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THE MULTISPECTRAL INSTRUMENT OF THE SENTINEL2 EM PROGRAM RESULTS

S2-MSI major development step

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***Abstract*—The MSI EM campaign has been conducted before releasing the flight model integration and test. This paper presents the MSI EM configuration and the various tests results. Experience gained through this extensive test program allowed securing the MSI PFM integration and test activities.**

Sentinel2; MSI; performances; tests; optical; radiometric; EMC; thermal

I. INTRODUCTION

The presentation provides an outlook of the S2 MSI EM program findings.

Sentinel-2 will provide a permanent record of comprehensive data to support services such as: risk management (floods and forest fires, subsidence and landslides); European land-use/land-cover state and changes; forest monitoring; food security/early warning systems; water management and soil protection; urban mapping; natural hazards; and terrestrial mapping for humanitarian aid and development [3]. In the Sentinel-2 mission programme, Astrium in Friedrichshafen is responsible for the satellite's system design and platform, as well as for satellite integration and testing. Astrium Toulouse will supply the MultiSpectral Instrument (MSI), and Astrium Spain is in charge of the satellite's structure pre-integrated with its thermal equipment and harness. The industrial core team also comprises Jena Optronik (Germany), Boostec (France), Sener and GMV (Spain).

Sentinel-2 is designed to image the Earth's landmasses from its orbit for at least 7.25 years. Its on-board resources allow prolonging the mission by an extra five years. The 1.1-metric-ton satellite will circle the Earth in a sun-synchronous, polar orbit at an altitude of 786 kilometers, fully covering the planet's landmasses in just ten days. The first satellite is expected to be launched end of 2013 and the second satellite is expected to be ready for launch in 2015.

The multi-spectral instrument (MSI) will generate optical images in 13 spectral channels in the visible and short-wave infrared spectral ranges down to a resolution of 10 meters with an image width of 290 kilometers.

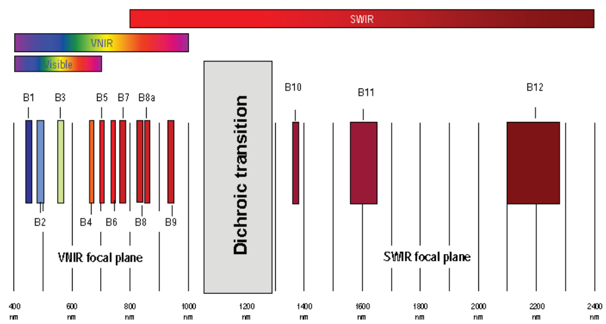

Figure 1: MSI spectral bands

II. MSI ARCHITECTURE & DEVELOPMENT

A. MSI architecture [4]

The sentinel2 multi spectral instrument is built around a Silicon Carbide Three Mirrors Assembly (TMA) telescope. Two separate focal planes are implemented for the 3 SWIR and the 10 VNIR spectral bands. These are made of Silicon Carbide focal planes equipped with 12 detectors and 12 filter assemblies. The spectral separation between VNIR and SWIR is achieved thanks to a large dichroïc plate embedded in the splitter assembly.

Main interfaces (power, TM/TC, mission data) with the platform are ensured by the Video and Compression Unit (VCU) while the detector interface is provided by the Front End Electronics (FEE).

The mechanical and thermal architecture is built around the primary (made of the Payload Interface Plate (PIP) and the telescope struts) and secondary structures.

Mechanical and electrical architectures are presented on Figure 2 and Figure 3.

