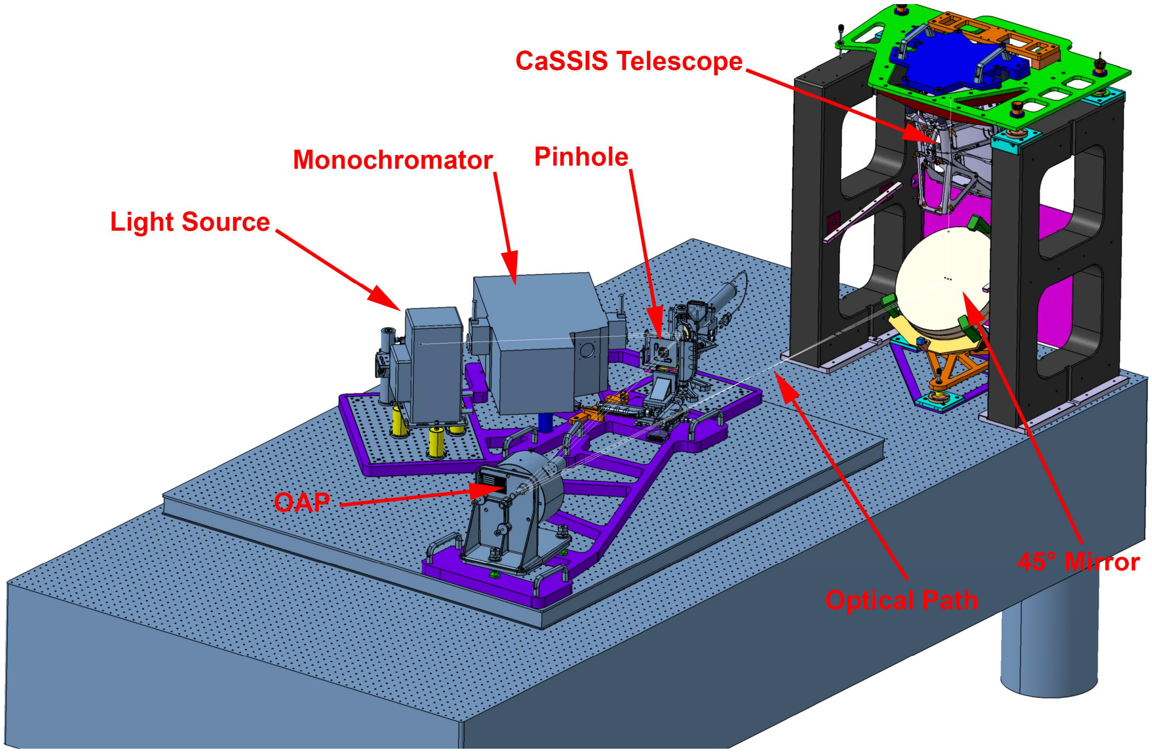


Figure 2. Schematic view of the whole setup for the alignment. The optical elements are indicated and the path of the optical beam is highlighted in white.

2.3 Instrumentation

The available instrumentation for alignment included two Leica Geosystem TM5100A theodolites with a nominal precision of 2" [5]. The precision of the instrument is limited, in our case, by the short distance between the theodolites and the reference surfaces. The surface of the laboratory limits at a maximum of 3 m the distance between the theodolites and the autocollimation surfaces or between the two theodolites themselves.

The theodolites have to be correctly mounted and set in place before measurement, in particular they have to be levelled accurately before to start using them. To improve the measurement accuracy, i.e. to compensate some of the errors introduced by the theodolite not being perfectly calibrated, we measured the azimuth (Az) and elevation (El) of the target surface, or those of the other theodolite, in both of the surfaces of the theodolites [6]. The measured Az and El have been taken as the mean of the two measurements.

2.4 Optical setup: references and relative and global Reference Systems

In order to be able to characterize each optical component, a relative reference system has been considered for each optical element. The relative RS is identified by an optical cube mounted on the structures or supports of the optical component thus fixed with the element. Optical glass cubes are carefully machined in order to have high precision perpendicularity among the faces. Three or more faces are polished down to λ/20 and treated with reflecting coatings. Thus, vectors perpendicular to three of these surfaces can be used as an orthonormal basis. Each of these bases can be then used to describe the features of the optical system. The CaSSIS structure, as an example, was provided with two reference cubes, in two different positions (called Ruag optical cube - RuagRS - and Bern optical cube). Then, during the integration of the mirrors, the RUAG Optics Department has characterized the CaSSIS optical axis with respect to these two RSs (cubes).

