International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

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International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127771G · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2689288

Meteosat Third Generation : MTG-I FCI PFM instrument radiometric performance

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ABSTRACT

Meteosat Third Generation (MTG) is the new European mission for accurate observation of the Earth dedicated to meteorological applications. MTG Program is being realised through the well-established and successful cooperation between EUMETSAT and ESA. MTG system will ensure continuity and enhancement of operational meteorological (and climate) data from Geostationary Orbit as currently provided by the Meteosat Second Generation (MSG) system.

The industrial Prime Contractor for the Space segment of MTG is Thales Alenia Space (France) with a core team consortium including OHB (Germany). This contract includes the provision of six satellites, four Imaging satellites (MTG-I) and two sounding satellites (MTG-S), which will ensure a total operational life of the MTG system in excess of 20 years. MTG-I first satellite will be launched end of 2022, starting point of the in-orbit story of MTG.

MTG-I embarks the FCI (Flexible Combined Imager), optical payload developed at Thales Alenia Space in France. The FCI is an imaging radiometer which provides simultaneously to the users 16 spectral channels from Visible to Very Long Wave InfraRed (0.4µm – 13.3µm) delivering full disk services (in 10 minutes) at their nominal sampling distance (1 to 2km). Four channels are also delivered at a smaller spatial sampling distance (down to 500m). FCI also provides local area scanning possibilities with a higher repeat cycle (down to 2.5 minutes).

The present paper is dedicated to the FCI end-to-end radiometric performance. After an overview of the FCI and the design specificities of its detection chains, its key radiometric performance will be presented. It will focus on FCI PFM test results, which has successfully passed the on-ground fine radiometric calibration and characterization campaign under optical vacuum in 2021.

After 10 years of development at Thales Alenia Space, with a fruitful cooperation of many European sub-contractors, the results of the performance characterization and calibration of the FCI have been successfully demonstrated. This work has been achieved thanks to the major support and supervision of ESA.

Keywords: Meteosat, MTG, FCI, Earth Observation, radiometry, Visible, Infrared, accuracy, SNR, NEdT

1. INTRODUCTION

The first MTG-I satellite (MTG-I1) will be launched end of 2022, starting point of the in-orbit story of MTG. MTG-I1 embarks the FCI PFM instrument, an imaging multi-spectral radiometer, which has been designed, integrated and tested in Thales Alenia Space Cannes.

The present paper is dedicated to the FCI end-to-end radiometric performance. After an overview of the FCI instrument capabilities in the first paragraph, a description of the design specificities of its detection chains in the second paragraph, the paper will focus on FCI PFM radiometric test results. Indeed, FCI PFM has successfully passed the on-ground fine radiometric calibration and characterization campaign under global optical vacuum in 2021.

2. FCI INSTRUMENT OVERVIEW

2.1 A new generation of instrument, for improved imaging performance

FCI on board MTG-I provides improved performance on multiple image characteristics, in comparison with previous generation of MSG satellites. Among other characteristics, one can mention the Earth full disk (FD) image cycle that will be of 10 minutes, with capability to perform some rapid scanning on local areas (in cycles down to 2.5 minutes). Whatever the cycle, i.e. whatever the Earth coverage, the image in 16 spectral channels will be provided simultaneously to the users. The number of solar spectral channels has doubled with regard to MSG instrument, allowing addressing more scientific needs. The spatial sampling distance (SSD) is also noticeably improved. This is summarized in the Figure 1 here below.

