

MAP PFM camera optical and radiometric calibration test results

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ABSTRACT

The Copernicus Carbon Dioxide Monitoring (CO2M) mission will measure atmospheric anthropogenic carbon dioxide and nitrogen dioxide on Earth, and is a part of the Copernicus program of the European Space Agency (more details in [2]). To compensate for the significant error in CO2 measurements caused by aerosols in the Payloads field of view, the Multi Angled Polarimeter (MAP) instrument has been developed and will be mounted on the same satellite. The satellite will fly in a sun-synchronous low earth orbit altitude between 732 to 768km. The CO2M Mission consortium is led by OHB as satellite prime, and Thales Alenia Space in France as Payload and MAP prime. Three flight models have been ordered by ESA.

This article will first recall the main design features of MAP instrument, with description of main sub-systems of the MOU such as the telescope, calibration unit, and the focal plane assembly with polarizer and spectral filters. Then the main steps of camera integration and optical and radiometric calibration plan will be described. It includes in particular focus verification, radiometric gain calibration, polarization and spectral response measurements, but also stray-light calibration for further algorithm correction. The test results will be presented and compared to the success criteria. The 4 MAP PFM cameras have been integrated and have undergone the complete on-ground performance calibration tests at Thales Alenia Space France premises.

Keywords: carbon dioxide, polarization, calibration

1. MAP INSTRUMENT DESIGN

The MAP instrument retrieves the radiance and degree of linear polarisation of solar reflected light in 7 spectral channels ranging from 400 to 900nm, and in at least 40 different observation zenith angles. The instrument is constituted by two units, the Optical Unit (MOU) which will be the object of this article, and the Electrical Unit (MEU) that provides power to the MOU and drives the detector and calibration mechanism. A harness establishes the electrical link between both optical and electrical units. The following figure shows a view of the MOU and the MEU.

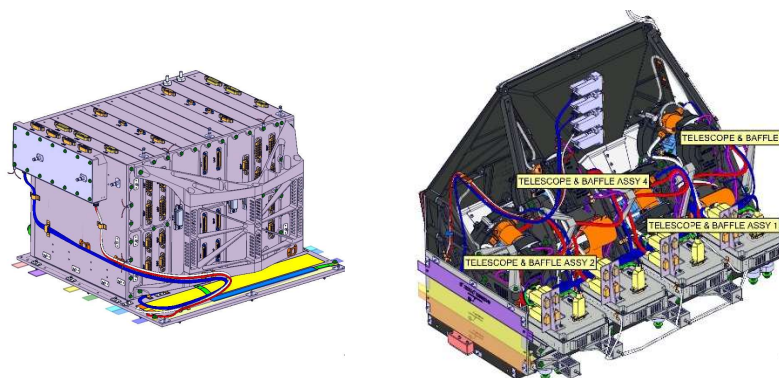


Figure 1. View of the MAP instrument optical and electrical units

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The MOU is made by an optical bench which support 4 cameras with different orientation, in order to cover the specified global field of view of $\pm 60^\circ$. Each camera is constituted by a Flight Calibration Mechanism (FCU) developed by MICOS, a telescope with 2 mirrors developed by Optec, a focal plane assembly delivered by Teledyne e2V, and proximity electronics for the detectors. Entrance baffles are also implemented for stray-light rejection purpose. The FCU function is to insert in the entrance port of the camera a diffusor when the sun is in the field of view, in order to perform in-orbit radiometric calibration. The figure below show an image of two PFM cameras without the FCU, mounted on their optical bench in the frame of alignment measurements.