In order to reconstruct the RS, it is sufficient to measure at least two vectors perpendicular to two cube surfaces (the third can be calculated as the vector perpendicular to the plane identified by these two vectors).

All the cubes fixed to optical elements define a relative-RS. In order to have an absolute reference, an optical cube has been placed on the optical bench and it has been considered to be the main, or global, reference system (OBRS).

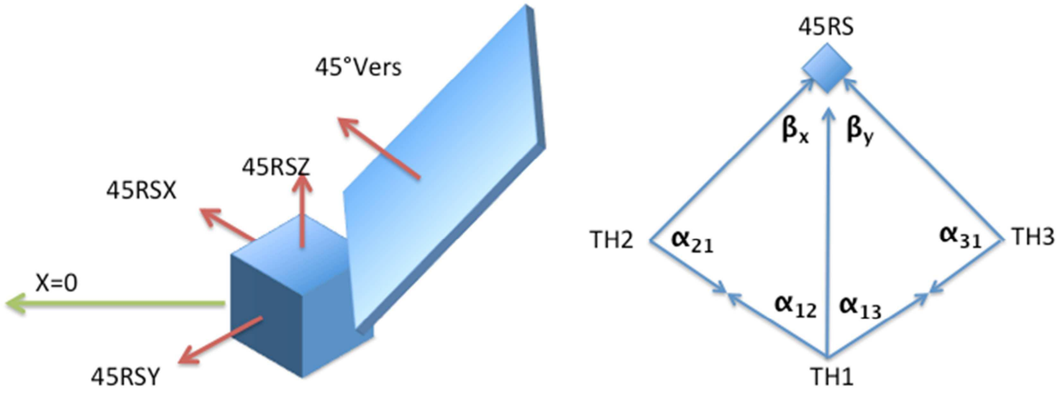
3. MEASUREMENTS

Here, all the procedures, the theodolites placements, the vector analyses and the expedients we found to optimize the data acquisition will be described.

In the first phases, the OB active damping system was not functional avoiding possible orientation corrections introduced by the stabilization of the table. Thus, in the beginning we decided to use a RS having one of its axes fixed with one of the axes of OBRS. In particular, we will refer to a RS composed by the gravity (vertical and horizontal plane perpendicular to the gravity) with the X vector in the same direction of the X vector of the OB cube, i.e. GOBRS.

The aim of the procedure is to align the collimated optical beam provided by the OGSE with the CaSSIS telescope optical axis. The elements of the OGSE to be measured in the global RS are the collimated beam direction exiting the OAP and the 45° mirror orientation, since it’s reflecting the OAP collimated beam. Then also the CaSSIS telescope optical axis has to be measured in the global RS.

At the end of the procedure, the collimated beam optical axis, after the reflection on the 45° mirror, has to coincide with the CaSSIS telescope optical axis within the allowable tolerance. The available degree of freedom to align the two directions is the orientation (tip-tilt) of the 45° mirror, which can be adjusted via the three micrometric screws on its baseplate mounting.



(a) (b)

Figure 3. In (a) a sketch of the mutual position of the 45° mirror and its optical reference cube (45RS). The arbitrary position where the X axis of the reference system of this measurement is taken is also reported as a green arrow and it corresponds to the projection of the 45° mirror vector onto the horizontal plane. In (b) a diagram illustrating, a 2D projection, of the geometries and the angles that have to be considered.

3.1 The Optical Ground Support Equipment characterization

The telescope alignment requires some preliminary operations in order to characterize each optical component or subsystem. In particular the 45° relay mirror characterization with respect to its reference optical cube and the direction of the collimated beam exiting the OAP have also to be defined. We will use the description of these two measurements as a template for all the following ones, in order to avoid repetition.

