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## *FCI instrument on-board MeteoSat Third Generation satellite: design and development status*



## FCI instrument on-board MeteoSat Third Generation Satellite - design and development status

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### ABSTRACT

2020 has been a key year in the MeteoSat Third Generation (MTG), with the integration and tests of the Flexible Combined Imager (FCI) proto-flight model (PFM). The FCI is the imaging instrument of the MeteoSat Third Generation mission, whose first satellite MTG-I1 will be launched in the second half of 2022. Its large spectral coverage, its fast and flexible scanning, associated with demanding radiometric and optical performances will allow a step forward in Europe weather nowcasting.

In 2018, three complementary development models were successfully integrated and tested. The Engineering Model validated the optical and radiometric performances of the detection chain. The Structural and Thermal Model qualified the robustness of the design against launch and in-orbit environments and validated the consistency with the thermal and microvibration mathematical model predictions. The Avionic Test Bench with the software which reached a very good level of maturity, validated the control, command and data handling of the instrument.

The completion of these developments enabled to successfully hold the instrument Critical Design Review (CDR) end 2018.

In 2019, the two main components of the instrument, namely the telescope assembly and the detection control electronics assembly (DCEA) successfully passed the acceptance tests and have been delivered.

The article will present first an overview of the instrument design and the main outcomes of the development models. Then, it will discuss the up-to-date status of the FCI PFM development. Finally, it will introduce the overall planning for the four FCI models to be delivered to the MTG-I satellite series.

This work has been performed under an ESA contract to Thales Alenia Space-France.

**Keywords:** MTG, FCI, development, tests

## 1. MTG FLEXIBLE COMBINED IMAGER DESIGN

### 1.1 Mission overview

The MTG Observation Mission will provide the operational meteorological community with observations and meteorological products/data fulfilling user needs in the fields of Nowcasting and very short term Weather Forecasting (NWC), medium/short range Global and Regional Numerical Weather Prediction (NWP), and Climate and Air Composition Monitoring.

The Imagery Mission is composed of the High Resolution Fast Imagery (HRFI) and the Full Disk High Spectral Imagery (FDHSI) missions, both performed by a single instrument named the Flexible Combined Imager (FCI).

The FCI instrument is able to function in a flexible manner (operations wise) and provides samples for 4 out of the 16 total spectral channels at High Spatial Sampling/Resolution (HRFI mode) as well as samples in all of the 16 spectral channels at the nominal (lower) Spatial Sampling/Resolution (FDHSI mode).

The instrument is able to transmit data to the ground station at full resolution and for all spectral channels in both nominal (Full Disk Coverage, FDC) and reduced scan (Local Area Coverage, LAC) modes, as illustrated in Figure 1, allowing HRFI and FDHSI missions to be fulfilled simultaneously for LAC.

Table 1: FCI coverages versus Repeat Cycle duration

Coverage	Repeat Cycle duration	Service Type
FDC : full Earth Disc Coverage	10 minutes	Full Disc Scanning Service (FCI-FDSS)
LAC = FDC / 2 : half of the FDC	5 minutes	
LAC = FDC / 3 : a third of the FDC	3.33 minutes	
LAC = FDC / 4 : a fourth of the FDC	2.5 minutes	Rapid Scanning Service (FCI-RSS)

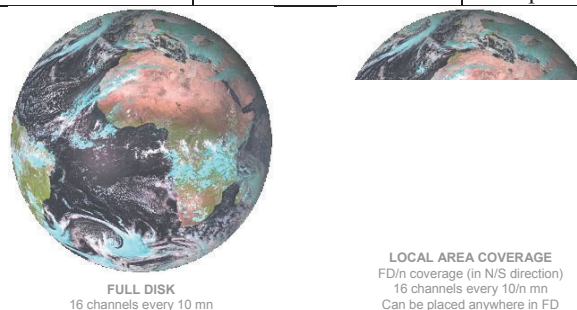


Figure 1:FCI coverage modes

The scan pattern follows a repetitive pattern from image to image in terms of sample acquisition time, which is necessary for wind tracking. It may also be phased if needed with a master timeline for the MTG data acquisition, so as to synchronize repeat cycles of the Imagery Mission MTG-I and the Sounding Mission MTG-S, if needed.

