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Copernicus Sentinel-2C/D Multi Spectral Instrument Straylight characterization due to the Earth albedo

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ABSTRACT

The Sentinel-2 (S-2) mission is part of the Copernicus Space Component (CSC) – the European Commission's Earth Observation program. It is designed to provide systematic global acquisitions of land and coastal areas at high-spectral resolution and with a five days revisit frequency, generating products feeding a large range of operational applications in domains such as agriculture, ecosystems management, natural disaster monitoring or water quality monitoring.

The mission is currently in its operational phase with a constellation of two satellites (S-2A and S-2B) launched in 2015 and 2017 respectively, each designed for a minimum lifetime of 7.25 years with consumables sized for 12 years. In order to provide a long-term service (up to 20-year of overall mission duration), two additional satellites S-2C and S-2D were funded by the European Commission in order to take over on the constellation. The first one is expected to be launched at the end of 2023 and the second one will be stored until the replacement of S-2B.

The main S-2 payload, the Multi Spectral Instrument (MSI), is a push broom instrument with 13 spectral bands covering from the visible and the near infrared (VNIR) to the short wave infrared (SWIR). The optical architecture is based on a Three Mirror Anastigmat (TMA) with a pupil size of 150 mm and an across-track field of view of 20°. As for all Earth observation instruments and specifically for MSI instrument with a design without field stop and an entrance pupil smaller than the first mirror, it is crucial and valuable to characterize the straylight due to the Earth albedo with a good accuracy. In the frame of S-2, an innovative straylight characterization method has been developed in order to simulate the illumination of the Earth albedo seen by the MSI instrument in orbit at 800km altitude leading to a field cone of ±63°. As it is difficult to simulate in one step this configuration, a small source is moved all around the instrument in order to cover the whole Earth field cone.

This paper describes this innovative approach as well as the test setup using a robot to quickly place the source for the several required positions to cover the Earth field cone. The last results of the straylight test obtained during the MSI-D test campaign executed in 2022 and their associated accuracy are presented, showing a successful AIT sequence and completion of all tests with delivery in time that pave the way for next generation of Sentinel-2.

Keywords: Copernicus, Sentinel-2, Multi Spectral Instrument, MSI, straylight characterization

1. INTRODUCTION

1.1 Sentinel-2 mission and MSI instrument

The Copernicus program is a joint initiative of the European Commission (EC) and the European Space Agency (ESA), designed to establish a European capacity for the provision and use of operational monitoring information for environment and security applications. ESA's role in Copernicus is to provide the definition and the development of the space and ground-related system elements. As part of the Sentinels family, the Sentinel-2 mission provides continuity to services relying on multi-spectral high-resolution optical observations over global terrestrial surfaces. The key mission objectives for Sentinel-2 are: (1) To provide systematic global acquisitions of high-resolution multi-spectral imagery with a high revisit frequency, (2) to provide enhanced continuity of multi-spectral imagery provided by the SPOT series of satellites, and (3) to provide observations for the next generation of operational products such as land-cover maps, land change detection maps, and geophysical variables. Consequently, Sentinel-2 directly contributes to the Land Monitoring, Emergency Response, and Security services. The corresponding user requirements have driven the design towards a dependable multi-spectral Earth-observation system featuring the Multispectral Instrument (MSI) developed by Airbus Defence and Space. It is composed of 13 spectral bands spanning from the visible and the near infrared to the short wave infrared. The spatial resolution varies from 10-meter to 60-meter depending on the spectral band with a 290 km field of view. This unique combination of high spatial resolution, wide field of view and large spectral coverage represents a major step forward compared to previous multi-spectral missions. The mission has already a constellation of two satellites (Sentinel-2A and Sentinel-2B) launched in June 2015 and March 2017, each having a 7.25-year lifetime with consumable sized for 12 years. The two satellites are maintained in the same Sun synchronous orbit with a phase delay of 180º providing a revisit time of five days at the equator. The Sentinel-2 mission is largely detailed in [1]. To cover the 20-year overall mission duration, two additional satellites Sentinel-2C and Sentinel-2D were funded by the European Commission, the first one is expected to be launched at the end of 2023 and the second one will be stored until the replacement of S-2B.

1.2 MSI design description

The MSI instrument is a push-broom multispectral imager. It provides imagery in 13 spectral bands with spatial ranging from 10 to 60 meters. The instrument features an optical telescope providing a wide field of view (FOV) to achieve the required swath width of 290km: 20.0° across-track by 3.5° along-track. An oblong pupil equivalent to 150mm diameter is implemented to achieve a compact design and optimized optical performance.

The instrument is required to operate over a wide spectral range extending form the visible and the near infrared (VNIR, 400-1100nm) to the short wave infrared (SWIR, 1100-2500nm). A concept based on two separate focal planes is implemented. Separated focal planes are used with a dichroic filter which does the splitting between the two spectral domains:

- The VNIR focal plane assembly (FPA) is based on monolithic Silicon CMOS technology, where 10 spectral bands are combined on a single detector
- The SWIR FPA is based on hybrid HgCdTe-CMOS technology, where 3 spectral bands are integrated in a single detector. To achieve the radiometric performance, this FPA is cooled down to 195K

The instrument architecture is composed of:

- Three-Mirror Anastigmat telescope (TMA)
- A single Calibration and Shutter Mechanism (CSM)
- A VNIR focal plane
- A SWIR focal plane passively cooled
- Primary and secondary structure with thermal housing

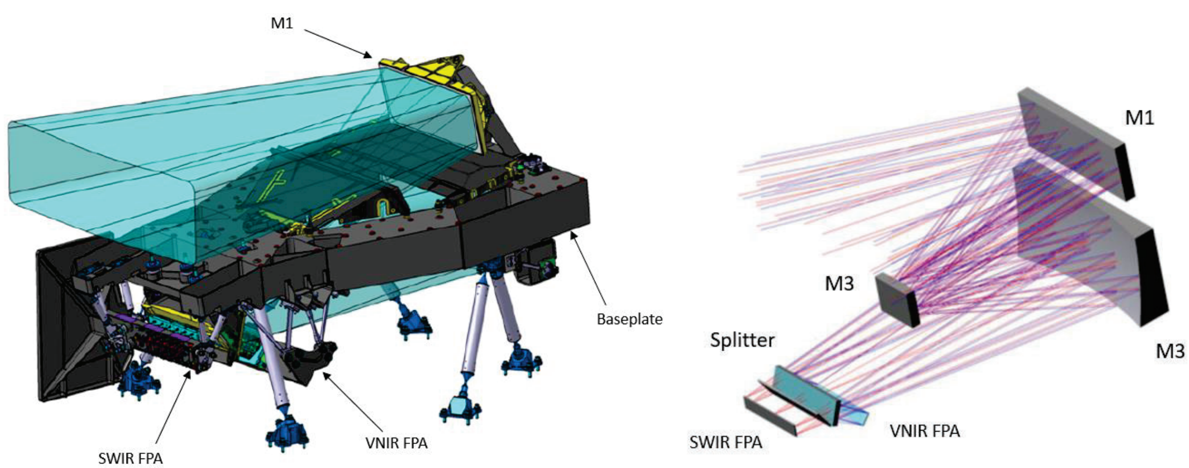


Figure 1 – Sentinel-2 MSI optical architecture overview

The optical design of the instrument is based on a TMA concept that corrects spherical aberration, coma and astigmatism – it features mirror dimensions up to 600mm. In order to ensure the homogeneity of the filter spectral response, a telecentric configuration is designed. The optical beam is split between VNIR bands (in reflection) and SWIR bands (in transmission) by a splitter close to the focal planes.