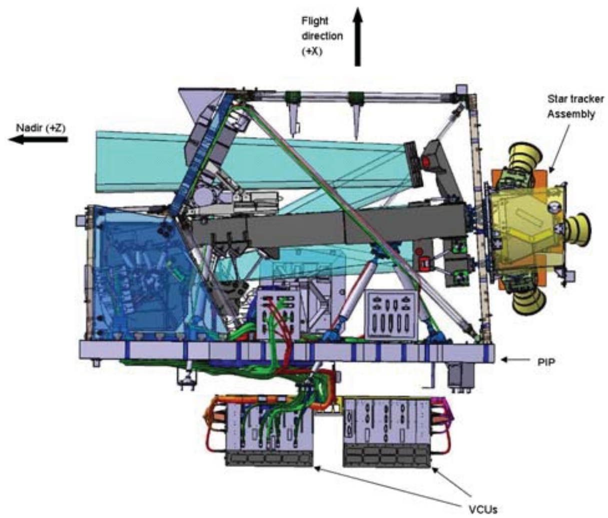

Figure 2: MSI mechanical architecture

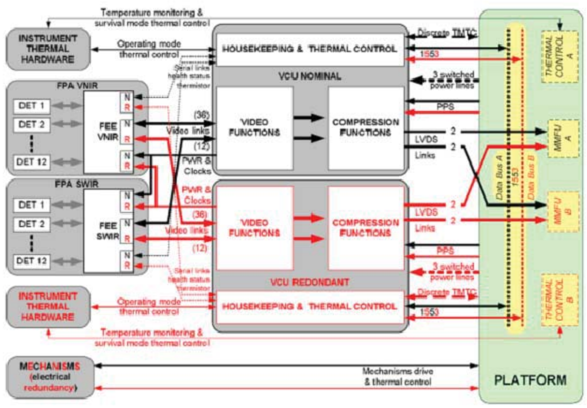

Figure 3: MSI electrical architecture

B. *MSI development*

The MSI development is based on several models dedicated to the validation of the critical elements and the preparation of the PFM & FM2 activities.

The MSI Development Model (DM) was limited to the VNIR and SWIR detection chains with main objective related to the validation of the interfaces between the detectors and the electronics. These activities have been conducted in the early period of B2CD phase.

The instrument Engineering Model (EM) program is a major step in the development logic. It provides an early validation of both VNIR and SWIR focal planes integration procedure, tests configurations and performances. The main elements verified on this model are :

- the detectors and filters alignment capability within required accuracy,
- the detection chain radiometric performances
- the optical performances
- the SWIR FPA thermal control (operating temperature at 190 K)
- the advanced validation of EMC performances and the MSI ESD qualification.

Next step is the integration and test of the MSI ProtoFlight Model (PFM) followed by the second flight model (FM2).

III. MSI ENGINEERING MODEL PROGRAM

A. *MSI EM description*

The MSI EM model is made of one VNIR and one SWIR FPA. These are fully representative of FM focal planes but are equipped with EM detectors and filters and connected to EM electronics. Where the FM FPAs embed 12 detectors and filters (in order to cover the MSI swath), the EM FPAs include only 4.

EM detectors built by Astrium-E2V (VNIR) and Sofradir (SWIR) are representative of flight models in terms of packaging, interfaces and functionalities. Some minor performance limitations are nonetheless allowed. The VNIR detector is made of a CMOS die [1], using the 0.35 µm CMOS technology, integrated in a ceramic package. The VNIR detector has ten spectral bands, B3 and B4 having two adjacent physical lines allowing the TDI operating mode. The TDI summation is performed at VCU level. The SWIR detector is made of an MCT photosensitive material hybridized to a silicon readout circuit (ROIC) and integrated into a dedicated hermetic package with an electrical flexible link [2]. The SWIR detector has three spectral bands. Several lines of pixels of 15x15 µm2 have been designed for each spectral band, allowing the selection of the best responding pixel(s) per column and per band.

Filter assemblies are procured from Jena Optronik (JOP). A filter assembly is made of filter stripes (one for each spectral band) mounted in a Titanium frame. The aims of the filter assembly are: i) to separate, close to each focal plane, VNIR spectral domain into the ten bands B1 to B9 and SWIR spectral domain into the three bands B10 to B12, ii) To prevent stray light effects. This stray light limitation is very efficient since it is made very close to the focal planes. Each filter stripe, corresponding to each spectral band, is aligned and glued in a mechanical mount. A front face frame mechanically clamps the assembly together.