3.1.1 45° mirror relative RS characterization

The first measurement is to characterize the vector identifying the direction perpendicular to the 45° mirror (45Vers) with respect to the RS defined by the reference cube glued to its gimbal (45RS). Such a measurement has to be performed only once, since the mutual position of the 45RS and the mirror itself is fixed. In Figure 3a a sketch of mutual position of the 45RS as well as the direction of the versor perpendicular to the mirror are shown. An auxiliary direction, to fix one of the axes of the RS, is highlighted in green. It corresponds to the projection of the 45° mirror vector onto the horizontal plane. This measurement, and all the following, have been carried out by using only two theodolites. One of the two theodolites remains fixed (in position TH1) while the other one can be moved in two different positions (TH2 and TH3) to measure the directions of the other reference surfaces 45RSX and 45RSY. In this kind of measurement each theodolite is the center of a reference system (RS) identified by the gravity (the theodolite must be levelled) and by an arbitrary direction onto the plane perpendicular to the gravity itself.

Thus, with respect to the scheme in Figure 3b, we autocollimate TH1 on the 45° mirror, allowing us to measure directly the direction of the versor perpendicular to the mirror. TH2 (TH3) is then autocollimated on the vertical surfaces of the 45RS cube faces (45RSX and 45RSY). After these operations, autocollimating TH1 in TH2 (and TH3), and vice-versa, we can determine the vector identifying the other theodolite in each relative RS. By combing all the angular information acquired it is possible to reconstruct, in the space of the RS of TH1, both the triangles as shown in the sketch of Figure 3b. Carefully considering the correct signs of the angles to be added, it is possible to calculate, for each versor, the elevation angle with respect to the horizontal plane, δ, and the azimuth, Az, with respect to the arbitrary direction. The components of the versor ($\hat{v}$) are then its projections on the three Cartesian axes as follows:

$$\begin{cases} v_x = \cos\delta \cos Az \\ v_y = \cos\delta \sin Az \\ v_z = \sin\delta \end{cases} \tag{1}$$

In the case we have described, we can reconstruct directly from the measurements only two of the three versors of the 45RS reference system, since the third face (RS45Z) is horizontal and cannot be autocollimated with the theodolites. In fact this surface has a direction parallel to the theodolites nadir one. Anyway, the third versor of the 45RS can be calculated as the perpendicular to the plane individuated by the other two and composing a right-handed orthonormal basis, i.e. 45RSZ can be determine as the cross-product of 45RSX and RS45Y. Since we have, in the same RS, the position of the versor perpendicular to the mirror (45Vers) surface and the 45RS, then we calculate the direction cosine of 45Vers in the 45RS.

It is worth to be noticed that all these calculations are complex and require continuous verification. Moreover, computer approximation processes, the limited precision of the instruments and the not perfect perpendicularity of the cubes faces affect the precision of the results. So continuous checks are made in order to verify that the procedures are still reliable. In particular it has to be checked that the magnitude of the versors is unitary (i.e. their modulus must be 1), mutual angles between the vectors defining the RSs (i.e. they must be 90°), orientation with respect to the gravity, etc. All these factors can be modified by the fact that all RSs, rotation matrix, perpendicularity among the faces of the RS cubes, etc. are not known exactly and are approximated by the computer calculation.

3.1.2 Collimated beam characterization in the global RS

To determine the orientation of the collimated beam exiting the OAP, a theodolite can be used to look into the OAP. In this way TH2 can be positioned to be parallel to the beam optical axis and thus the collimated beam direction can be defined in the global reference frame through the TH1 theodolite autocollimated on the OB reference cube (see Figure 4).

This measurement is based on the fact that if the pinhole is correctly placed in the focal point of the parabola, when the theodolite is seeing the pinhole at the centre of the crosshair the direction measured by the theodolite is that of the collimated beam. Expressing this direction in the GOBRS allows us to identify the orientation of the collimated beam directed to the 45° mirror. The corrected position of the pinhole is guaranteed by an ad hoc alignment procedure described in [2].