Characteristics	MSG	MTG-I (FCI)
Full disk image cycle	 15 min	 10 min
Spectral channels	HRV VIS 0.6 VIS 0.8 NIR 1.6	VIS 0.4 VIS 0.5 VIS 0.6 VIS 0.8 VIS 0.9 NIR 1.3 NIR 1.6 NIR 2.2
	IR 3.8 IR 6.2 (WV) IR 7.3 (WV) IR 8.7 IR 9.7 (O_3) IR 10.8 IR 12.0 IR 13.4 (CO_2)	IR 3.8 IR 6.3 (WV) IR 7.3 (WV) IR 8.7 IR 9.7 (O_3) IR 10.5 IR 12.3 IR 13.3 (CO_2)
Sampling distance	1 km (HRV) 3 km (others)	0.5 – 1.0 km (VIS-NIR) 1.0 – 2.0 km (IR)

Figure 1. Main improved performance on image characteristics from MSG to MTG-I (FCI)

Figure 2. FCI coverage modes

FCI spectral bands cover a very wide range if the spectrum, from Visible to Very Long Wave InfraRed (from 0.4µm to 13.3µm) – see Figure 3 for illustration. Table 1 presents each of these 16 spectral bands, with their associated spatial resolution on ground. In addition, the FCI provides one channel for Fire Applications, the so-called IR3.8-FA channel. The goal of this specific channel is to detect fires on Earth with brightness temperature up to 490K. So the IR3.8 spectral channel is divided in two video channels with a dedicated gain for each. And therefore the FCI actually counts 17 video channels.

It shall be noted that four channels, often called HR channels, are provided with 2 spatial resolutions: HR resolution (e.g. 500m for VIS0.6) and FD resolution (e.g. 1km for VIS0.6, i.e. same as per all other solar VNIR channels). Those four channels are identified in bold blue in all tables of this paper. Detectors design is adjusted to the lowest SSD in that case, and binning is performed on ground to provide the image in the two spatial resolutions.

Table 1. FCI spectral channels and their associated spatial resolution

		Solar VNIR channels								Thermal IR channels							
Spectral channel	[-]	VIS0.4	VIS0.5	**VIS0.6**	VIS0.8	VIS0.9	NIR1.3	NIR1.6	**NIR2.2**	**IR3.8**	IR6.3	IR7.3	IR8.7	IR9.7	**IR10.5**	IR12.3	IR13.3
Central wavelength	[µm]	0.444	0.510	0.640	0.865	0.914	1.38	1.61	2.25	3.80	6.30	7.35	8.70	9.66	10.5	12.3	13.3
Spectral width	[µm]	0.06	0.04	0.05	0.05	0.02	0.03	0.05	0.05	0.4	1.0	0.5	0.4	0.3	0.7	0.5	0.6
SSD	[km]	1.0	1.0	**0.5** - 1.0	1.0	1.0	1.0	1.0	**0.5** - 1.0	**1.0** - 2.0	2.0	2.0	2.0	2.0	**1.0** - 2.0	2.0	2.0

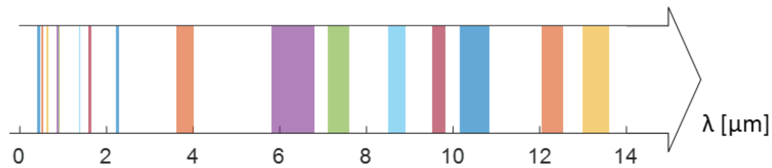

Figure 3. FCI 16 spectral channels, from 0.4 µm to 13.3 µm, represented on the spectrum *(arbitrary colors)*

The dynamic range coverage of the FCI is as wide as its spectral range. Table 2 presents the coverage in terms of scene level for each video channel, i.e. radiance at Top Of Atmosphere (TOA) for solar VNIR channels and brightness temperature for thermal IR channels. The radiance from the calibration source is also included in the channels dynamic range.

Table 2. Earth radiance coverage per FCI channel, and specified SNR (resp. NEdT) at reference scene level

		Solar VNIR channels								Thermal IR channels								
Channel	[-]	VIS0.4	VIS0.5	**VIS0.6**	VIS0.8	VIS0.9	NIR1.3	NIR1.6	**NIR2.2**	**IR3.8**	**IR3.8-FA**	IR6.3	IR7.3	IR8.7	IR9.7	**IR10.5**	IR12.3	IR13.3
Lmin (resp. Tmin)	[TOA] (resp. [K])	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	200	350	165	165	165	165	165	165	165
Lref (resp. Tref)	[TOA] (resp. [K])	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	300	350	250	250	300	250	300	300	270
Lmax (resp. Tmax)	[TOA] (resp. [K])	1.2	1.2	1.2	1.2	0.8	0.8	1.0	1.0	350	490	270	285	330	310	340	340	300
Radiometric noise: SNR (resp. NEdT) at Lref	[-] (resp. [K])	25	25	**12** - 30	21	12	40	30	**12** - 25	**0.2** - 0.1	1.0	0.3	0.3	0.1	0.3	**0.2** - 0.1	0.2	0.2