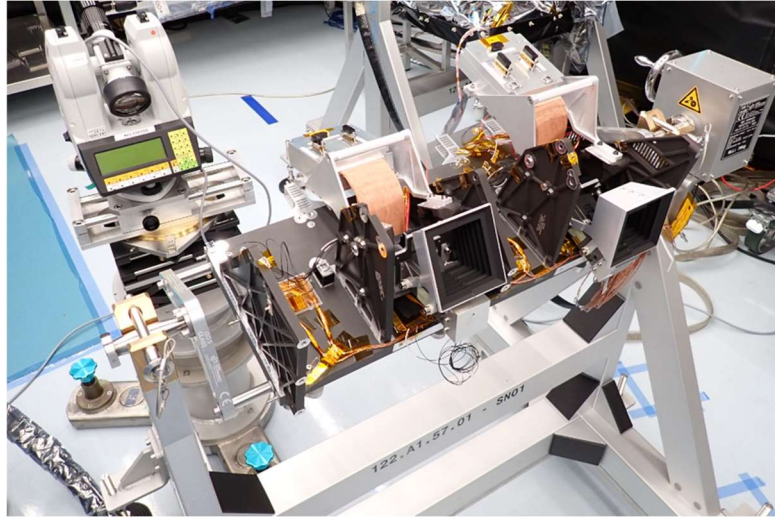


Figure 2. View of the 2 PFM cameras on their optical bench during alignment

Each camera has a focal length of about 47mm and a f-number of F/13. The field of view of each camera is larger than 25 degrees both along track and across track. The telescope is made with 2 BK7 mirrors coated with protected silver. Its design is off-axis and telecentric in image space in order to avoid variation of spectral transmission of the filters in the field of view. The SSD of each raw pixels is about 150m on ground, but binning is performed on board in order to deliver 1km x 1km products. The following table presents the main spectral characteristics of the 7 MAP bands, and the figure below shows the optical lay-out of the telescope.

Table 1. MAP spectral bands definition

	Central wavelength (nm)	Spectral width (nm)
MAP 1	410	20
MAP 2	443	20
MAP 3	490	20
MAP 4	555	20
MAP 5	670	20
MAP 6	753	9
MAP 7	865	40

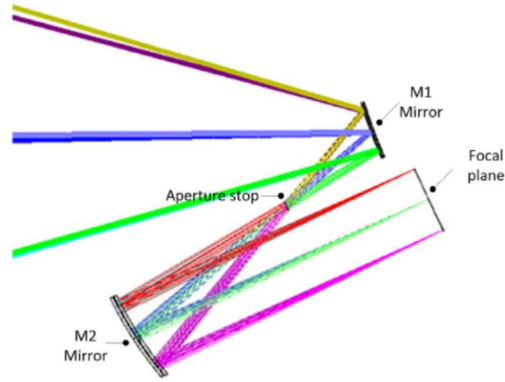


Figure 3. Telescope optical lay-out

The central part of the instrument providing the degree of linear polarization is the focal plane assembly. It is constituted by a stack of micropolarizer matrix and spectral filter which are glued directly onto the detector. The micropolarizer matrix is made of a succession of polarizer triplets arranged in along track direction, which have a polarization axis of 0° , 60° and 120° respectively. The filter plate is a 1mm fused silica substrate on which are deposited the spectral coatings on the bottom face. There is a succession of 6 different coatings for each spectral band, which are repeated 24 times allowing to provide 24 different viewing angles per camera. The detector is the CIS120 visible CMOS from Te2V, which is a matrix of 2048×2048 pixels of 10 microns size. The integration of housing holding the focal plane assembly to the telescope structure is performed by pinning, which insures excellent positioning and reproducibility. The following figures shows the principle of focal plane assembly, as well as an exploded view of the detector mounting on the telescope mechanical structure.

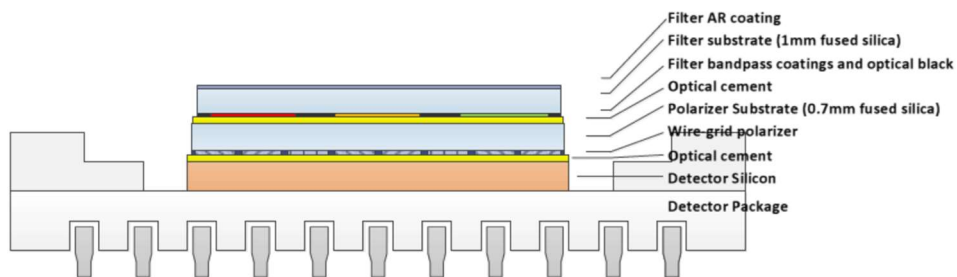


Figure 4. View of the focal plane assembly with filter plate, micropolarizer and detector