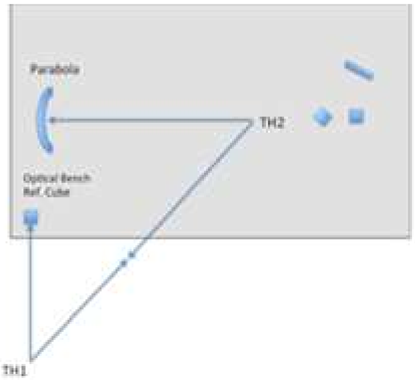


Figure 4. Schematics of the characterization of the OAP collimated beam direction in the GOBRS. The optical elements and the theodolites placements are shown.

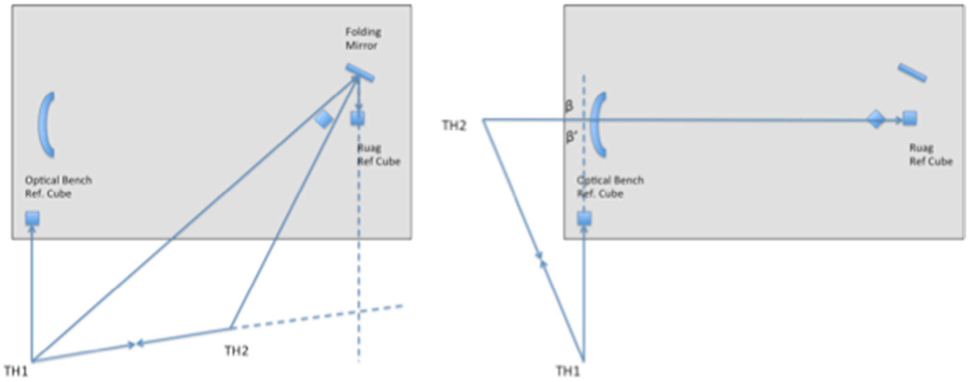
3.1.3 45° mirror in the global RS

After the preliminary characterization of the 45° mirror and of the OAP, the 45° mirror has been moved below the nominal position of the entrance pupil of CaSSIS. The 45° mirror position has been then characterized with respect to that of the optical axis of the parabola (collimating system) and to the reference system of the optical bench (GOBRS).

All angular considerations are similar to the ones described in the characterization of the 45° mirror and they are not repeated here.

The Optical Ground Support Equipment is then fully characterized when the following two operations have been done:

1) characterization of the collimated beam exiting the OAP in the GOBRS (Figure 4);
2) characterization of the orientation of the 45° mirror in the GOBRS.



(a) (b)

Figure 5. Here the mutual position of the optical components and the position of the theodolites during the characterization of the telescope position are reported. In particular (a) Characterization of the X axis of the RuagRS. (b) Characterization of the Z axis of the RuagRS.

3.2 CaSSIS optical axis characterization in the global RS

To completely characterize the system, the orientation of the optical axis of the CaSSIS telescope has to be determined. Thus two other measurements have to be done:

3) characterization of the Z axis of the RuagRS on the telescope in the GOBRS (Figure 5a);

4) characterization of the X axis of the RuagRS on the telescope in the GOBRS (Figure 5b).

In Figure 5 some sketches of the disposition of the optical components on the optical bench and layout of the measurements are reported. It is to be noticed that the position of TH1 has been fixed to be autocollimated with the X reference face (axis) of the OB reference cube. Such an operation allows us to express all the vectors, that identify the optical elements, in the unique reference system GOBRS.

Here, the procedures are similar to those described in the 45° mirror characterization with the exception that in point 3, the X face of the Ruag RS was not accesible due to the presence of the structure to keep the CaSSIS telescope. We placed then a folding mirror in order to allow, from the TH1 position, to autocollimate on the reflection on the folding mirror of the X face of the Ruag Cube. Then, the second theodolite has been placed to be able to characterize the vector normal to the folding mirror surface. The real versor $\hat{r}$**,** characterizing the X surface of Ruag cube, can be thus calculated by using the law of reflection in formula (2) [7].

$$\hat{r} = \hat{\imath} - 2\,(\hat{\imath} \cdot \hat{n})\,\hat{n} \tag{2}$$

where $\hat{\imath}$ is the versor reflected by the folding mirror and $\hat{n}$ is the versor of the folding mirror surface normal.