The 3 mirrors of the TMA telescope are made of Silicon Carbide (SiC) and supported by a SiC main baseplate structure. This structure is connected to the platform top panel by 3 bipods performing an isostatic mounting for preventing the instrument from being distorted by platform top panel deformations.

The CSM provides for the required observation, calibration and protection functions. It allows the closing of the aperture to protect the instrument from direct Sun illumination. The CSM integrates a diffuser for absolute calibration and allows opening the aperture for nominal Earth imaging. The absolute calibration is performed by means of a Sun diffuser inserted in front of the primary mirror. The focal plane is fully illuminated during this phase.

The primary and secondary structure is a carbon fibered stable structure carrying the telescope assembly, the CSM and the thermal housing of the instrument.

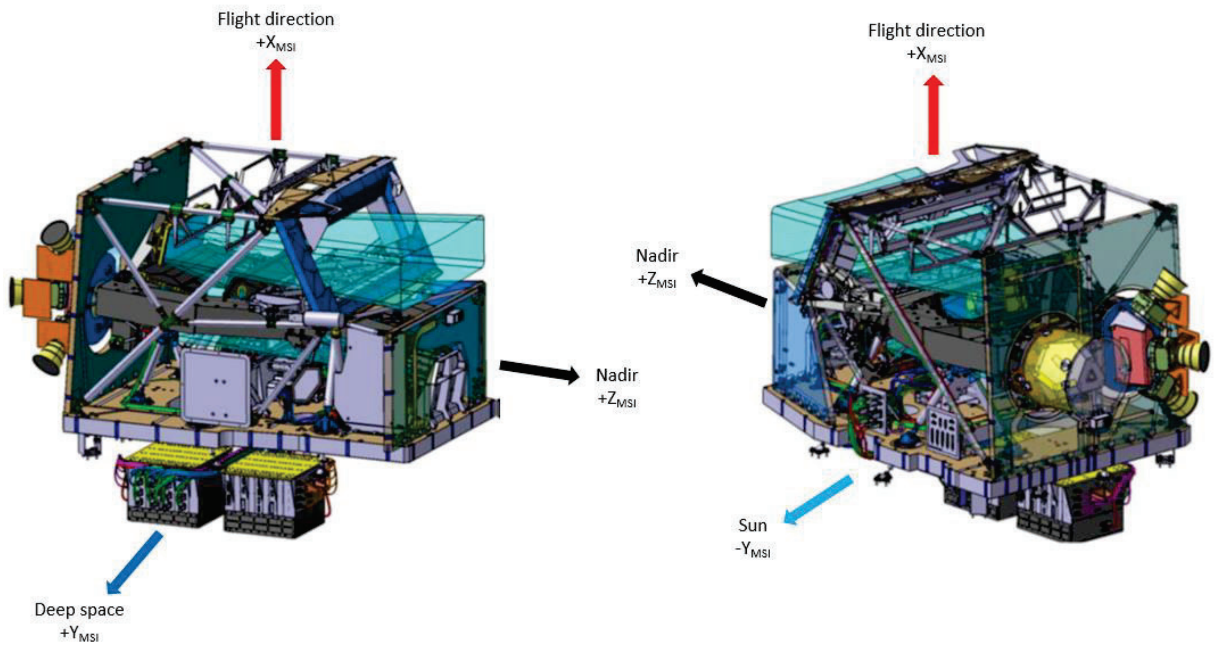


Figure 2 – Sentinel-2 MSI general overview

The main characteristics of the 13 bands are described in the following Table 1.

		Central wavelength (nm)	Bandwidth (nm)	Ground sample distance (m)
VNIR bands	B1	443	20	60
	B2	490	65	10
	B3	560	35	10
	B4	665	30	10
	B5	705	15	20
	B6	740	15	20

	B7	783	20	20
	B8	842	115	10
	B8a	865	20	20
	B9	945	20	60
SWIR bands	B10	1375	20	60
	B11	1610	90	20
	B12	2190	180	20

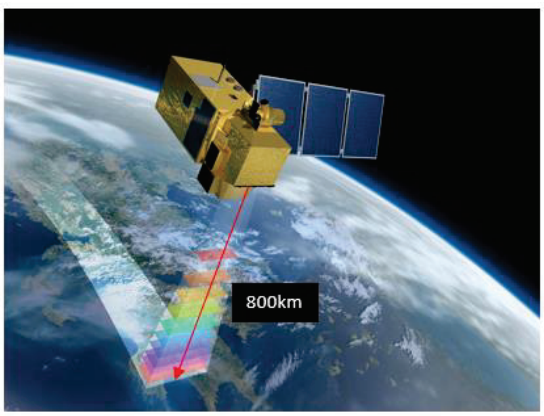
Table 1 – Sentinel-2 MSI spectral bands description

As any Earth observation instrument, the straylight is one of the major preoccupations. The main optical design drivers on the MSI instrument led to a disadvantageous design regarding the straylight minimization since: (1) there is no intermediate focal plane to include a field stop; (2) the diameter of the entrance pupil, localized behind the M1 mirror, is significantly smaller than the size of this latter mirror – which is unfavorable for the straylight out-of-FOV. That is why the characterization of the straylight due to the Earth albedo becomes mandatory.

2. STRAYLIGHT CHARACTERIZATION

2.1 Principle of the test

The principle of this test is to simulate the illumination of the Earth albedo seen from the MSI instrument in orbit. In orbit at 800km altitude, it leads to a field cone of ±63° as shown in the following Figure 3.



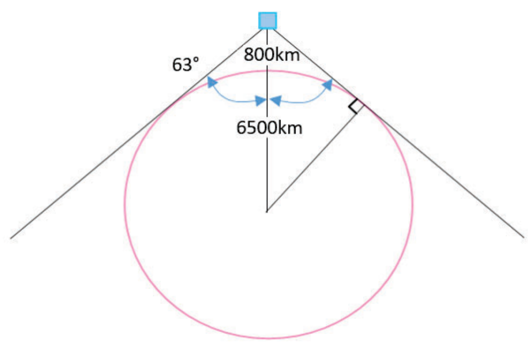


Figure 3 - The Earth is seen from the telescope under a field of view of ± 63°

As it is difficult to simulate in one step this configuration, a smaller source shall be moved at several positions around the entrance of the MSI instrument in order to map the whole Earth field cone. Images are recorded for each position of the source allowing us to assess by summation the straylight due to the Earth albedo.

A large light trap is placed in front of the MSI instrument covering its entire field of view (FOV) in order to neutralize the light seen by all pixels inside the FOV. The principle of the light trap is schematized in the Figure 4 below.

