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S. Espuche

V. Chorvalli

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VNIR FOCAL PLANE RESULTS FROM THE MULTISPECTRAL INSTRUMENT OF THE SENTINEL2 MISSION

Authors: S. Espuche[1], V.Chorvalli[1], A. Laborie[1], F. Delbru[1], S. Thomas[1], J. Sagne[1], C.Haas[2]
Co-Authors: P. Martimort[3], V. Fernandez[3], V. Kirchner[3]
[1]Airbus Defence & Space, France. [2]Airbus Defence & Space, Germany. [3]ESA/ESTEC, The Netherlands

***Abstract*— The development and testing of the MSI PFM for the first Sentinel-2 satellite is now completely achieved, in particular tests and characterization of the VNIR FPA and of the whole instrument. This paper provides main results obtained for the 12 VNIR detection chains of the Sentinel-2 Multi-Spectral Instrument and highlights some of the most outstanding characteristics and performances achieved.**

Sentinel2; MSI; performances; tests; radiometric; detection;

I. INTRODUCTION

The presentation provides a synthesis of the measured performances of the detection channels of the Visible Near-Infra-Red (VNIR) focal plane enclosed in the PFM MultiSpectral Instrument (MSI) of the Sentinel 2 mission.

COPERNICUS is a joint initiative of the European Commission and the European Space Agency. Sentinel-2 will provide a permanent record of comprehensive data to support services such as 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…[2].

In the frame of Sentinel-2 mission program, Airbus Defence & Space Friedrichshafen are responsible for the satellite system design and platform, as well as for satellite integration and testing, while Airbus Defence & Space Toulouse supply the MSI.

Sentinel-2 is designed to image the Earth 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. Two satellites are needed for allowing a revisit of the same spot every 5 days. The first satellite is expected to be launched in 2015 and the second satellite is expected to be ready for launch in 2016.

The Sentinel-2 MSI is a filter based push-broom imager. It provides imagery in 13 spectral channels (see Fig. 1) with spatial resolutions ranging from 10 to 60 m. The instrument features an optical telescope offering a wide field of view to achieve the required swath width of 290 km.

MSI is required to operate over a wide spectral range extending from the VNIR (400-1100 nm) to the Short-Wave-Infra-Red (SWIR, 1100-2500 nm). The instrument encompasses two Focal Planes Assemblies (FPA): a VNIR FPA based on 12 monolithic CMOS image sensors in charge of the 10 VNIR channels; a SWIR FPA based on 12 Mercury Cadmium Telluride (MCT) IRCMOS detectors in charge of the 3 SWIR channels. A total of 48 detectors flight models will therefore be integrated in the two instrument models (24 for VNIR, 24 for SWIR).

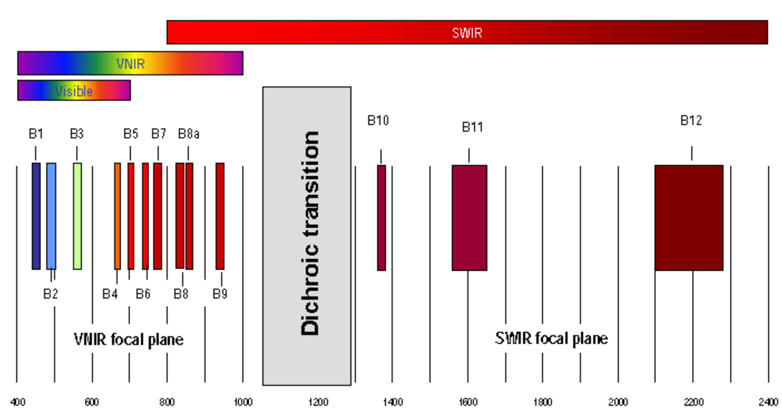


Fig. 1. MSI spectral bands

II. ARCHITECTURE OVERVIEW

The Sentinel2 MultiSpectral Instrument is built around a Silicon Carbide Three Mirrors Assembly (TMA) telescope **[3]**. Two separate focal planes are respectively implemented for the 10 VNIR and the 3 SWIR spectral bands. These are made of Silicon Carbide and are equipped with 12 detectors and 12 filter assemblies. The spectral separation between VNIR and SWIR is achieved thanks to a large dichroïc plate.

Main electrical 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).

Electrical architecture is presented on Fig. 2.