2.2 Instrument description and flight models development status

A description of the instrument design and its development status including previous test campaigns can be found in [1]. For now, the FCI PFM has been delivered as planned to the MTG-I1 satellite in July 2021, after the optical vacuum test campaign which radiometric results are presented in this paper. MTG-I1 is currently finalizing its test sequences, for a launch campaign in Autumn, the launch being planned end 2022. In parallel, FCI FM2 was integrated and the end-to-end tests are on-going. Some storage will occur for next flight models, at different levels depending on the model, for a launch of the last MTG-I4 around 2033.

3. DESIGN SPECIFICITIES OF THE FCI DETECTION CHAINS

The FCI characteristics presented above led to some choices during the design phase, and in particular some detection chains characteristics. A presentation can be found in [2].

One specificity of FCI is the rhombus pixels design. This very specific shape and pixels arrangement is a Thales Alenia Space design already used on MSG and adapted in particular to the MTF need. Moreover, the detectors design counts 4 columns of pixels per channel. That means that the linear array is redounded. The goal is to ensure a complete image, with no missing sample, through the entire life of the FCI. Indeed, for each line, one pixel is selected among 4, leaving some space for a few defective pixels and allowing performance optimization. From on-ground fine characterization campaign the preferred selection for flight is implemented in the instrument, and all data are provided to the users so that it could be modified in flight as needed. A schematic of the pixels arrangement per channel is represented on Figure 4.

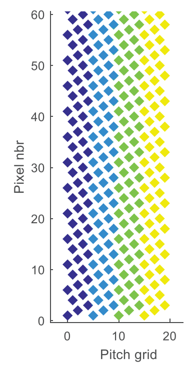

Figure 4. Schematic of the specific arrangement of pixels implement for each channel of the FCI

The number of lines and the pitch of the pixels grid is adapted to the needed swath and spatial sampling distance for each channel. Channels are grouped inside detector assemblies. The repartition per Detector Assembly (DA) is indicated in Table 3. The FCI counts 5 DAs in total:

- the VIS DA, which has been developed by Teledyne E2V. It works at room temperature and forms the Visible focal plane of the instrument.
- the NIR/IR1/IR2/IR3 DAs, which have been developed by LYNRED. These 4 DAs are mounted and grouped at instrument level on the IR focal plane, which is maintained at cryogenic temperature below 60K in operational mode.

Each FCI DA presents a similar structure, that is:

- a sensitive retina area encompassing multiple channels (from 2 to 5 depending on the DA)
- a package which makes the optical, mechanical and thermal interface with the instrument. It includes a pass-band filtering plane for spectral discrimination per channel. It also makes the electrical interface between the retina and the flexible cable.
- a flexible cable, with a connector at its extremity, which ensures the electrical link between the instrument front-end electronics and the detector's package.

The FCI detectors all use CMOS technology and work in Integrate While Read mode. All selected pixels of a channel are acquired at the same time.

Table 3. Format of the detectors per FCI channel

		Solar VNIR channels								Thermal IR channels								
Detector Assembly	[-]	VIS					NIR			IR1				IR2		IR3		
Channel	[-]	VIS0.4	VIS0.5	VIS0.6	VIS0.8	VIS0.9	NIR1.3	NIR1.6	NIR2.2	IR3.8	IR3.8-FA	IR6.3	IR7.3	IR8.7	IR9.7	IR10.5	IR12.3	IR13.3
Number of lines	[-]	224	224	448	224	224	224	224	448	224	224	112	112	112	112	224	112	112
Pitch grid	[µm]	46	46	23	46	46	25	25	12.5	12.5	12.5	25	25	25	25	12.5	25	25

The radiometric noise is a driving requirement for the FCI video chains:

- For VNIR channels, as one can see in Table 2, the reference signal level Lref corresponds to the minimum signal level Lmin. So the constraint on SNR in these bands is at low flux. This leaves much margin on performance for the higher part of the dynamic range, as shown on SNR results presented in section 5.1.