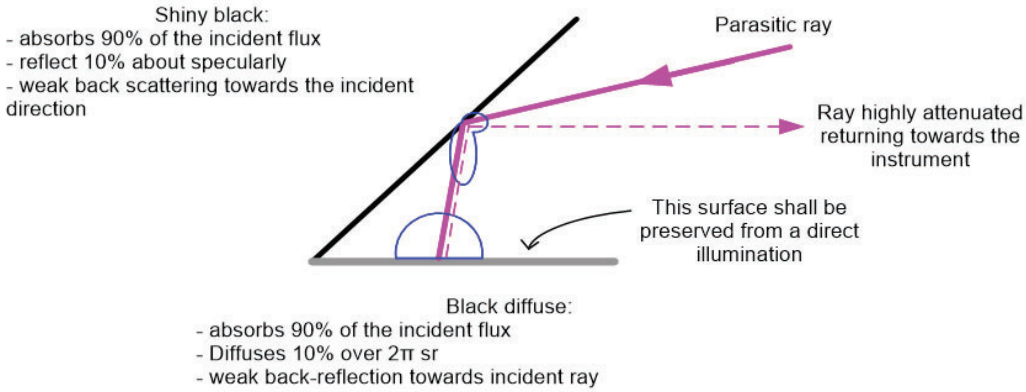


Figure 4 - Principle of the light trap

The MSI instrument is installed on a trolley and can be oriented around Z_{MSI} axis, in such a way that the light source can be placed with the purpose of mapping the Earth albedo. In order to optimize the test duration, a robotized arm is used to precisely and rapidly place the source in every defined positions described in the next section *Mapping of the Earth albedo*.

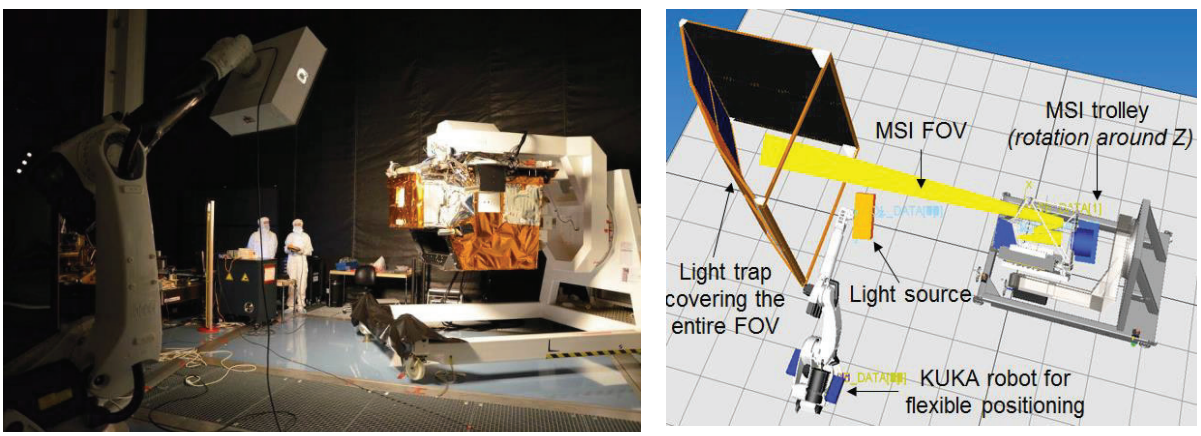


Figure 5 – Overview of the straylight setup

2.2 Mapping of the Earth albedo

The positions of the source are calculated in the MSI reference frame. The source plane shall be orthogonal to the direction of the FOV that is why it is positioned on a virtual sphere around the entrance of the MSI instrument at a distance of 3 meters. The relative positions of the source are chosen in order to minimize the overlapping but also to avoid any gap between them.

An exclusion area corresponding to the FOV of MSI instrument with some margins is defined so that no mechanical part of the source interfere with this area. The purpose is to be sure that all the pixels of the instrument can see completely the light trap without mechanical interferences.

The following Figure 1Figure 6 presents the 98 positions defined to cover the full ±63° of Earth field cone during this test.

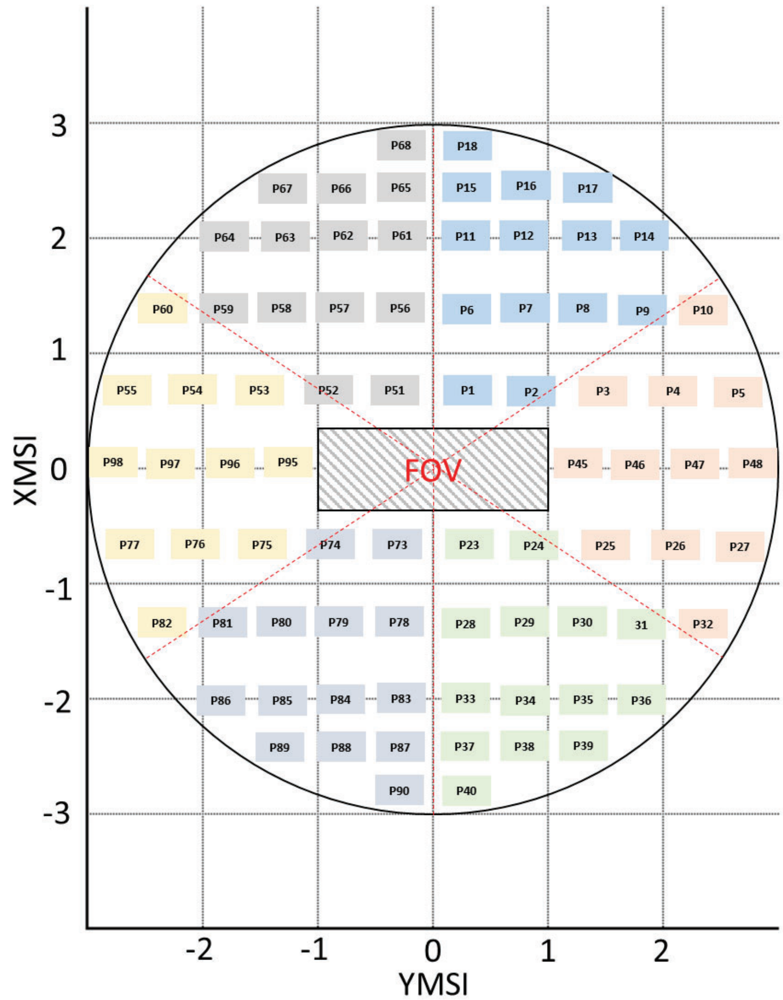


Figure 6 - Positions of the diffusing source out of the field of view

For the sake of avoiding the interference risks between the FOV of the MSI instrument and the robotized arm, 6 MSI orientations of the trolley (segments of 60°) are defined each including 12 or 14 source positions.