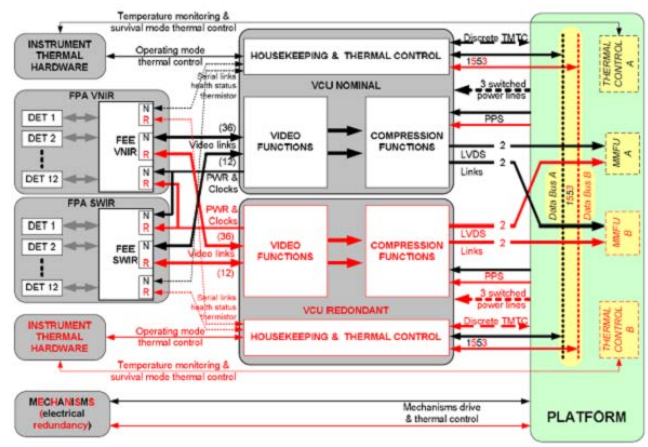


Fig. 2. MSI electrical architecture

Detectors are built by Airbus Defence and Space-ISAE-e2v: they are made of a CMOS die [2][3], using 0.35µm CMOS process, integrated in a ceramic package (see Fig. 3). The VNIR detector has ten spectral bands, two of them featuring an adjacent physical line allowing TDI operating mode, with digital summation performed at VCU level. On-chip analogue Correlated Double Sampling (CDS) allows to reach a readout noise of the order of 130µVrms. For each detector, the ten bands are read through 3 outputs at a sample rate of 4.8MHz. The detector sensitivity has been adjusted for each band through Charge to Voltage conversion Factor (CVF) in view of meeting SNR specification for a reference flux while avoiding saturation for maximum flux.

A black coating deposition on the non-photosensitive area of the CMOS die is implemented to provide high straylight rejection.

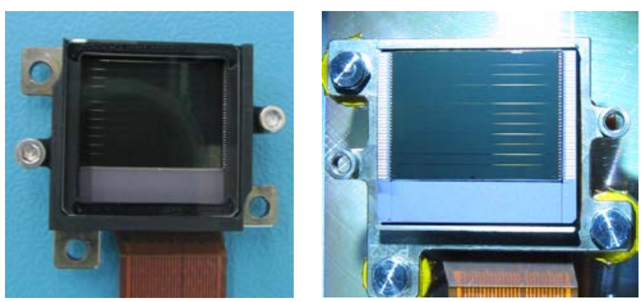


Fig. 3. MSI VNIR detector

Filter assemblies are procured from Jena Optronik (JOP) in Germany. 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 VNIR spectral domain into the ten bands B1 to B9, ii) to prevent stray light effects. This stray light limitation is very efficient since it is made very close to the focal plane. 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 in Spain. Each FEE unit provides electrical interfaces to 3 detectors (power supply, bias voltages, clock and video signals) plus video signal filtering and amplification.

Video and Compression Unit (VCU) is manufactured by JOP and 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 VNIR focal plane operating temperature is 20°C: operating temperature requirements are driven by the radiometric performance stability. VNIR FPA architecture is provided in Fig. 4, pictures are provided in Fig. 5.

The validation and characterization of the VNIR detection chains have been performed in 2 major steps: i) measurements at focal plane level before integration in the instrument, ii) measurements with the whole instrument in final configuration.

III. VNIR FPA PFM DETECTION PERFORMANCES

A. Overview

The main objectives of the FPA radiometric tests are detection chain tuning (Integration times adjustment, video sampling adjustment) but also major performances determination (linearity, signal stability and noise in darkness, SNR). Test set-up consists in a large integrating sphere (80cm diameter port) and the associated baffling in order to ensure the desired illumination level with proper aperture size and f-number. Crosstalk and MTF performances have been characterized via a geometric tests setup.

B. Linearity performance

The FPA linearity test allowed characterizing the linearity behavior of the whole focal plane with an excellent accuracy thanks to: i) the use of dedicated test setup and processing, ii) the choice to characterize the FPA in its end-to-end configuration.

The FPA linearity test is more than simple performance verification: it consists in full radiometric model determination. The response function from 3T structures used for each pixel of the VNIR focal plane requires a cubic fitting. The test setup offered the possibility to increase the level of radiometric accuracy: for all the pixels, residue after cubic fitting keeps within +/-0.3% from radiances starting as low as 0.03*Lmax (refer *Table I* and Fig. 6). Above 0.1*Lmax, this residue decreases within +/-0.1% for most of the bands.