Front End Electronics (FEE) are procured from CRISA. Each FEE unit provides electrical interface to 3 detectors (power supply, bias voltages, clock and video signals) and allows for detector initialization (SWIR pixel selection) and video signal filtering and amplification.

Video and Compression Unit (VCU) aims i) at processing the video signals delivered by the FEEs : digitalization on 12 bits, numerical processing, compression and image CCSDS packet generation, ii) interfacing with the platform (power supply, MIL-BUS, PPS), iii) providing the nominal thermal control of the MSI. The VCU EM is similar to a flight model with following limitations: only half of the video chains are

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implemented (VCU EM allows operating 6 VNIR detectors + 6 SWIR detectors) and all functionalities are implemented with reprogrammable FPGAs instead of anti-fuse.

One of the main differences between VNIR and SWIR focal planes deals with the operating temperature: 20 deg C for VNIR FPA, -83 deg C for SWIR FPA. The operating temperature requirement is driven by the radiometric performance stability.

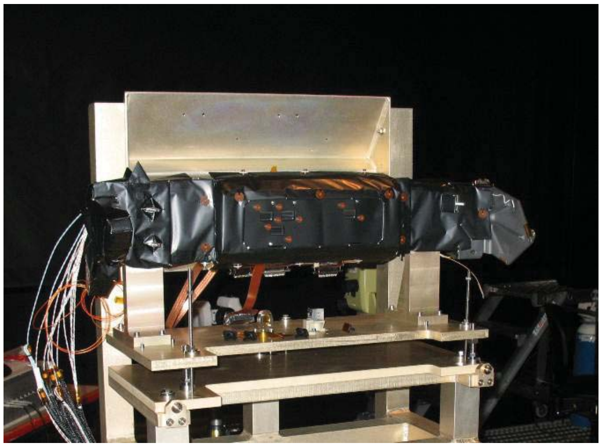

Figure 4: VNIR FPA EM

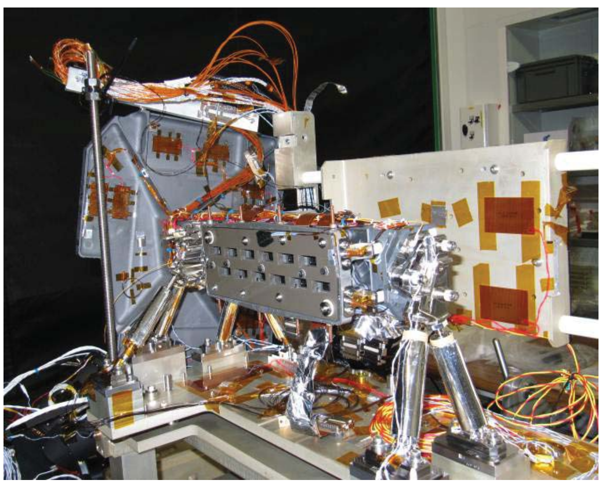

Figure 5: SWIR FPA EM

B. MSI EM integration sequence

The VNIR and SWIR focal planes have been submitted to 2 independent AIT sequences up to final EMC test campaign where both focal planes were operated simultaneously.

For each focal plane, the detectors and then the filter alignment has been performed using a 3D machine. The alignment procedure is based on fiducial crosses sighting for both in-plane and out-of-plane. The out-of-plane alignment requirement is very stringent (+/- 10 µm) due to system MTF requirement and sensitivity to defocus (due to system f-number). Dedicated focus and tilt shimming is defined and procured for every detector.

Electrical integration of the VCU with the FEEs and the detectors has been conducted followed by functional tests demonstrating the readiness of the performance testing.

In addition to these mechanical and electrical activities, the SWIR FPA has also been prepared for the thermal vacuum test with the implementation of the thermal hardware (MLI, heaters and thermistors).