- For IR channels, in particular the very long wave bands, the main constraint is to reduce sufficiently the dark current noise to reach the NEdT need. For that purpose, the IR focal plane array temperature is maintained at 59K.

The Video Chain Unit for FCI has been developed by Thales Alenia Space in Spain. It includes one Front-End Electronics (FEE) unit for each DA. Those 5 FEEs are linked to a common main unit that allows powering the detectors and digitalizing the video output signal for transmission to the Instrument Control Unit. The Video Chain Unit integrates a 14 bits ADC. It delivers the data in 12 bits, after some temporal binning, as needed per channel to meet the specified spatial sampling. The frame period duration is 0.378ms. It is fixed and common to the five detectors of the instrument. The effective integration time is then adjustable per channel, in order to optimize performance while ensuring no saturation of pixels at maximum useful scene level.

4. FCI TESTING CONFIGURATION

In order to address this wide range of spectral channels, with even wide panel of dynamic ranges, some dedicated Optical Ground Segment Equipments (OGSE) have been developed for MTG FCI testing. Those OGSEs allow performing the FCI on-ground fine optical, radiometric calibration and characterization under global optical vacuum.

One OGSE, called MOTA, is dedicated to solar VNIR channels characterization. Some description of the MOTA and its improved calibration method can be found in [3].

The other OGSE is dedicated to thermal IR channels. It is constituted of two blackbodies: i) a cold black body, the Deep Space Black Body (DSBB), which is maintained stable below 100K during the whole test sequence ; ii) a variable black body (VBB) which temperature is monitored to address the dynamic range of all IR channels.

Thanks to the pointing capabilities of the scan mirror of the FCI, each source is viewed as needed during the test sequence.

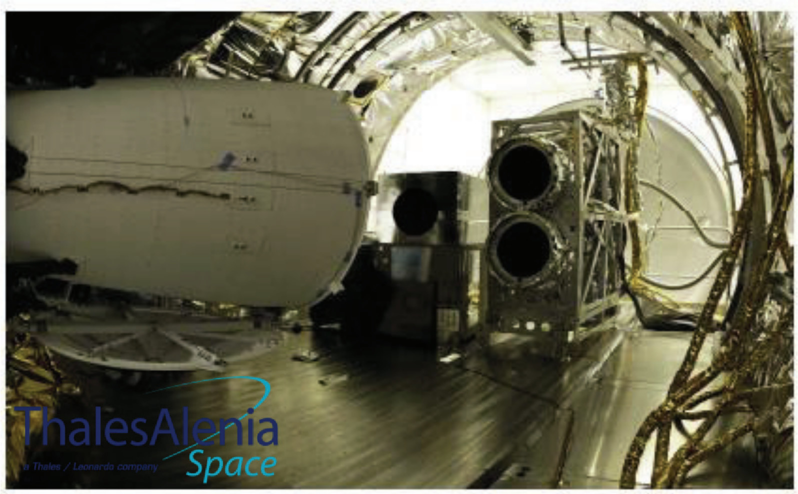

Figure 5. FCI PFM inside the optical vacuum chamber in Thales Alenia Space Cannes premises, ready for tests. One can see the FCI with its telescope baffle on the left of the picture, and the two OGSEs in front of it (MOTA for VNIR channels, DSBB/VBB for IR channels).

5. FCI PFM FINE RADIOMETRIC PERFORMANCE TEST RESULTS

After setting all adjustable parameters to optimize the dynamic range of each channel, radiometric performance and characteristics of each pixel (nominal and redundant ones) are precisely measured. This allows pixels ranking and finally pixels selection generation for flight.