### 1.2 FCI imaging channels

The FCI consists in 16 imaging channels ranging from 0.4  $\mu\text{m}$  to 13.3  $\mu\text{m}$  (plus an additional, Fire Application channel in IR-3.8) :

- 8 Solar channels
  - 5 VIS channels (VIS-0.6 in HR mode),
  - 3 NIR channels (NIR-2.2 in HR mode),
- 8 Thermal channels (IR-3.8 and IR-10.5 in HR mode).

Table 1. FCI spectral channels definition and corresponding on-ground spatial sampling. It illustrate the large spectral coverage and the high spatial sampling of the instrument.

Spectral group	Spectral Channel	Central Wavelength, $\lambda_0$ ( $\mu\text{m}$ )	Spectral Width, FWHM ( $\mu\text{m}$ )	On-ground spatial sampling distance (km)
VIS	VIS 0.4	0.444	0.060	1.0
	VIS 0.5	0.510	0.040	1.0
	VIS 0.6	0.640	0.050	1.0 / 0.5
	VIS 0.8	0.865	0.050	1.0
	VIS 0.9	0.914	0.020	1.0
NIR	NIR 1.3	1.380	0.030	1.0
	NIR 1.6	1.610	0.050	1.0
	NIR 2.2	2.250	0.050	1.0 / 0.5
IR1	IR1 3.8	3.800	0.400	2.0 / 1.0
	IR1 6.3	6.300	1.000	2.0
	IR1 7.3	7.350	0.500	2.0
IR2	IR2 8.7	8.700	0.400	2.0
	IR2 9.7	9.660	0.300	2.0
IR3	IR3 10.5	10.500	0.700	2.0 / 1.0
	IR3 12.3	12.300	0.500	2.0
	IR3 13.3	13.300	0.600	2.0

### 1.3 MTG FCI functional description

The functional instrument architecture achieves the mission performances and offers robustness as well as easing sub-systems management and AIT sequence thanks to a modular approach. The architecture selection is supported by consolidated trade-offs which have led to an entrance cavity design, a dedicated spectral separation and a single infra-red focal plane cooled by an active thermal control.

The scan assembly unit primary function ensures full Earth-disk coverage in a whiskbroom mode thanks to a double-gimbaled scan-mirror mechanism which permits North/South and East/West motions simultaneously. The secondary function is performed by the scan-mirror size itself which collects photons at the entrance pupil of the telescope to satisfy the needed radiometric performance.

The entrance cavity represents one of the most sensitive modules of the instrument architecture. Its role is to manage the Sun intrusions inside the instrument around midnight to preserve FCI performance in terms of image quality and line-of-sight stability. This function is efficiently handled by dedicated baffling and supporting structure, mechanically and thermally decoupled from the rest of the instrument notably the main optical bench which supports sensitive components as mirrors.

The entrance telescope function is to image the on-Earth instrument swath with the required image quality and to provide a highly stable line-of-sight with respect to thermo-elastic effects. This telescope also offers the capability to form an intermediary image (field-stop level after secondary mirror) for calibration device and diaphragm implementation.

The spectral separation splits the input light into 5 optical beams corresponding to 5 different parts of the complete spectrum covering the required spectral channels. Four of them are collimated (interface eased with cold assembly) and spatially closed (reduced volume) leading to a single and compact NIR/IR cryostat. The 3D geometrical arrangement offers a suitable polarization management by in-plane and out-of-plane balancing.

The two focal plane assemblies (VIS and NIR/IR) ensure the optical image detection (photons to electrons conversion) with suitable signal-to-noise ratio performance. The modules carry out the final spectral separation at detector level by dedicated optical filters for each spectral band in order to minimize the in-field separation effect.

The cryostat assembly cools and maintains NIR/IR detectors at 58K operating temperature by advanced active coolers (Large Pulse Tube Coolers (LPTC)) to reach radiometric performance in terms of noise and especially dark current effect (dark level and associated fluctuations).