C. MSI EM test program

1) Radiometric tests

Radiometric tests are performed in order to check the detection chain functionalities and performances. Main verification steps deal with detection chain tuning (Integration time freezing, numerical sampling adjustment) and performances (signal and noise in darkness, SNR, linearity). For the VNIR FPA, the test set-up consists in a large integrating sphere (80cm diameter port) and the associating baffling in order to ensure the desired illumination level with proper aperture size and f-number. For the SWIR FPA (operated under vacuum), a smaller sphere is used with partial illumination of the FPA. Illumination of the full FPA is achieved through displacement of the sphere in front of the FPA.

Tests results are summarized in Table I and Table II. Figure 6 to Figure 8 illustrates the measurement results. Test results have been found in very good agreement with predictions both in term of SNR and linearity. Linearity results have been found slightly out of expectation at low illumination level (below 10% of Lmax), this is mainly due to the low amplitude of the signal and the stringent linearity performance requirement (residual error < 1%). Best measurements were obtained under fixed illumination with varying integration time; this method will be kept and enhanced for characterizing the FM FPAs. The design of both VNIR and SWIR detection chains could be confirmed and the flight models manufacturing was released. Based on the EM tests results, radiometric performances of both VNIR and SWIR chains are expected to comply with specification for the flight models. Moreover, operability of SWIR FPA at ambient temperature has been demonstrated, that will allow functional and simplified SWIR FPA performance checks also after MSI integration on the platform, in the frame of satellite testing activities.

Figure 6: SWIR EM FPAs test configuration under vacuum

TABLE I. VNIR FPA RADIOMETRIC TESTS RESULTS

Parameter	*Description*	*Expected*	*Measured*
Dark noise	Noise level at room temperature	0.42 to 0.80 lsb	0.55 to 0.71 lsb
Dark signal stability	Stability over test campaign	+/- 0.1 lsb	< 0.1 lsb
SNR@Lref	SNR measurement under illumination	B1:350 B2:185 B3:212 B4:184 B5:168 B6:165 B7:213 B8:194 B8a:137 B9: 94	B1:534 B2:174* B3:208 B4:187 B5:197 B6:189 B7:229 B8:199 B8a:153 B9:136
Linearity	Non linearity residue after cubic fitting	+/- 0.42 %	+/-0.50%

* : 20 pixels among 2592 are below prediction

TABLE II. SWIR FPA RADIOMETRIC TESTS RESULTS

Parameter	*Description*	*Band*	*Expected*	*Measured*
Dark noise	Noise level at operating temperature (lsb)	B10 B11 B12	1 - 1.5 0.5 - 1.5 0.5 - 1.5	1.15 0.73 0.77
Dark signal stability	Evolution of dark signal versus temperature (around 200 K)	B10 B11 B12	~0 lsb/K ~0 lsb/K ~2 lsb/K	~0 lsb/K ~0 lsb/K ~2 lsb/K
SNR@Lref	SNR measurement under illumination	B10 B11 B12	155 198 177	154 191 184
Linearity	Non linearity residue after bilinear fitting	B10 B11 B12	< 1%	< 1%