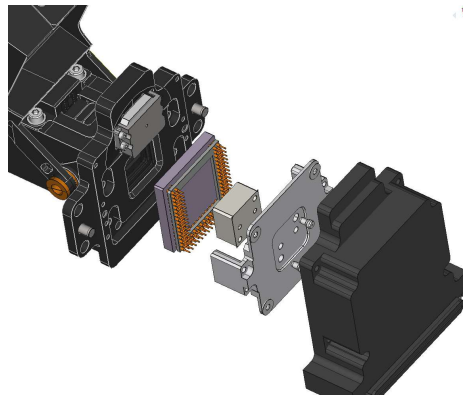


Figure 5. exploded view of the telescope interface (left), detector, titanium shim, detector housing and protective cover (right)

A more detailed description of the instrument design and expected performances can be found in [1].

2. OPTICAL AND RADIOMETRIC CALIBRATION TESTS

The camera calibration is the first phase which occurs just after the integration of the sub-systems, namely the focal plane assembly with the telescope. All the activities are performed in ISO5 clean room for contamination control purpose. The camera is powered and operated thanks to EGSEs named camera controllers. Each camera is individually tested and the sequence is optimized so that up to 3 cameras can be measured in parallel on different test benches. For each type of measurement and performance, a specific OGSE has been developed. The following section will describe for each type of test: the objective, the parameters to measure, the OGSE used, the measurement conditions, and the success criteria.

2.1 Focus verification

The first test performed is a verification of the focus of each camera, in order if necessary to modify the focalization by shimming before starting the calibration campaign. The test bench used for geometrical verification is called the Point Source Generator (PSG) bench. Two identical PSG benches are available to perform several camera calibration in parallel. The PSG is constituted of a fixed pinhole located in the focal plane of a collimator, the camera being mounted on an hexapod which rotates around the instrument pupil to address several points in the field of view. A matrix of 3 x 3 points are measured, and this also allows to measure the focal length of the camera. The success criteria of this test is on the FWHM dimension of the Point Spread Function, which is by design about 2 to 3 pixels (20 to 30 microns). The following figure shows an example of test results for one PFM camera, with the images of the 9 points (called P1 to P9). The table shows the FWHM of the spot both in ALT and ACT directions in number of pixels, with the measured value in green compared to the success criteria : the focus is compliant.

Table 2. Focus measurement results for one PFM camera

	ACT width		ALT width	
P2	1.81	<3.06	2.73	<3.85
P4	1.71	<3.12	1.82	<3.16
P6	1.74	<3.12	1.87	<3.16
P8	1.86	<3.40	2.12	<3.47