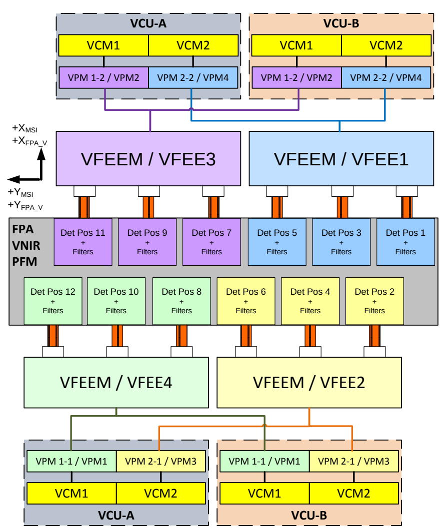


Fig. 4. VNIR FPA detection architecture

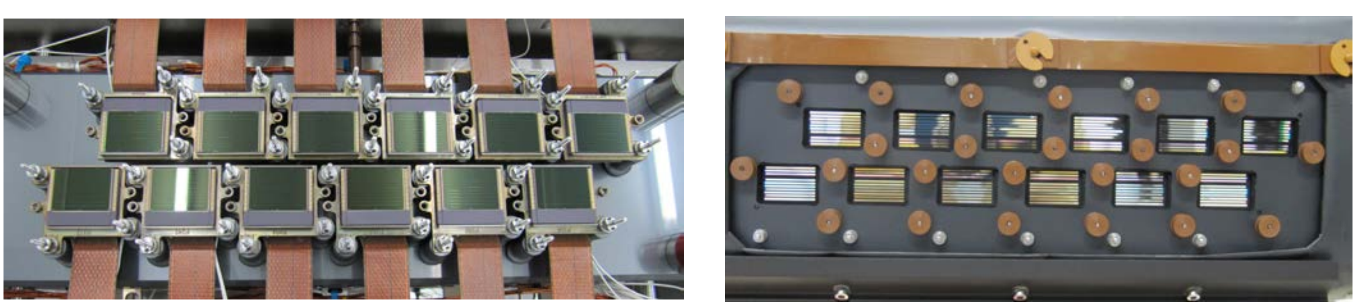


Fig. 5. VNIR FPA PFM, before and after integration of the filters

Table I - FPA PFM LINEARITY TESTS RESULT

Description	*Specified or Expected*	*Measured*	*Extrapolated to EOL*
Non linearity residue after cubic fitting	< +/- 0.42% (*)	< +/-0.30%	< 1% (**)

(*) for radiance level in the range 0.01*Lmax to Lmax ; (**) for radiance level in the range 0.03*Lmax to Lmax

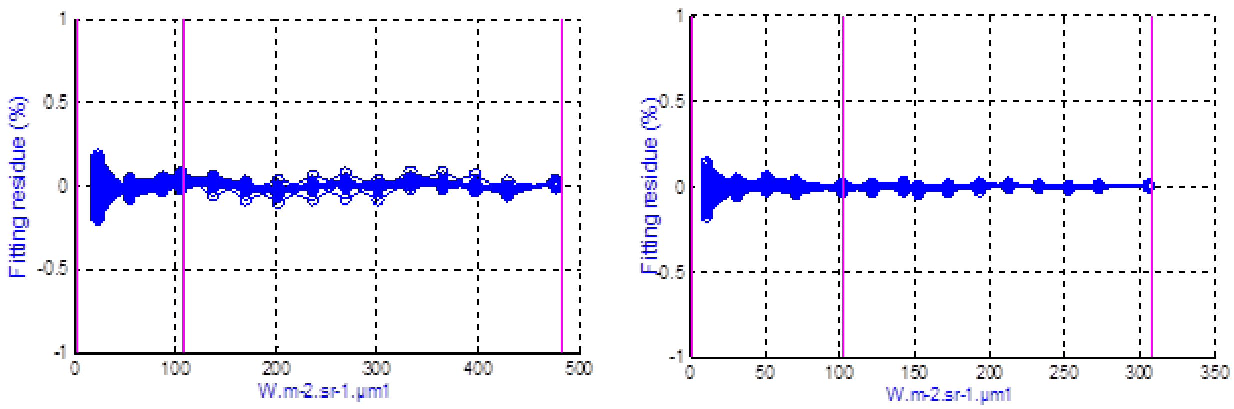


Fig. 6. *Example of fitting residue respectively on B4(left) and B8 (right)*

C. Noise in darkness and dark signal reproducibility/stability

The noise of the full detection chain including digitalization is expressed at detector output and has been measured in its expected range around 200µVrms.