2.3 Characteristics of the source

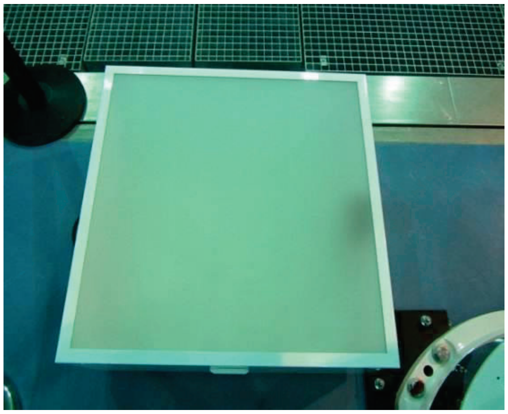
The following characteristics have been considered for the choice of the source:

- Large dimensions, to minimize the number of positions
- Good uniformity (diffusing light), to have a spatially uniform response
- High modulation of the light at 100Hz, required for the processing as explained here below
- Transportable with the robotized arm, to simplify the measurement
- Spectral range from 400nm to 2500nm, to cover all the MSI spectral range

A halogen source is consequently a good candidate as it covers all the spectral range but its main drawback is the bad modulation (thermal source and high frequency) without chopper which is not implementable because of the source size. Based on measurements, it appears that only low power halogen lamps have a good modulation: for lamps of 20W, around 25% of the averaged signal is modulated at 100Hz. Therefore, the choice of a matrix of several lamps with a screen diffuser is the best solution.

This modulation will help avoiding the effect of dark signal drift, help reducing the measurement noise and also help avoiding to measure the contribution of parasitic light in the clean room.

The main characteristics of the diffusing source are described the Figure 7 below.



Mechanical Dimensions:	800x800x350mm
Optical useful area:	740x740mm
Lamps:	70 Halogen lamps of 20W
Electrical power:	1400W 220V 50Hz

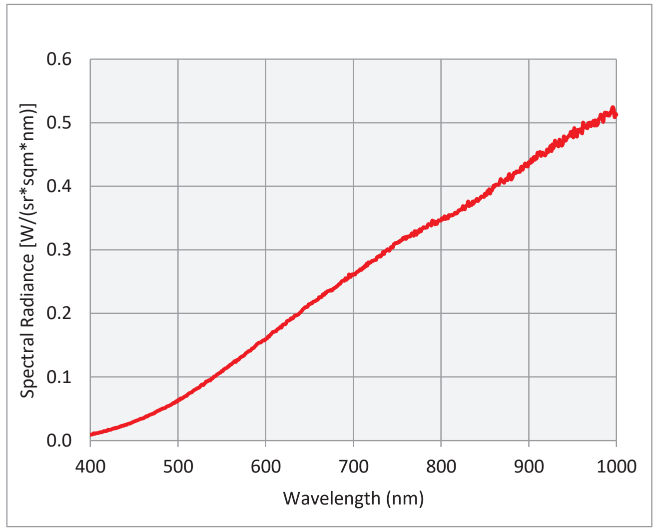


Figure 7 - Characteristics of the diffusing source

2.4 Processing and normalization

The straylight processing is based on the Fourier transform spectral analysis of the temporal measurement at 100Hz for which the FFT peak magnitude at this frequency is directly proportional to the magnitude of the modulated signal (ratio 4). The straylight detection sensitivity depends on:

- The optical power of the source and its modulation rate
- The measurement noise of the instrument around 100Hz
- The sampling frequency of the instrument

At the frequency of 100Hz (10ms), the signal is not detectable for the 60-meter bands because of their sampling period (9,3ms) which does not respect the Shannon criteria. These bands are thus not considered for the straylight analysis. Also, as the test is performed at ambient condition the SWIR bands B10 and B12 are not measurable due to high thermal noise.

The measurement noise depends especially on the number of pixels used for averaging and on the acquisition duration. It will be then the lowest for the 10-meter bands. For this test, each pixel line of detector is divided in 10 segments. The number of pixels used for averaging is typically 250 pixels for 10-meter bands.

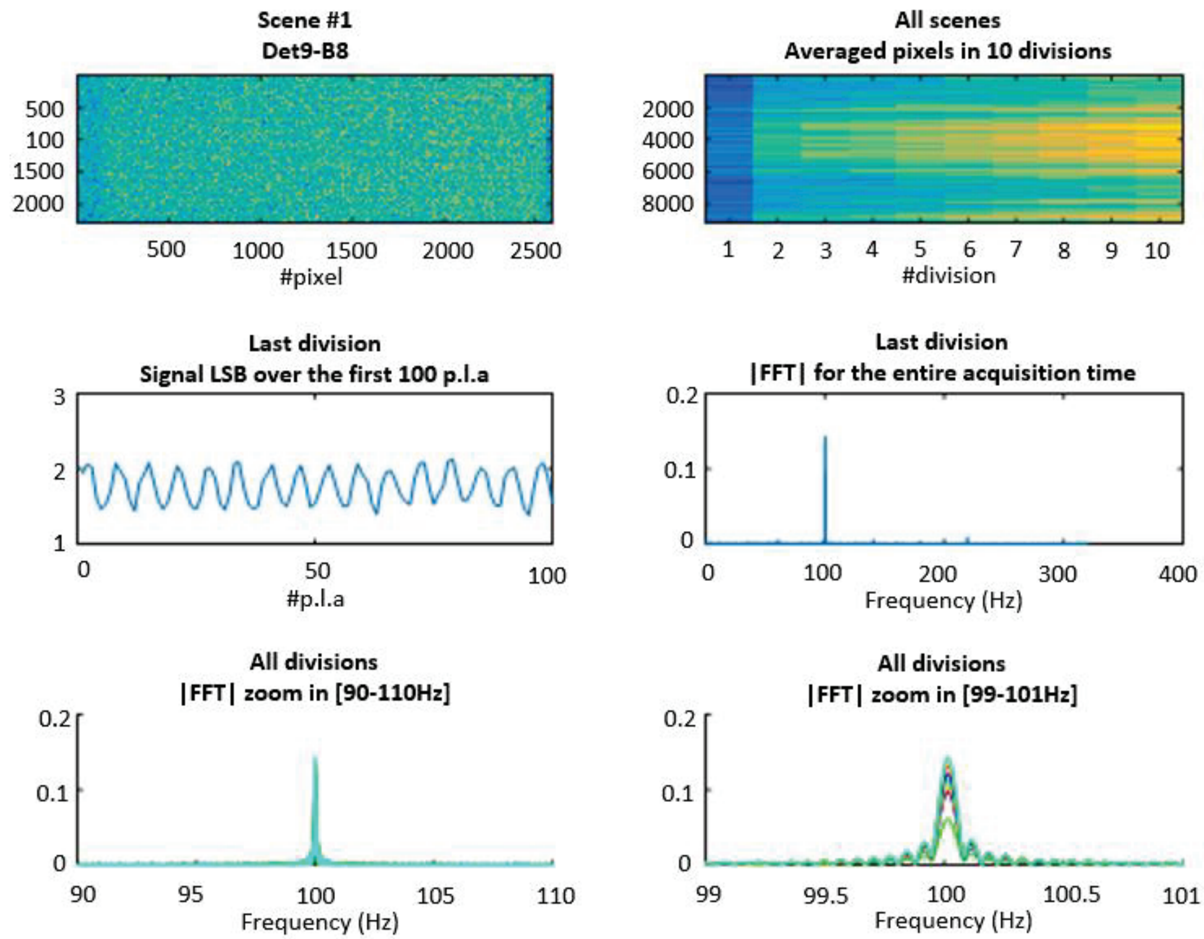


Figure 8 - Example of FFT processing with straylight

The Figure 8 above shows:

(1) The first elementary scene acquisition for detector #9 band B8 (2596 pixels), with a number of pixel lines acquisitions (p.l.a) depending on the time sampling of the considered band over the duration of an elementary scene (3,6s)

(2) The 4 acquired scenes with the pixel averaging for the 10 divisions

(3) The temporal signal for the last division over the first 100 pixel lines acquisitions

(4) The FFT signal for the last division

(5) Same signal as (4) but zoomed on the range [90-110Hz] with the overlapping of the 10 divisions in order to verify the FFT peaks evolution compared to the noise or any artefacts

(6) Same as (5) but zoomed on the range [99-101Hz]

At the end of the processing, the FFT peak frequency is checked if it is included in the narrow range 100Hz ± 0,1Hz otherwise the FFT peak is not considered as straylight.