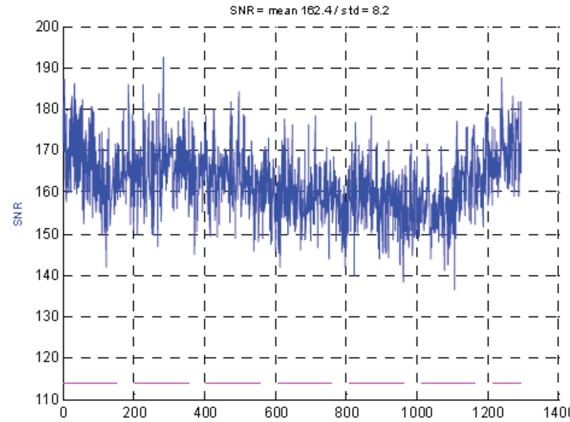

Figure 6: SNR results on band B9

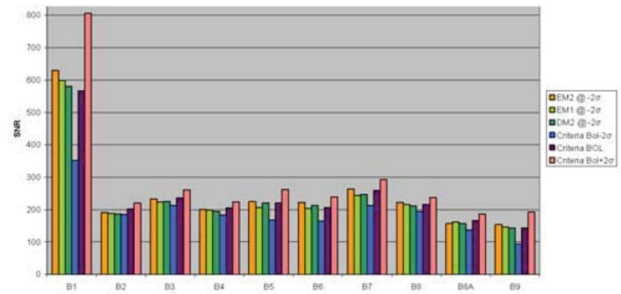

Figure 7: SNR results - Comparison of measurement and predictions for all VNIR bands

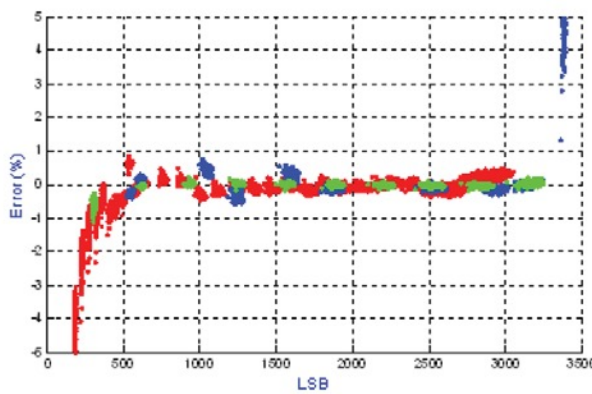

Figure 8: SWIR band B11 linearity residual (red : Sofradir, blue : ASF radiance, green : ASF integration time)

2) Geometric tests

Geometric tests are performed in order to validate the proper alignment of the detectors and filter both in plane (vignetting) and out of plane (focus) and to assess the optical performances (MTF, ghost, and crosstalk). The test set-up consists in a dedicated OGSE imaging various patterns on the focal plane. Similar set-up is used at ambient for VNIR FPA and under vacuum for the SWIR FPA. The complete OGSE is mounted on a 3 axes translating stage that allows addressing any pixel of the focal plane.

Thanks to the high stability of the mechanical set-up and the good optical quality of the OGSE, geometric tests on the EM FPAs allowed measuring very accurately the FPA performances. Main results are summarized in table III and IV.

Alignment results are very good both for in-plane (vignetting margin) and out-of-plane (planarity) measurements. It confirms that the alignment procedures are appropriate to achieve the required accuracy.

Optical measurements have been found in agreement or close to expectation with the exception of the ghost measurements on the VNIR focal plane. Crosstalk measurements are illustrated on Figure 9: with an illumination level over 1500 lsb on band B5, the other bands remain not affected. Same measurement has been performed with individual illumination of each spectral band. All crosstalk results have been found as expected demonstrating the proper design of the filters assemblies and FPAs. For the ghost measurements, some VNIR bands have been found presenting ghost levels significantly higher than predictions. Deep investigations have been conducted and a phenomenon of Large Angle Scattering (LAS) inside the filter stripe has been identified. This phenomena leads to generate significant straylight out of band in directions far from the nominal path explaining the measured performances. On the SWIR FPA, the ghost level at 1000 m from the cloud edge is higher than expected but still compatible with system requirements. Due to the low reference levels on the SWIR bands (~5% of Lmax), the main difficulty is related to the radiometric accuracy of the measurements (specified ghost level correspond to attenuation levels below 5/1000th).

In order to recover the performance for the VNIR flight model, design modifications have been implemented on all bands: substrate roughness has been improved and the manufacturing of some stripes has been subcontracted to Materion (US). An improvement by a factor 5 to 10 is expected.