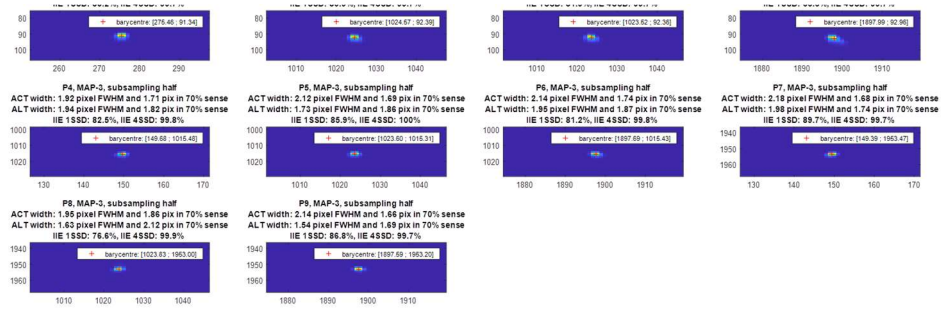


Figure 6. Images of the 9 points during focus verification

2.2 Radiometric gain calibration

The gain of each pixel of every camera is calibrated thanks to a source which radiance has been itself absolutely calibrated relatively to international standards. The bench developed for this purpose is called the Absolute Radiometric Accuracy bench (ARA). It is made of an integrating sphere with both halogen and LED lamps, and a photodiode monitoring system to be able to correct any drift of the lamps. The camera is placed in front of the output port of the sphere at a known and fixed distance, and dedicated baffles are put between the port and the camera to avoid any stray-light perturbation. In order to reach the dynamic range of every MAP spectral channels the acquisitions are performed with several sources configurations. In order to average out the measurement noise, 500 images are acquired for each configuration. The requirement about absolute radiometric accuracy is quite challenging since it specifies a 3% performance at 2 sigma. The acquisitions have been performed as required, by checking that there was no saturation of the signal, the source monitoring was acquired and the number of needed images was reached. The following figure shows two acquisitions for two positions of the same PFM camera, confirming that the whole field of view is calibrated.



Figure 7. Images of absolute radiometric calibration for one camera at two positions

2.3 Polarization calibration

The main performance of the MAP being its capability to retrieve the degree and angle of linear polarization, each camera is subjected to an accurate polarization calibration. By measuring the signal on each polarizer triplet, one can deduce the degree of linear polarization of the input beam. The OGSE used is called the Wide Field Polarisation bench. It is constituted by an integrating sphere which produces a uniform radiance of its output port, Xenon and QTH lamps, spectral filters to cover each MAP band, as well as high performance polarizer. The camera is placed on a hexapod and is moved in front of the sphere in 9 different positions, in order to cover the whole field of view of the camera. The polarizer is rotated from 0° to 360° by steps of 20° . The following figure show the bench set-up for polarization measurement.

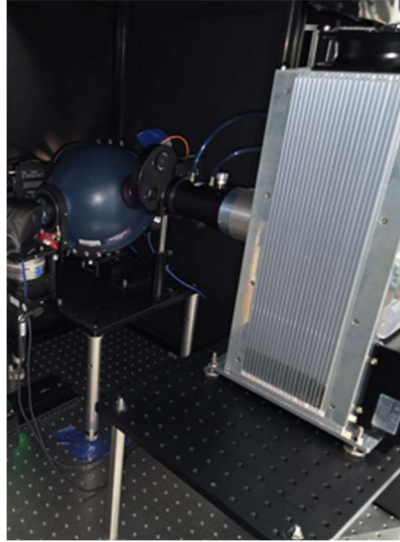


Figure 8. Wide Field Polarization bench with Xenon lamp, spectral filters and integrating sphere

The following table shows the error at 2 sigma on the retrieved degree of linear polarization on one PFM camera, for each MAP band and for the 9 measured positions of the camera (each line in the table). The obtained uncertainty is lower than 0.75% at 2 sigma which compliant to the success criteria.

Table 3. Error on the degree of linear polarization at 2 sigma for each band on one PFM camera (absolute value)

Filtered Light	MAP1	MAP2	MAP3	MAP4	MAP5	MAP6	MAP7
HG	0,0060	0,0062	0,0062	0,0069	0,0048	0,0030	0,0040
HC	0,0062	0,0062	0,0062	0,0068	0,0046	0,0032	0,0038
HD	0,0061	0,0061	0,0061	0,0067	0,0048	0,0030	0,0039
CG	0,0057	0,0060	0,0062	0,0065	0,0048	0,0037	0,0042
CC	0,0059	0,0064	0,0064	0,0063	0,0046	0,0039	0,0041
CD	0,0058	0,0063	0,0062	0,0064	0,0047	0,0039	0,0039
BG	0,0067	0,0059	0,0060	0,0066	0,0052	0,0046	0,0047
BC	0,0060	0,0063	0,0061	0,0068	0,0052	0,0040	0,0048
BD	0,0058	0,0064	0,0063	0,0065	0,0051	0,0074	0,0046