In addition, an image of 10 minutes simulating a full disk acquisition with a pixels selection as per flight is acquired. Here below are presented the end-to-end performance measurement results obtained on all spectral channels from these full disk-like acquisitions after post-processing, i.e. at Level 1b. The SNR performance (resp. NEdT for IR channels) over an image is evaluated. The absolute radiometric accuracy as well as the inter-pixel relative accuracy is also retrieved.

5.1 SNR/NEdT on a full image

Figures here below present the SNR performance (resp. NEdT performance) on a full image measured simultaneously on all VNIR channels (resp. IR channels) at various scene levels. A comparison to the required value shows that radiometric noise need is largely met on the entire dynamic range, for all FCI spectral channels.

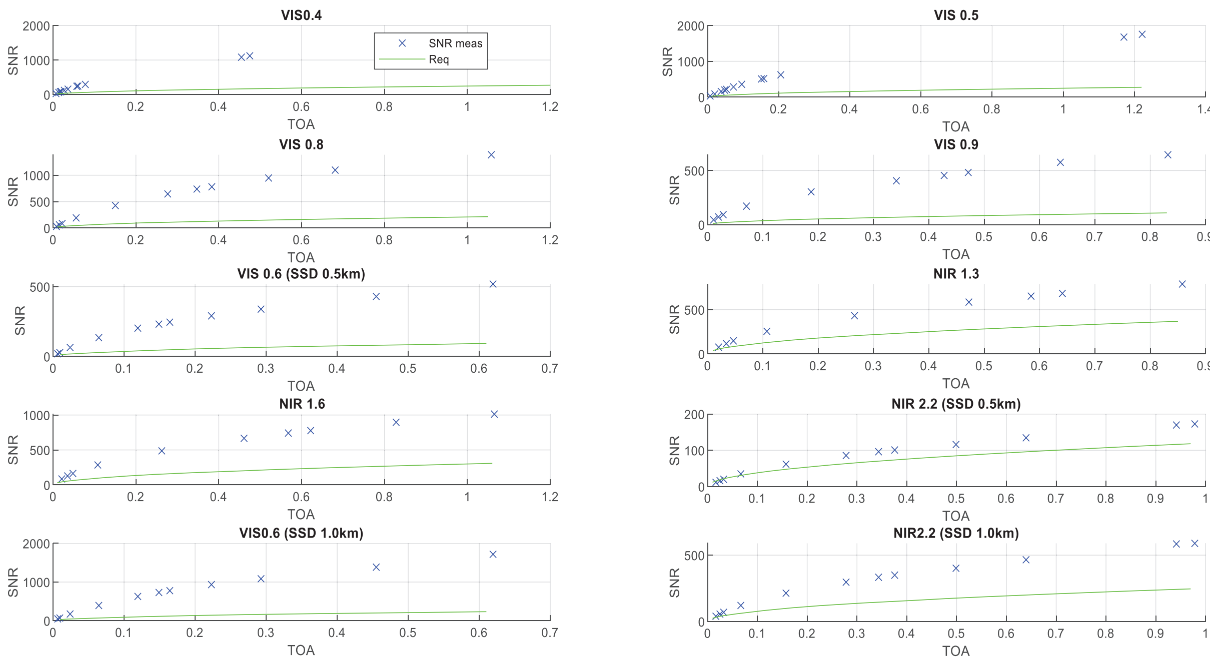

Figure 6. FCI PFM SNR performance measured on a full disk-like acquisition, for all solar VNIR channels