Finally, we can identify in the GOBRS the two fundamental vectors to perform the alignment. One is the direction of the beam at the entrance pupil of the CaSSIS telescope ($\overrightarrow{Beam}$). It has been calculated by using the law of reflection formula, described in the (2), with $\hat{\imath}$ the direction of the collimated beam exiting the OAP and $\hat{n}$ the versor of the 45° mirror surface normal.

The second vector is represented by the optical axis of the CaSSIS telescope ($\overrightarrow{OpAx}$). It has been measured by Ruag during the integration phases of the mirrors of the telescope and reported as a versor espressed in the RuagRS. By using our measurements of RuagRS-X and RuagRS-Z we calculate the RuagRS-Y and then the matrix $[\boldsymbol{A}]$ to change from RuagRS→ GOBRS. Using that matrix with the informations provided by Ruag we obtained the direction of the optical axis as:

$$\overrightarrow{OpAx}_{GOBRS} = [\boldsymbol{A}] \cdot \overrightarrow{OpAx}_{RuagRS} \tag{3}$$

3.3 Alignment Procedures

In order to be able to align correctly the beam to the axis of the telescope, it is necessary to set up an alignment-check procedure. This can be done by calculating the mutal angle α between the collimated beam direction ($\overrightarrow{Beam}$) and the CaSSIS optical axis ($\overrightarrow{OpAx}_{GOBRS}$). Such an angle can be calculated as the inverse of the cosine of the normalised dot-product between the two vectors as shown in the formula (4).

$$\alpha = \arccos \frac{\overrightarrow{Beam} \cdot \overrightarrow{OpAx}_{GOBRS}}{|\overrightarrow{Beam}||\overrightarrow{OpAx}_{GOBRS}|} \tag{4}$$

By comparing the single components of the two vectors it is possible to determine the direction of the angular shift and to compensate it by rotating the 45° mirror around one of its axes. The effect of the rotation is then calculated by measuring again the 45RS cube and, as a consequence, the new position of the vector normal to the 45° mirror is derived and the alignment-check procedure is reapplied.

In order to optimize the whole alignment process, we developed a software routine that automatically calculates the rotation of the 45RS in order to minimize the angular mismatching between the optical axis and entrance beam. Then, we calculate the direction cosine of the 45RS axis in the GOBRS after applying such a rotation. This procedure allowed us to verify, in real time with the theodolites, the magnitude of the applied rotation.

Such a procedure has been repeated several times in order to set up a feedback loop, the alignment process has been stopped when the angular difference has been found to be below 30”.

It is to be noticed that such a value is larger than the requirements but it is, in this phase, below the precision of the OGSE. Many experimental errors (the uncertainty in the perpendicularity of the cube faces, the precision of the theodolites, the short optical lever reachable, etc.) were limiting the precision of the measurements. In order to improve the accuracy, the detector has been positioned on the focal plane. In this phase it was not fastened but it was mounted on an on-purpose developed moving-tool that allowed us to rotate and translate the detector onto the surface of the focal plane. The image generated by the OGSE on the focal plane was a spot, close to the diffraction limit (we will not discuss here the adjustments of the depth of focus [2]), whose position can be determined with a sub-pixel precision by using centroid fitting procedures. We started orientating the detector angle, letting the columns be parallel to the future motion of the spacecraft. Then, we centred the image in the detector and we used the movements on the focal plane to monitor the adjustments done on the 45° mirror.

4. CONCLUSIONS

In this paper all the alignment procedures carried out in the Assembly Integration and Verification phases to integrate the focal plane assembly in the CaSSIS telescope have been described. In particular the OGSE has been described with the procedures to align its components and to characterize them in an absolute reference system.

The same RS has been used to characterize the direction cosine of the optical axis of CaSSIS. A specially developed procedure to drive the OGSE adjustments in order to center the FoV of the telescope has been described.

The aim of the alignment procedure has been to match the orientation of the beam exiting the OGSE with the telescope optical axis. To this end the direction of the beam and that of the telescope have been measured using two theodolites and autocollimating them on the optical reference cube of the OGSE and of the telescope.

Once the detector has been installed, the analysis of its images has been simultaneously used as a positive feedback on the alignment procedures of the OGSE. That approach has allowed us to reach a high precision alignment level that is now confirmed by the preliminary data taken by the CaSSIS telescope during its commissioning in the cruise between the Earth and Mars.

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