For the lowest radiances, radiometric accuracy is driven by the darkness stability. Dark signal has been measured many times and in many conditions up to the MSI delivery: from test at FPA level to the Thermal Balance and Thermal Vacuum (TB/TV) test campaign of the MSI. In addition, dark signal stability has been kept within +/- 0.1LSB for a 2K FPA temperature variation which is a larger range than in-flight thermal stability. Performances in darkness of noise and stability are summarized in Table II.

Table II –Performances in Darkness

Parameter	*Description*	*Expected*	*Measured*
Noise in darkness	Noise in darkness	130 to 260 µVrms	175 to 220 µVrms
Dark signal stability	Reproducibility for FPA 2K increase	+/- 0.1 lsb	< +/- 0.1 lsb

D. SNR performances

Results are summarized in Table III. All results have been found in very good correlation with predictions and demonstrate margin with respect to the specification. SNR performances are met for all detectors/all pixels.

TABLE III - FPA PFM SNR TEST RESULTS

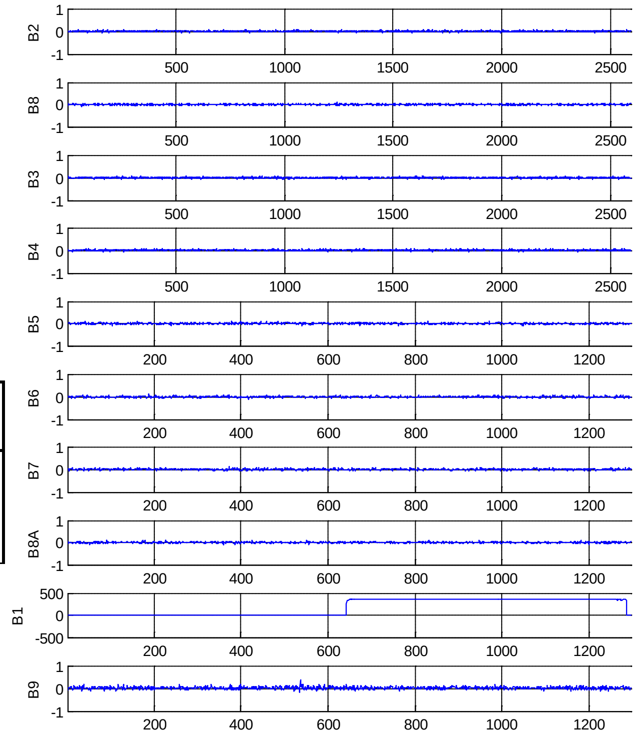
Bands	**Specified SNR**	**SNR@Lref: EOL extrapolation of measurements**		
		Mean	**-2sigma**	**Min**
B1	129	1261	1015	1004
B2	154	204	192	187
B3	168	238	224	219
B4	142	216	204	199
B5	117	243	219	214
B6	89	213	191	188
B7	105	214	188	180
B8	174	214	202	196
B8a	72	154	137	136
B9	114	189	151	147

E. Crosstalk performances

Crosstalk performance is measured with half a line of a band illuminated and all the others in darkness to enhance crosstalk identification. Insulation performance is very good (see *TABLE IV*); crosstalk can barely be observed and is mainly limited by the measurement accuracy: level is around -100dB with a worst case better than 80dB – far below the noise level. Measurement includes both detectors and filters performances. Crosstalk performance is illustrated in Fig. 7.

TABLE IV – CROSSTALK

Parameter	***Description***	***Expected***	***Measured***
Crosstalk	Impact of illumination of one band on the others	< 0.5 %	< 0.01% (~ 0.001%)



Half line test pattern illuminated on B1 with all the other bands remaining in darkness. Level is plotted for all bands after dark signal subtraction: no visible crosstalk measured.

Fig. 7. *Detector 12: Measurement of crosstalk with B1 illuminated*

F. MTF

MTF at FPA level provides the best characterization of the detector/filter assembly without any telescope contribution. Measurement of MTF is performed at best focus. All measurements are in line with expectations. Measured performances are provided in *Table V*.