In order to quantify the straylight, a normalization is applied on the values given by the Fourier transform spectral analysis. The normalization coefficients are obtained simply by measuring the FFT peak magnitude for each band of each detector when the source illuminates directly the FOV of the MSI instrument. This characterization must be performed with reduced integration time in order to avoid signal saturation. The convention used for the quantification is the part per million (ppm) which are well adapted for the low expected signals.

The Figure 9 below presents a synthesis of straylight processing after normalization for one position.

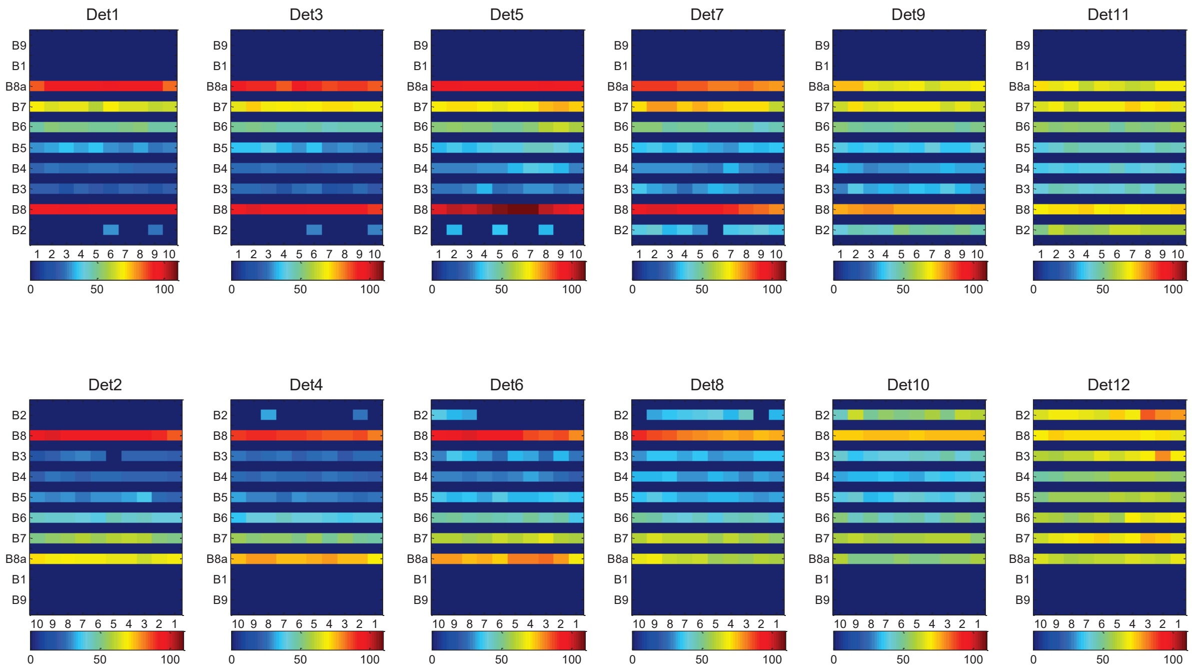


Figure 9 - Example of VNIR straylight processing after normalization for one position

At the end once all positions are processed, a summation is done giving the overall straylight due to the Earth albedo for all the analyzed positions.

2.5 Accuracy of the test

With such normalization, it is easy to estimate the straylight detection sensitivity. A simple dark acquisition will give the threshold under which straylight is not detectable. The following Figure 10 and Figure 11 show that the thresholds are typically 30ppm for VNIR bands and 40ppm for B11.