TABLE III. VNIR FPA GEOMETRIC TESTS RESULTS

Parameter	*Description*	*Band*	*Expected*	*Measured*
Vignetting	Vignetting margin between filter mask and pixel line	all	100 +/-25 µm	100 µm -10/+40 µm
Planarity	Overall	all	+/-10µm	+/- 7 µm
Ghost	Cloud edge impact on radiometric performance (@300 m)	B1 B2 B3 B4 B5 B6 B7 B8 B8a B9	< 0.5 %	3.5% / 1.8% 2.3% / 1.7% 1.8% / 1.1% 1.5% / 1.2% 1.9% / 2.0% 3.3% / 2.6% 4% / 2.9% 1.2% / 1.6% 3.2% / 2.4% 38% / 24%
Crosstalk	Impact of illumination of one band on the others	all	< 0.5 %	< measurement threshold

TABLE IV. SWIR FPA GEOMETRIC TESTS RESULTS

Parameter	*Description*	*Band*	*Expected*	*Measured*
Vignetting	Vignetting margin between filter mask and pixel line	all	100 +/-25 µm	100 µm -10/+40 µm
Planarity	Overall	all	+/-10µm	+/- 7 µm
Ghost	Cloud edge impact on radiometric performance @1000 m	B10 B11 B12	< 0.5 % < 0.5 % < 0.5 %	< 1.2 % < 1.2 % < 1.2 %
Crosstalk	Impact of illumination of one band on the others	all	< 0.5 %	< measurement threshold

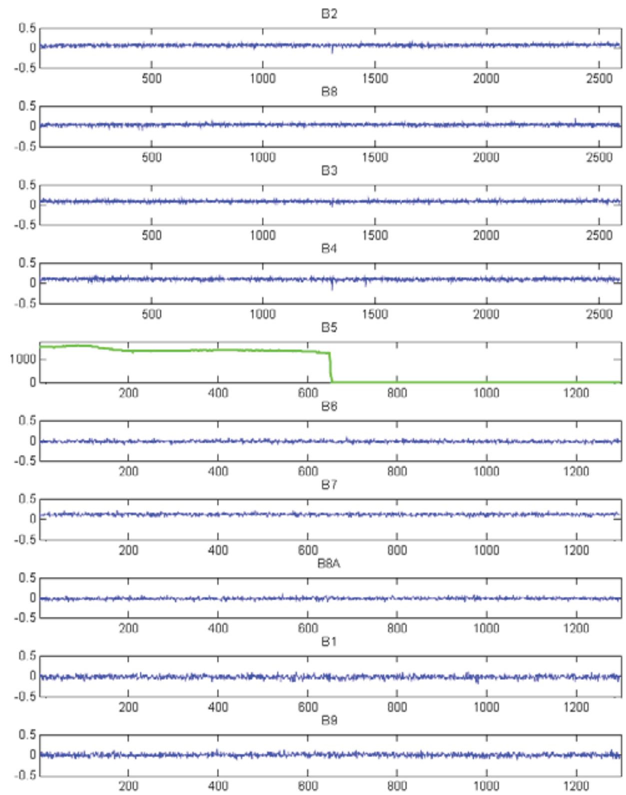

Figure 9: Crosstalk measurement on VNIR FPA

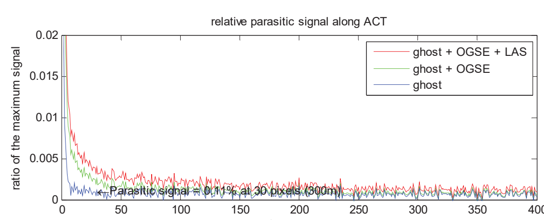

Figure 10: Ghost measurement on VNIR FPA

3) *Thermal tests*

Thermal tests have been performed on the SWIR FPA with following verification objectives: i) passive cooling efficiency, ii) temperature stability and robustness to environment, iii) decontamination heating efficiency, iv) thermal model correlation for flight configuration predictions.