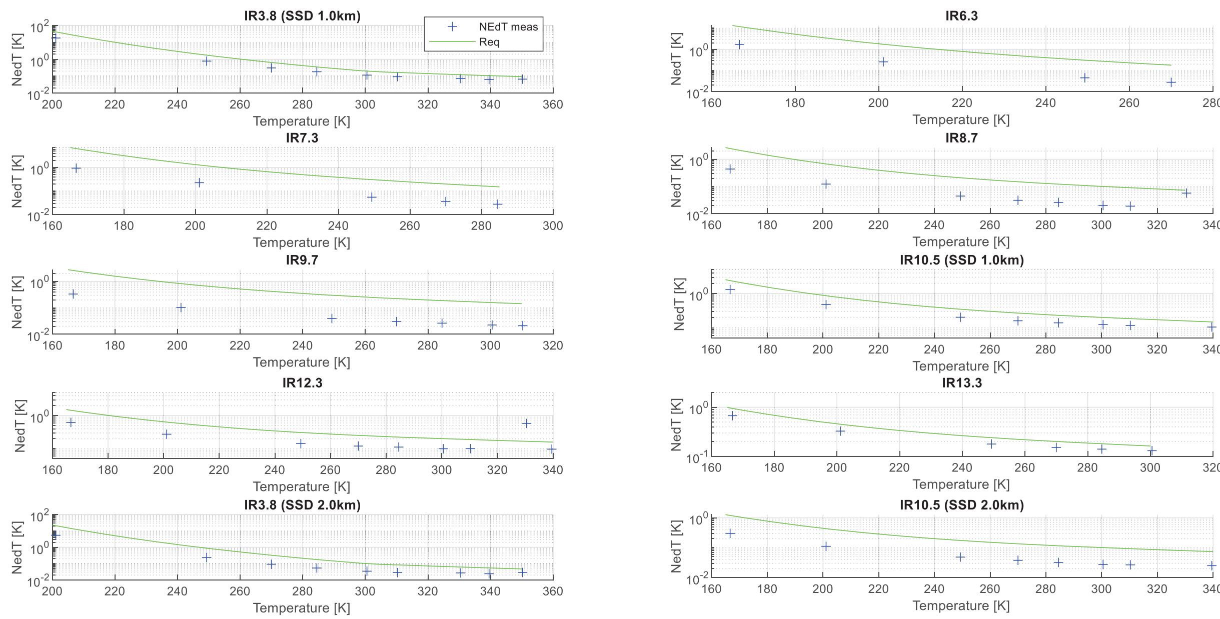

Figure 7. FCI PFM NEdT performance measured on a full disk-like acquisition, for all thermal IR channels

5.2 Absolute radiometric accuracy

The radiometric calibration error has been demonstrated to be very low on all channels, and anyhow below the required 5% (resp. 10% for HR channels) for VNIR channels and below 0.7K (resp. 1.0K for HR channels) for IR channels over the whole dynamic range. Some marginal exceptions are seen at the lowest scene radiance level where signal is almost dark.

This challenging performance is made possible thanks to the OGSE calibration method, the detection chains performances and some non-linearity correction in data processing to be applied on-ground.

5.3 Inter-pixel relative radiometric accuracy

The relative calibration error is demonstrated to be very low, and anyhow below the requirement for all channels, except at the very low end of the dynamic range due to the extreme sensitivity to residual errors in non-linearity correction. Measurement results are depicted on Figure 8 for VNIR channels and on Figure 9 for IR channels.