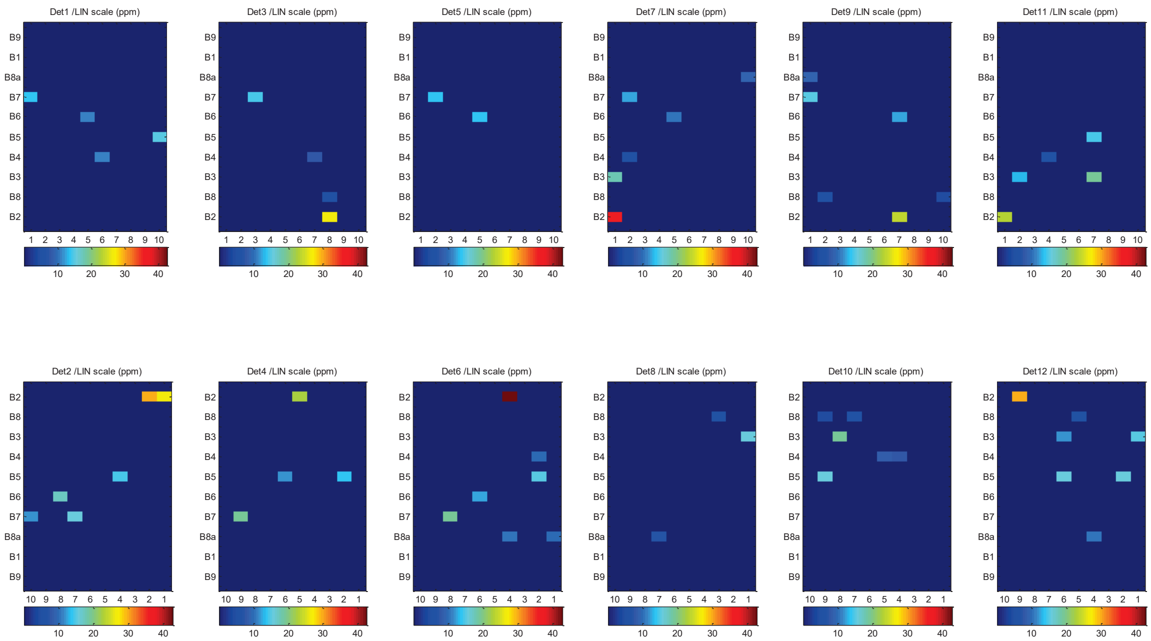


Figure 10 - Straylight processing with dark in VNIR

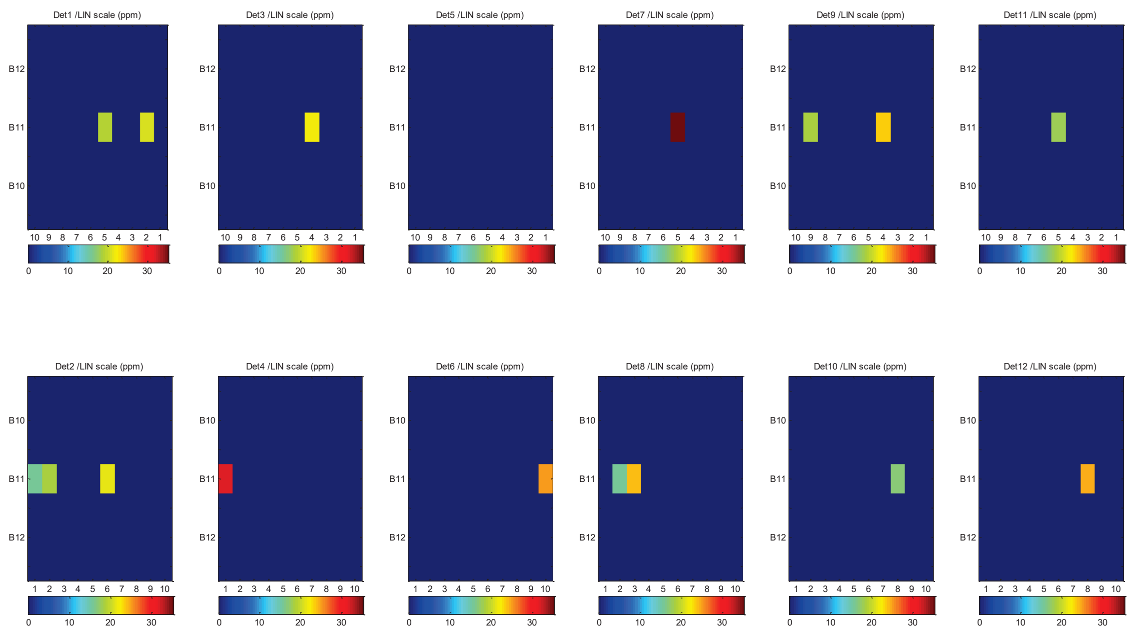


Figure 11 - Straylight processing with dark in SWIR

2.6 Light trap efficiency

For the characterization of light trap efficiency, a first radiance measurement is performed with the diffusing source illuminating directly in direction of the light trap. The Figure 12 below shows the acquired spectral radiance.

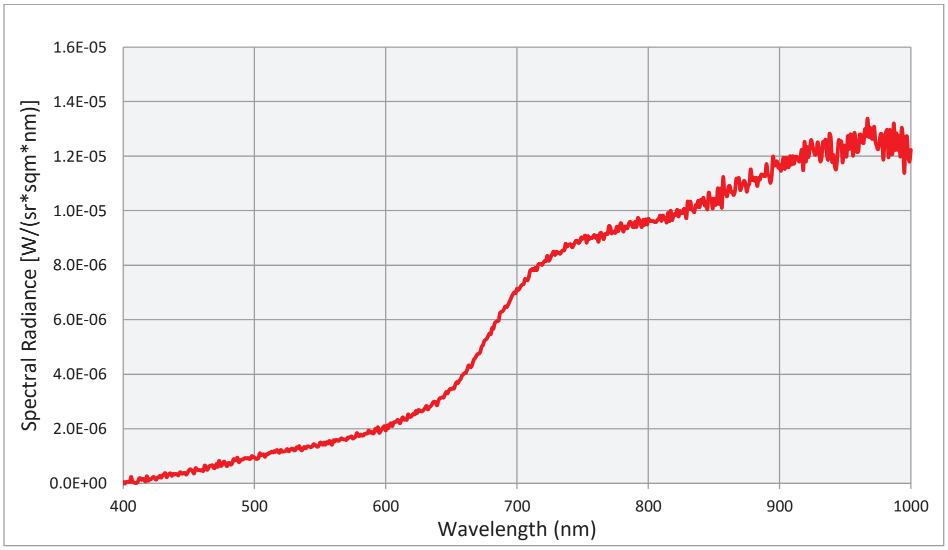


Figure 12 - Radiance of the light trap (with the diffusing source in direction of the light trap)

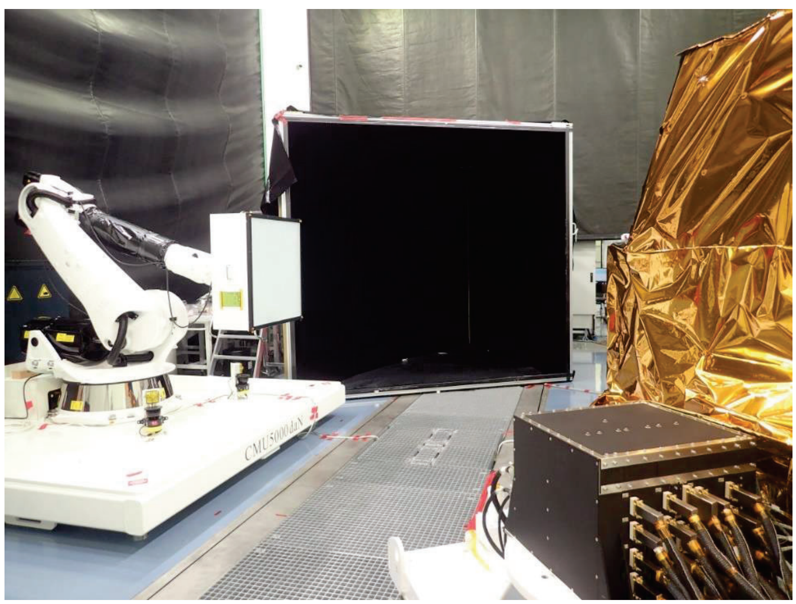


Figure 13 - Picture of the robotized arm and the light trap

Finally, the radiance of the light trap is compared to the radiance of the diffusing source (refer to the graph on Figure 7). The result given in Figure 14 shows a ratio around 0,004% (40ppm) over the spectral range, which is equivalent to the measurement accuracy, meaning that the contribution of the light trap is negligible.

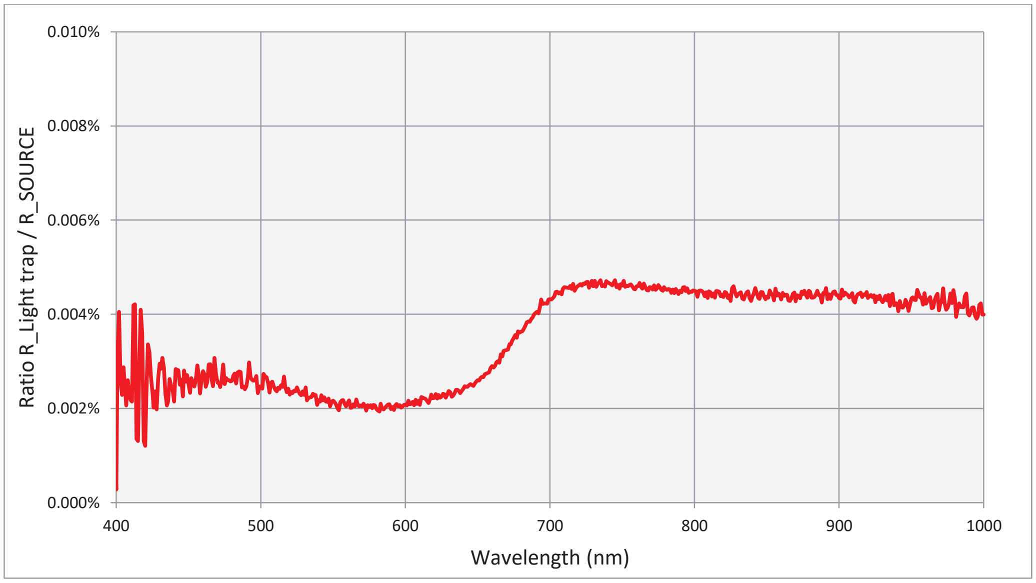


Figure 14 - Light Trap efficiency: radiance of the light trap / radiance of the source