2.4 Spectral Response Function measurement

Another characterization that is specified is to measure the spectral function response of all the pixels of each camera. The test is performed using the Instrument Spectral Response Function (ISRF) bench. Two identical ISRF benches are available to perform several camera calibration in parallel. The bench is constituted by a tunable laser which is coupled to an integrated sphere placed in front of the camera baffle. The flux of the laser is monitored in real time using a spectrometer to allow any drift correction by post-processing. The measurement consists in scanning the complete spectral range from 380nm to 1125nm with a step of 0.5nm. The following figure shows the normalized spectral response of 2 PFM cameras for all the MAP bands, compared to the specified template. It can be noticed that both cameras exhibit very similar spectral responses, this is due to the fact that spectral filters are from the same coating batch. Both camera spectral responses are compliant to the specified templates in all the spectral bands.

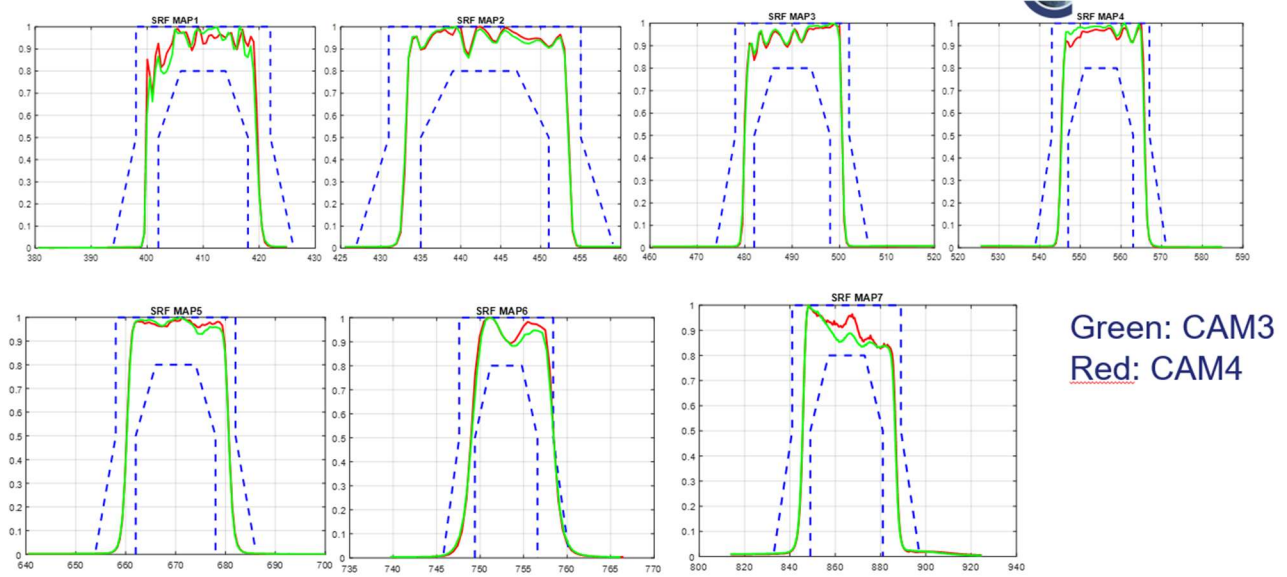


Figure 9. Spectral response of 2 PFM cameras for all MAP bands, compared to specified template

2.5 Stray-light characterization

In order to characterize the stray-light of each camera, an acquisition of the out-of-band signal is performed. Indeed the spectral filters being not perfect, a portion of MAP1 spectral content can reach the pixels below the MAP 2 filter, inducing an impact on the error on the retrieval of the degree of polarization. If this systematic term is characterized it is then possible to correct it by post-processing, since the instrument measures the radiance in all the MAP spectral bands. This measurement is called the Direct out-of-band (DooB) and is performed thanks to the PSG test bench. An horizontal slit is put at the focal plane of the collimator and spectral filters corresponding to each MAP band are put in place. The hexapod is then rotated so that the image of the slit on the camera reaches specific points in the field of view. If for instance the beam is illuminating in MAP1 spectral band, the slit will be positioned in front of MAP1 camera filter (providing in band high signal), then in front of MAP2 filter (providing out-of-band low signal), then in front of MAP3 etc... The following figure provides an illustration of the measurement results on one camera, in a form of an array of sub-images. Each sub-image has been zoomed to show only the slit image which is about 150 pixels, and the color scale has also been adjusted individually. While the in-band signal reaches about 1500 to 2000 LSB (out of 4096 LSB of dynamic range), the out-of-band signal ranges from 1 or 2 LSB to maximum 20 LSB. This confirms the good quality of filter coating and will allow to post-process the in-flight acquisition with this characterization.