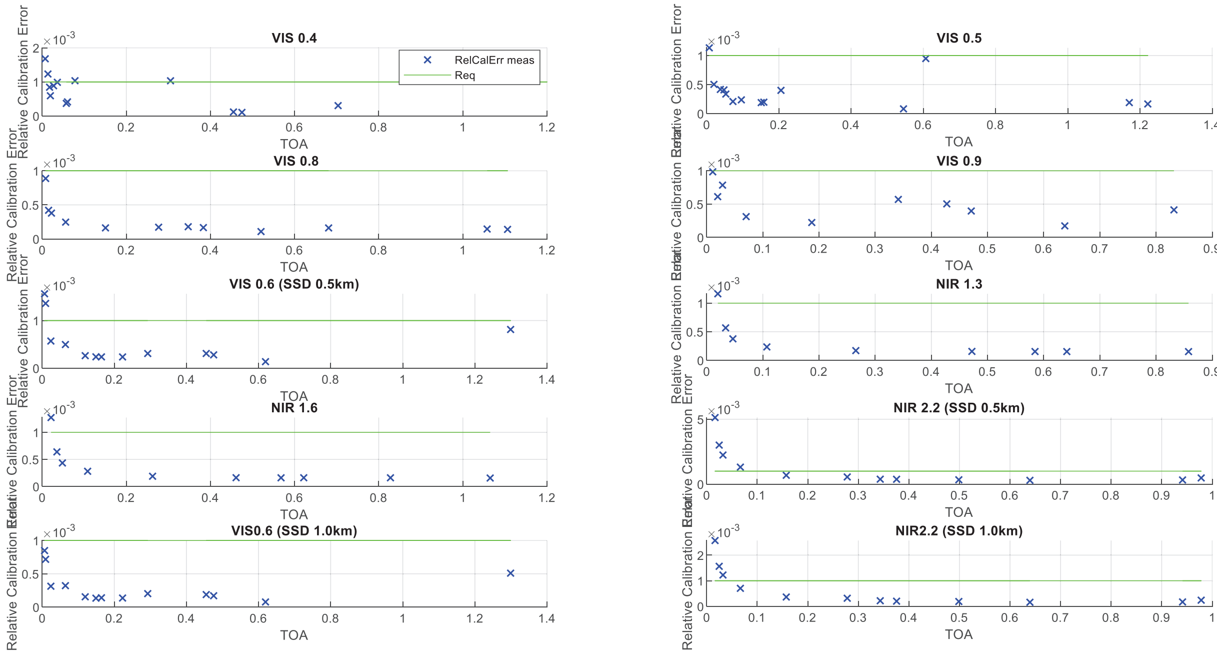

Figure 8. FCI PFM Inter-pixel measured radiometric accuracy, for all solar VNIR channels

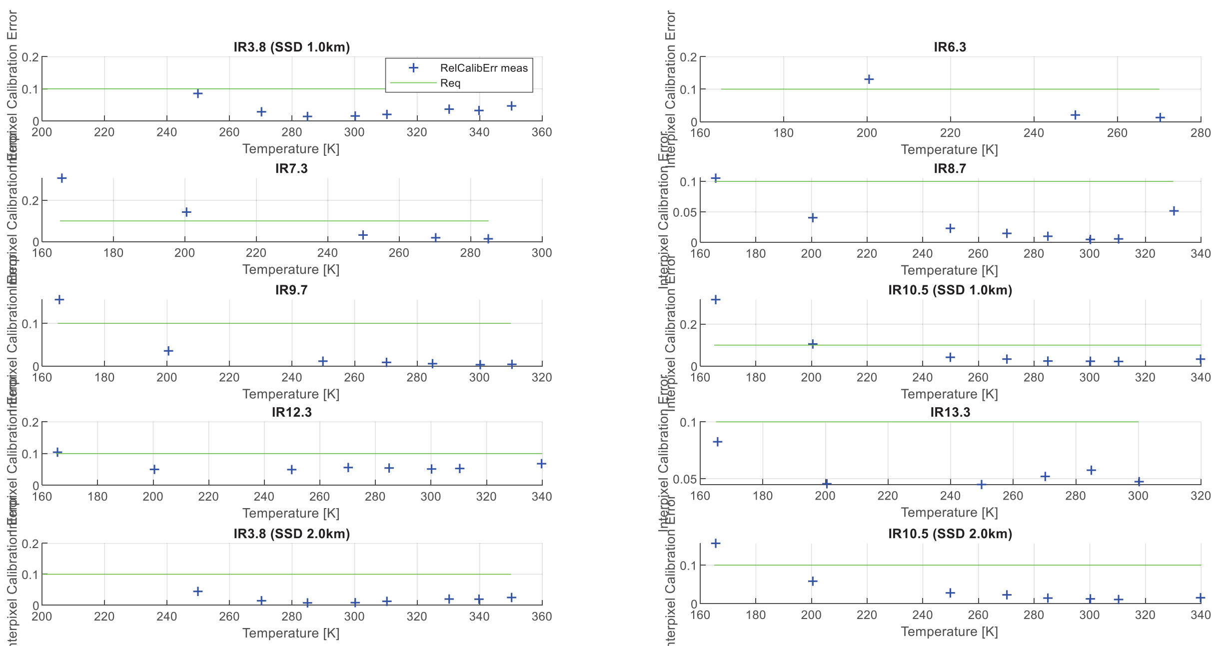

Figure 9. FCI PFM Inter-pixel measured radiometric accuracy, for all thermal IR channels