In order to cover these objectives, the test sequence is made of 6 phases as depicted on Table V and illustrated on Figure 11. In addition, the periods with stabilized operating temperature have been used to conduct the radiometric and geometric tests.

TABLE V. SWIR FPA THERMAL TEST SEQUENCE

Phase	*Description*
Phase 1	Reference under vacuum
Phase 2.1	Transient to cold operational (192 K)
Phase 2.2	Open loop thermal test
Phase 3.1	Decontamination heating
Phase 3.2	Decontamination (293 K)
Phase 4.1	Transient to 192 K
Phase 4.2	Performances at 192 K
Phase 4.3	Performances at 192 K + orbital variation of thermal environment
Phase 5.1	Transient to survival mode
Phase 5.2	Survival mode thermal control (189 K)
Phase 6	Transition to ambient temperature

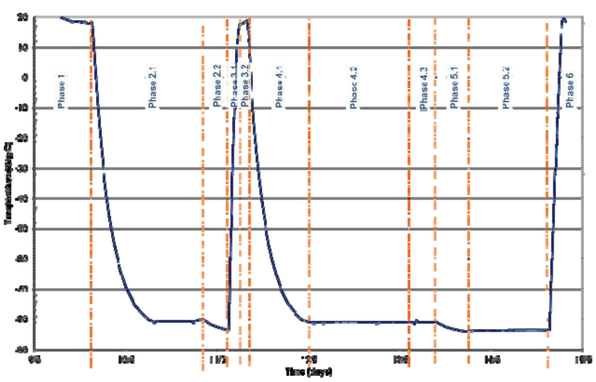

Figure 11: SWIR FPA temperature evolution

The SWIR FPA cooling is passively achieved thanks to the monolithic SiC FPA and radiator. The radiator surface is 0.15 m² and is oriented towards cold space (+Y), the heat rejection capacity of the radiator is about 7 W. Active control is achieved via heating implemented on the SiC barrel, it allows controlling accurately the detectors temperature while the environment is changing along the orbit. The efficiency of the active control has been demonstrated by test through a variation of the shroud temperature at orbital period (see Figure 12) and the acquisition of the detector temperature (see Figure 13). For each imaging period, following the transient generated by the detector switch-on, the temperature stability better than +/- 0.05 deg C is achieved well below the required one (+/- 0.14 deg C).

The SWIR FPA EM thermal test campaign has demonstrated the capacity and the performances of the most critical element of the MSI.

Through the detailed thermal model correlation, some improvements have been identified and will be implemented and validated on the SWIR FPA PFM. These improvements address reduction of the thermal leaks through the harness and local MLI shape modifications.

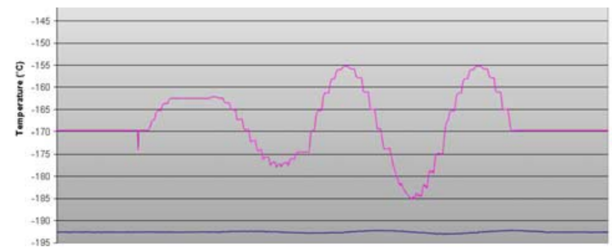

Figure 12: Shroud temperature evolution to simulate orbital variations

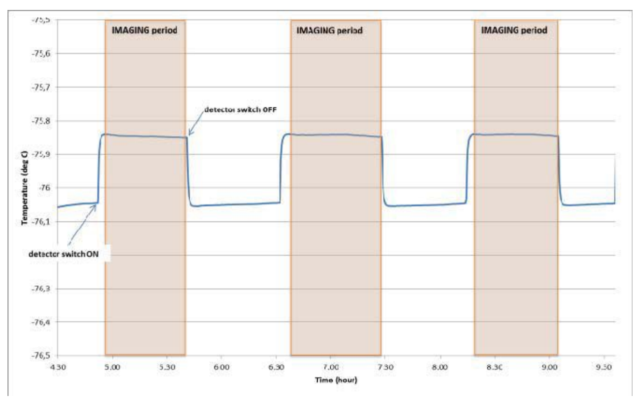

Figure 13: Detector temperature during orbital variations simulation

4) *EMC tests*

Early EMC performances verification on the EM focal plane is a major step forward for the MSI EMC qualification program. Both conducted and radiated EMC test campaign was conducted in March 2010 with the VNIR focal plane followed by SWIR focal plane activities. Finally, the EMC test campaign was concluded with the ESD qualification campaign performed end of 2011.