TABLE V – MTF AT NYQUIST FREQUENCY MEASURED AT FPA LEVEL

Parameter	***Band***	***Expected***	***ACT/ALT Measured***
Minimum MTF ACT/ALT	B1	> 0.35	0.54/-
	B2	> 0.45	0.54/0.55
	B3	> 0.45	053/0.51
	B4	> 0.40	0.47/0.48
	B5	> 0.25	0.55/0.61
	B6	> 0.25	0.56/0.60
	B7	> 0.25	0.55/0.62
	B8	> 0.30	0.40/0.58
	B8a	> 0.25	0.49/0.61
	B9	> 0.35	0.53/-

B1/B9 ALT performances have not been measured at FPA level.

IV. MSI PFM – DETECTION PERFORMANCES AND RESULTS

A. Overview

MSI PFM (refer Fig. 8) detection performances have been characterized with the instrument radiometric test setup at ambient temperature. Main objectives were integration time final adjustment, darkness characterization, SNR performances and gains equalization.

MTF performance was measured with geometric tests setup. Additional verifications on dark signal stability have also been performed during the MSI Thermal Balance and Thermal Vacuum (TB/TV) test campaign.

Fig. 8. *MSI PFM ready for radiometric tests*

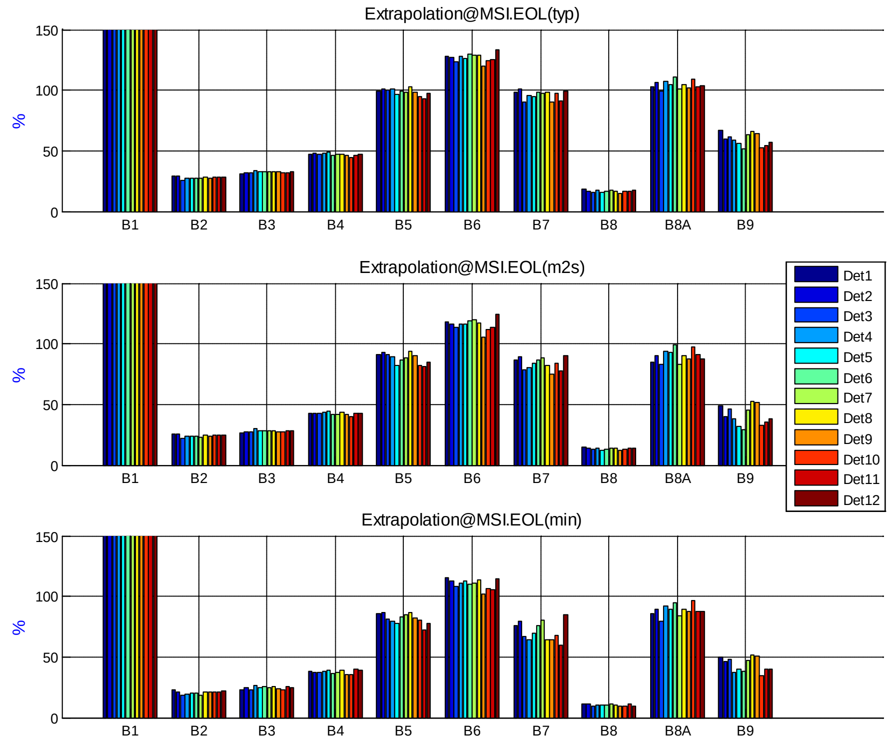
B. SNR performance

SNR performances (refer Table VI) are met for all detectors/all pixels. Results are fully in line with FPA measurements: difference is less than 5% and is mainly due to the radiometric setup differences between FPA and instrument configurations. B1 and B9 complete ground processing is used for this MSI SNR test: the binning of these 60m bands improved the -2sigma and min cases wrt FPA measurement.

TABLE VI - FPA PFM SNR TEST RESULTS

Bands	Specified SNR	SNR@Lref: EOL extrapolation of measurements		
		Mean	**-2sigma**	**Min**
B1	129	1221	1161	1129
B2	154	197	191	186
B3	168	223	215	209
B4	142	209	202	195
B5	117	232	220	212
B6	89	202	192	187
B7	105	206	193	180
B8	174	203	197	192
B8a	72	147	137	136
B9	114	182	160	164

SNR margins extrapolated in EOL conditions are also illustrated in Fig. 9.