6. CONCLUSION

The FCI PFM instrument has been fully characterized on ground in Thales Alenia Space Cannes premises, with a fine radiometric calibration campaign under optical vacuum in 2021. It demonstrated very satisfying end-to-end radiometric performance, as presented in this paper.

Those great results are expected to be reproduced for recurring models. Indeed, the on-ground fine radiometric calibration and characterization campaign has already been performed for VIS channels on FCI FM2. SNR performance on a full image measured on VIS channels for FCI FM2 are presented on Figure 10 here below. They are very similar to PFM ones.

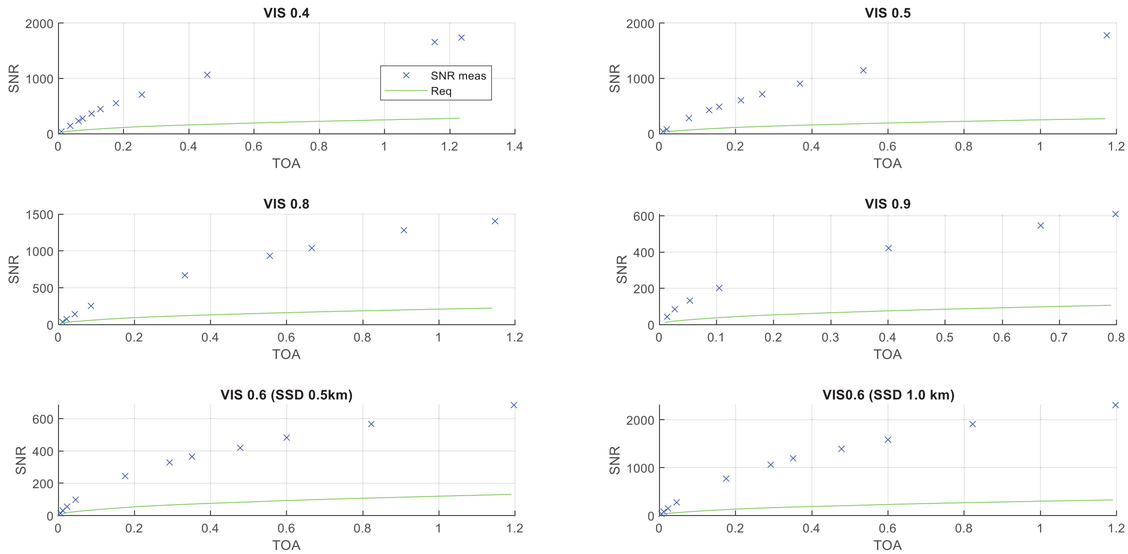

Figure 10. FCI FM2 SNR performance on a full disk-like acquisition, for VIS channels

All other performance of the FCI PFM instrument have been verified on-ground throughout the FCI test campaigns. Among others, one can mention the end-to-end optical performances (as line of sight, inter-channel co-registration, MTF, straylight), the thermal performance, the EMC tests,…

MTG-I1 will be launched end of 2022, with FCI PFM on-board. This will be the starting point of the in-orbit story of Meteosat Third Generation. And MTG-S1 will follow a year or so later, to complete the mission with great scientific interest.

ACKNOWLEDGEMENTS

Being there today, with an FCI instrument fulfilling its expectations for MTG, is the fruit of a wide collaborative work for more than ten years between people from companies all around Europe. The authors would like to thank all of them.

The authors acknowledge ESA for the confidence put in Thales Alenia Space, as well as their strong support given in all domains. Authors are grateful to EUMETSAT for fruitful exchanges and supervision all along this development.

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