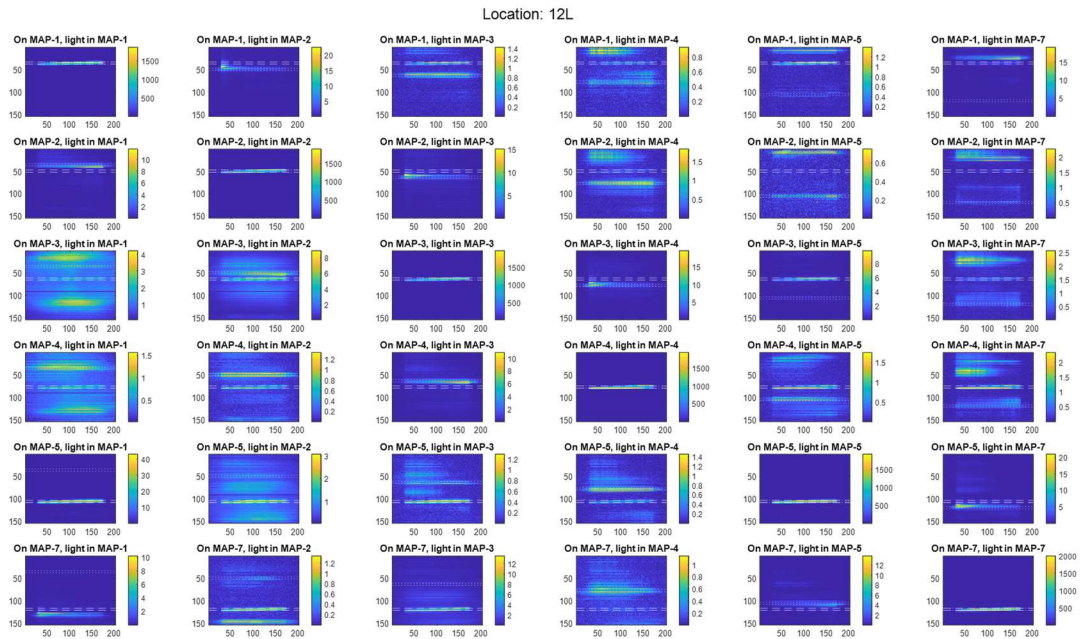


Figure 10. Measurement result of direct out-of-band characterization for one camera

3. CONCLUSION AND PERSPECTIVE

The CO2M mission of ESA's Copernicus program will provide to the scientific community quantified measurements of atmospheric anthropogenic carbon dioxide and nitrogen dioxide on Earth. To achieve this objective, the MAP instrument developed by Thales Alenia Space will retrieve the degree of linear polarization of the solar reflected light in 7 spectral channels in at least 40 different observation zenith angles, allowing to distinguish the natural CO2 emission from the one linked to human activity. This article has first recalled the design of the MAP instrument and its main characteristics. The PFM camera optical and radiometric calibration test results have been presented, including in particular focus verification, radiometric gain calibration, polarization and spectral response measurements, as well as stray-light calibration. The 4 PFM cameras have completed successfully this calibration phase and will be integrated onto the MOU optical bench at the time the article will be presented. The remaining activities will then consist into the environmental qualification tests sequence, with vibration loads and thermal vacuum cycling, before delivery of the MAP PFM instrument for integration onto the CO2M payload.

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