EMC performances measured during these campaigns have demonstrated very good results both in conducted and radiated environments.

Susceptibility has been tracked by comparing the detection noise of every pixel with and without EMC perturbation. It allowed identifying very precisely the critical frequencies. Figure 15 illustrates the detector noise analysis result during conducted susceptibility tests. EMC environment does not impact the detection chain noise or the MSI functionalities.

ESD testing consists in injecting 15 kV / 10 mJ electrical discharges either in conducted mode on a metallic part or in radiated mode 20 cm away from the sensible elements. The discharge is repeated every 6 seconds during 2 minutes. It has been checked that neither the FPA functionalities nor the performances (detection chain noise) are affected by these discharges. Both FPAs have been submitted to this test leading to the formal qualification of the MSI against ESD environment.

Figure 14: VNIR & SWIR EM FPAs during radiated EMC tests

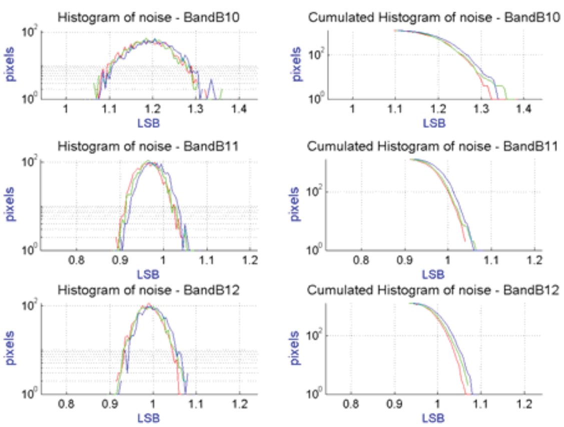

Figure 15: SWIR detector noise analysis during CS test (red and green: without injection, blue: with injection)

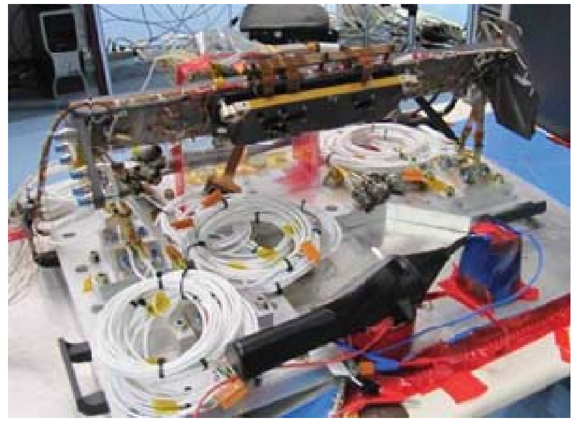

Figure 16: ESD test on VNIR FPA

IV. CONCLUSONS

The successful completion of the MSI EM test program is a major step in the instrument development. All critical fields related to newly developed equipment (detectors, filters, and control electronics) and stringent focal plane integration and test processes have been validated in a flight representative configuration. Most of the predicted performances could be confirmed and some design modifications have been identified in order to further improve the flight models performances. For the identified deviations, the test program has allowed to clearly understand the root causes and to consequently define suitable mitigation activities, for implementation in the PFM focal plane assemblies. The MSI EM program provides a sound basis for the MSI PFM and FM2 programs planned over the period 2012-2013.

ACKNOWLEDGMENT

We would to thank particularly the Astrium AIT team that has prepared and executed these tests.

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