Moreover, instrument acquisitions have been performed with the diffusing source illuminating directly in direction of the light trap. This configuration is a worst case because, during the straylight tests, the diffusing source is illuminating towards the instrument. The acquisitions have been done with 2 positions of the instruments (X_{MSI} axis vertical and X_{MSI} axis horizontal) in order to detect possible edge effects in the light trap. The results of the light trap efficiency are given by the following Figure 15 and Figure 16. For both MSI orientations, the maximum detected signal is around 30ppm (40ppm for B11) which is still comparable to the measurement accuracy.

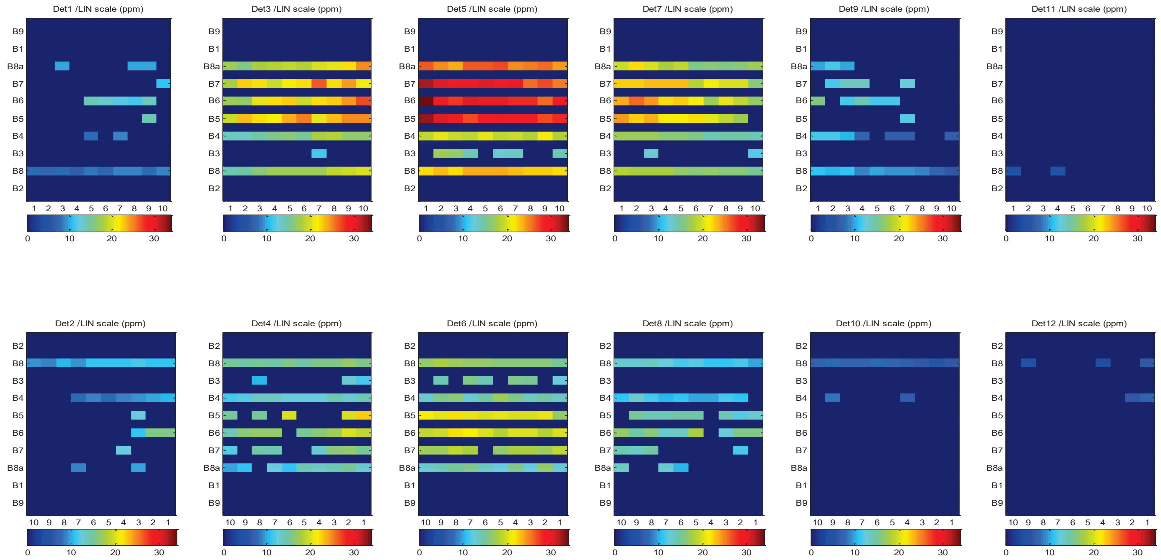


Figure 15 - Acquisition with MSI instrument vertical in front of the light trap and with the diffusing source in direction of the light trap

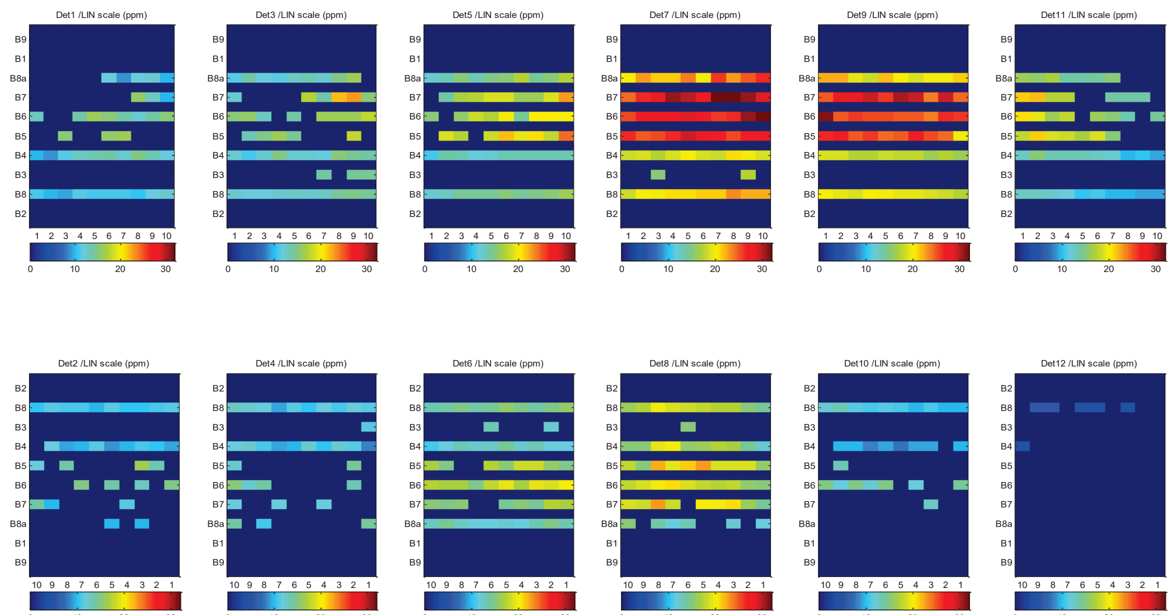


Figure 16 - Acquisition with MSI instrument horizontal in front of the light trap with and the diffusing source in direction of the light trap

3. MSI-D STRAYLIGHT TEST CAMPAIGN

The MSI-D straylight test campaign has been executed in the beginning of 2022. The test took place at the end of the AIT sequence once the good light tightness of the MSI housing – mainly composed of Multi-Layer Insulation (MLI) – had been previously checked.

Based on the experience acquired on the previous models, for MSI-C/D the tests have been only focused on the critical positions located around the FOV highlighted in red in the Figure 17 below. Indeed, it has been assessed that all the other positions do not impact the overall straylight level which is revealing of a good anticipated optical architecture minimizing the straylight out-of-FOV.