The upper figure provides mean SNR margin for all bands and detectors. The figure in the middle is representative of the performance lower case. The last figure provides the performance of the worst pixel for each detector/band. All pixels are in line with specification with comfortable margin.

Fig. 9. *SNR margin at MSI level (EOL extrapolation)*

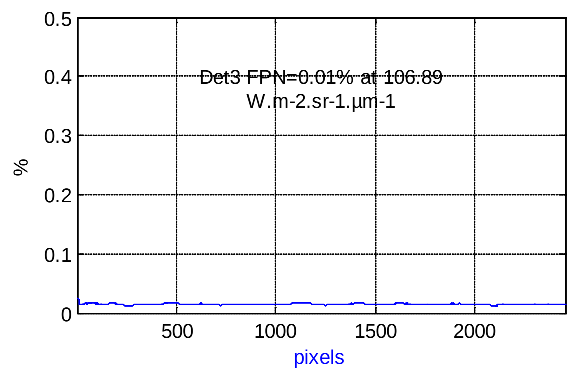
C. Gains equalization and FPN

After integration of the focal plane in the instrument, radiometric models require a calibration to compensate the non-uniformities due to the telescope. For this, absolute gain and relative gains shall be re-adjusted for each band with a uniform acquisition.

Since, MSI has a wide field of view, the complete equalization of the FPA requires a dedicated test setup to provide a highly uniform scene at the calibration radiance. After calibration of the radiometric models, performance is verified through the FPN (Fixed Pattern Noise) at Lref in a different radiometric configuration, and is calculated over all sections of 100 contiguous pixels. Measurements demonstrated an excellent level of performances and results are reported in *Table VII*. Performance is also illustrated in Fig. 10.

TABLE VII – *FPN AT LREF*

Parameter	***Band***	***Specified***	***Measured***
FPN at Lref calculated over all sections of contiguous 100 pixels (%)	B1	0.20	0.02
	B2	0.20	0.02
	B3	0.20	0.02
	B4	0.20	0.02
	B5	0.20	0.03
	B6	0.20	0.03
	B7	0.20	0.04
	B8	0.20	0.02
	B8a	0.22	0.04
	B9	0.31	0.11



The FPN requirement has been checked on acquisitions performed at Lref over all sections of 100 contiguous pixels.

Fig. 10. *Example of FPN on detector 3 / B4 at Lref*

D. MTF

Extensive MTF **[5]** versus focus measurements have been conducted in order to validate the proper positioning of the VNIR FPA. Considering the defocusing budget, the achieved MTF is above 20 % for a requirement of 15%. Measured performances are provided in Table VIII.

TABLE VIII – MTF MEASURED AT MSI LEVEL

Parameter	***Band***	***Specified***	***Measured***
Minimum MTF for worst case defocus ACT/ALT	B1 B2 B3 B4 B5 B6 B7 B8 B8a B9	>0.15	0.25 / 0.37 0.28 / 0.25 0.29 / 0.23 0.27 / 0.19 0.45 / 0.33 0.43 / 0.33 0.43 / 0.33 0.24 / 0.20 0.37 / 0.29 0.25 / 0.37

V. CONCLUSIONS

The VNIR detection/radiometric performance testing has been achieved with excellent results. Testing has been performed in 2 steps: at FPA then instrument levels.

Tests with focal plane allowed the linearity behavior of the detectors to be characterized with excellent accuracy. SNR performances have been found in very good correlation with predictions and demonstrate margin with respect to the specification for all detectors / all bands / all pixels. Crosstalk and MTF performances were also in line with expectations.

Tests at instrument level allowed an end-to-end characterization of the performances but also an adjustment of the radiometric models. SNR has been confirmed while MTF performances of the whole instrument have been measured as higher than the specification. Challenging equalization of the wide field of view has been performed and provided very low levels of FPN.

Challenging verification activities have been successfully conducted taking into account the very large field of view of the instrument and the huge amount of data generated (1.3 Gigabit per second). In order to support these activities, dedicated test configuration and post-processing tools have been developed and validated.

The MSI PFM has been delivered to Airbus Defence & Space Friedrichshafen and integrated in the first Sentinel2 satellite S2A which is now in final qualification and acceptance tests campaign, for a launch scheduled in first half of 2015.

Acknowledgment

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