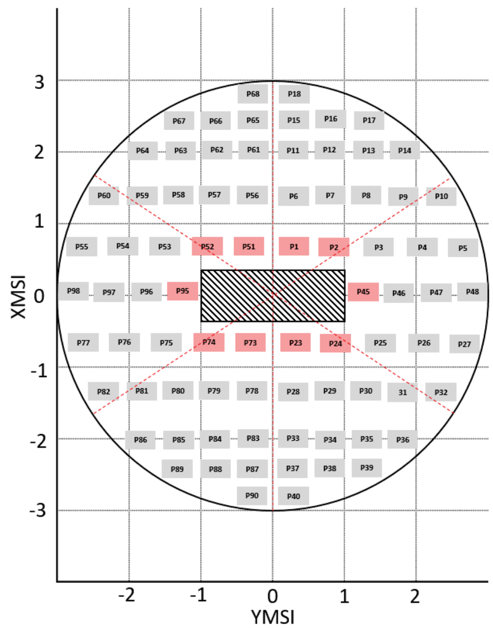


Figure 17 – The 10 most critical positions assessed for MSI-C/D

The AIT sequence regarding the straylight test was carried out over 5 days which included: (1) the preparation of the setup (light trap and robot installation), (2) the alignment of the robot with the MSI instrument, (3) the calibration and test. The last step is the shortest, counting 1 hour for 10 source positions, which is a duration drastically reduced thanks to the use of the robot. Without it, this step would have lasted several days.

The Figure 18 and Figure 19 below present, respectively for the VNIR bands and the SWIR band B11, the overall straylight for the 10 positions. As explained on the previous section *Processing and normalization*, the quantification of the straylight due to the Earth albedo is assessed by summing the 10 positions.

At the end, the straylight assessment per band is implemented into the radiometric performance budget in order to estimate the impact on the reference radiance and to verify the compliancy with the specification.

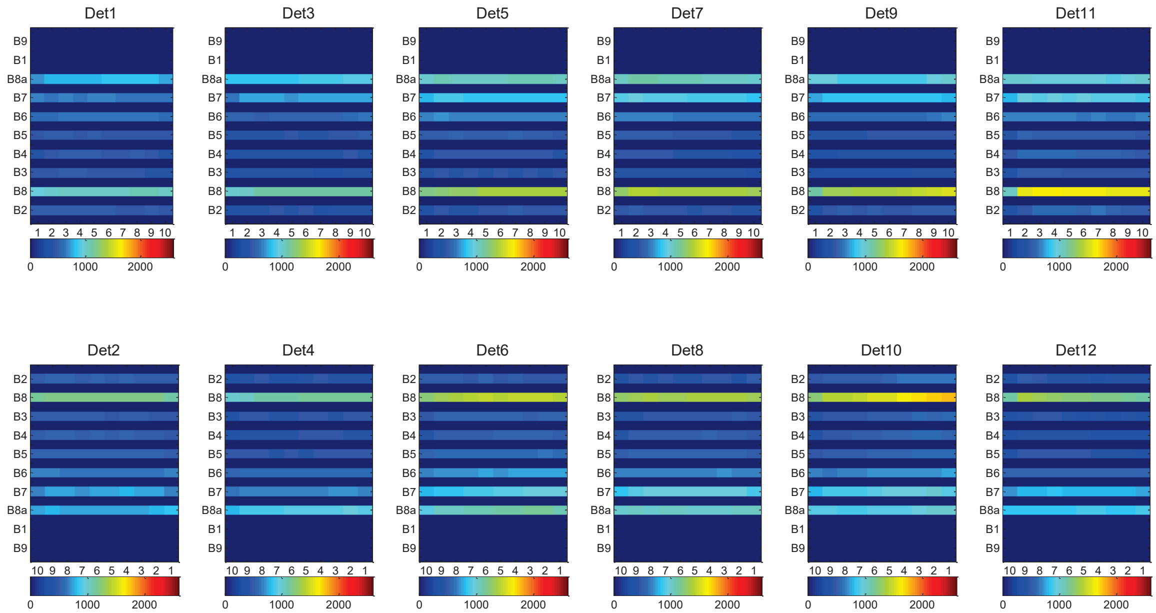


Figure 18 – MSI-D straylight due to the Earth albedo for VNIR bands

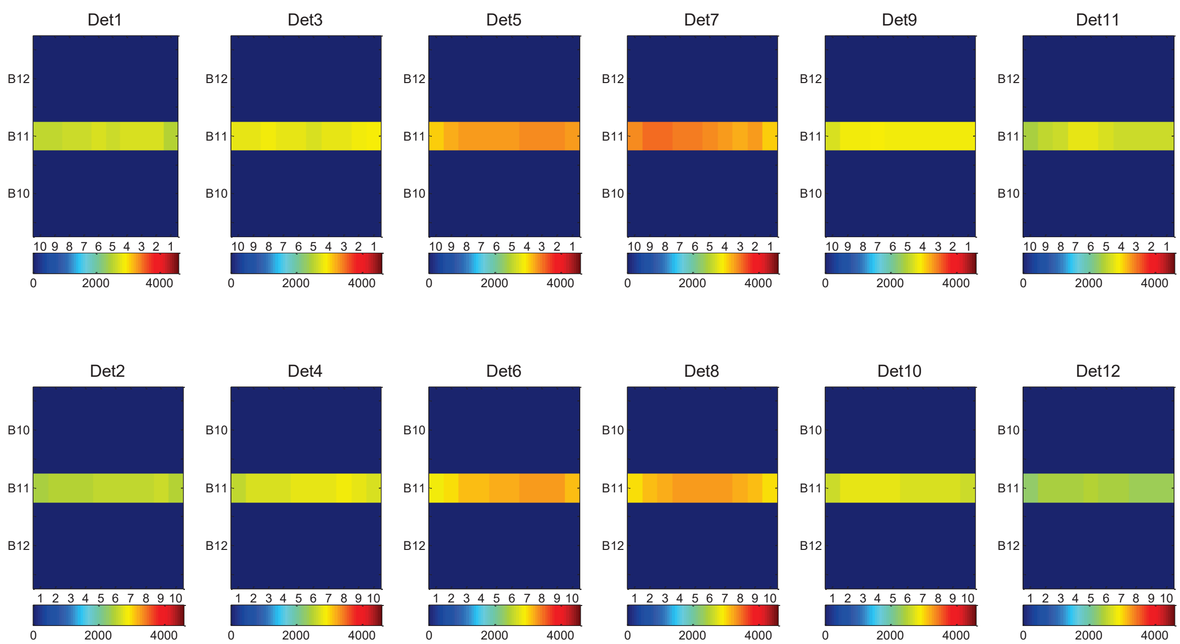


Figure 19 – MSI-D straylight due to the Earth albedo for SWIR band B11

4. CONCLUSION AND PERSPECTIVES

This paper describes the innovative straylight test approach used during the MSI instrument test campaign.

The last results of the straylight test obtained during the MSI-D test campaign executed in 2022 and their associated accuracy has been presented, as well as the test setup showing the gain of using a robotized arm leading to a successful AIT sequence and completion of all tests with delivery in time that pave the way for next generation of Sentinel-2.

Indeed, for this kind of characterization, the interest of using a robotized arm is linked to: the speed of the test, the capacity to repeat easily identical positions for investigation needs, and the possibility of easy transposition to other projects for multiproject use. The next generation of Sentinel-2 is currently under development at Airbus Defence & Space with a purpose to take over on the constellation. Obviously, an accurate straylight characterization will be performed based on the test described in this paper taking advantage of all the experience acquired on the last flight models of Sentinel-2.

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[1] V. Fernandez, P. Martimort, F. Spoto, O. Sy and P. Laberinti (ESA), "Overview of Sentinel-2," IEEE International Geoscience and Remote Sensing Symposium, 2012