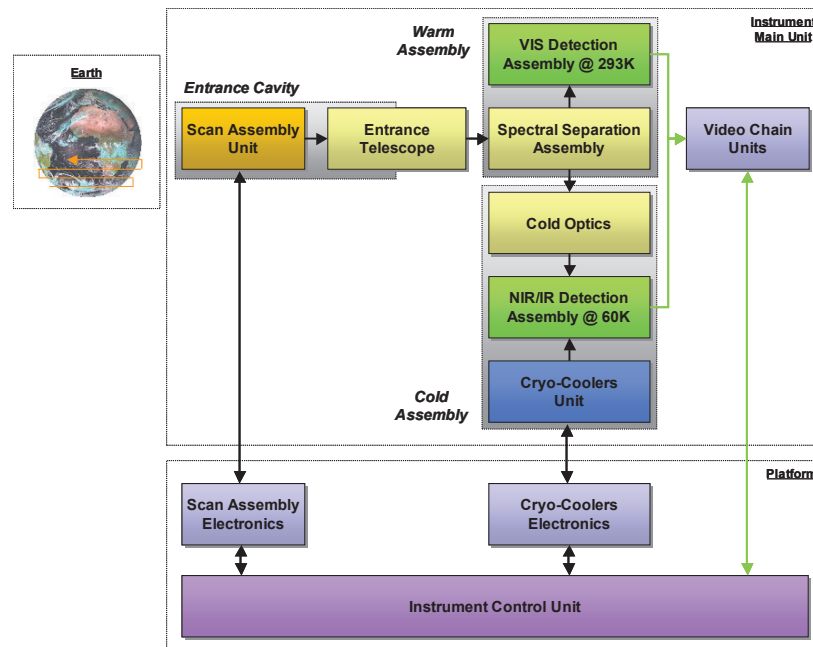


Figure 2:FCI functional architecture

#### 1.4 Units key design features

In accordance with the FCI functional block diagram based on modularity between the different sub-systems, this section details and illustrates the main FCI building blocks which constitute the instrument, and also presents the associated qualification status.

More details on the mechanisms design and development can be found in [1].

##### 1.4.1 Scan Unit

The two axis gimbaled scanner, supporting a 300mm aperture mirror, is controlled in closed-loop by its electronics, and provides both an excellent pointing accuracy and a high flexibility allowing to address, fast Earth scanning, deep space view and very stable pointing for on-ground characterization. More precisely:

- It is capable to scan East/West up to 2deg/s speed, and then performing 180° U-turn in less than 0.8s, but also has an accurate step and stare capability (used for the Infra-Red Sounder on board of the MTG-S satellite),
- It's in-flight Line of Sight absolute pointing performance (APE) is as good as of 170 $\mu$ rad including control error and encoder noise
- It's on-ground point-to-target stability is as good as 0.6 $\mu$ rad max half-cone over 10s.

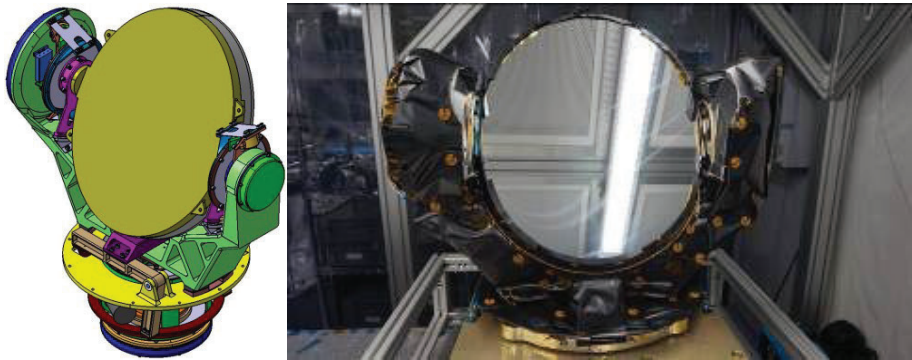


Figure 3: Scan Unit configuration

All development risks have been covered and the SCAN Unit design is fully qualified. The scan (including its drive electronics) is developed by SENER Aeroespacial, S.A. , under ESA/Thales Alenia Space /OHB contract.

### 1.4.2 Entrance Telescope

The FCI entrance telescope is “pupil-and-field” off-axis with a well-adapted 5.5 aperture number for channels grouping optimization. This optical layout has been designed to be diffraction limited for the whole instrument field-of-view, with no central occultation for straylight reasons, mainly sensitive in the infrared part of the spectrum.

The angular off-axis has been introduced to obtain an accessible intermediary focal plane after the secondary mirror to simplify the calibration device and diaphragm implementation (solar input baffling). This off-axis angle allows keeping the chief ray of the FOV center parallel to the optical axis.

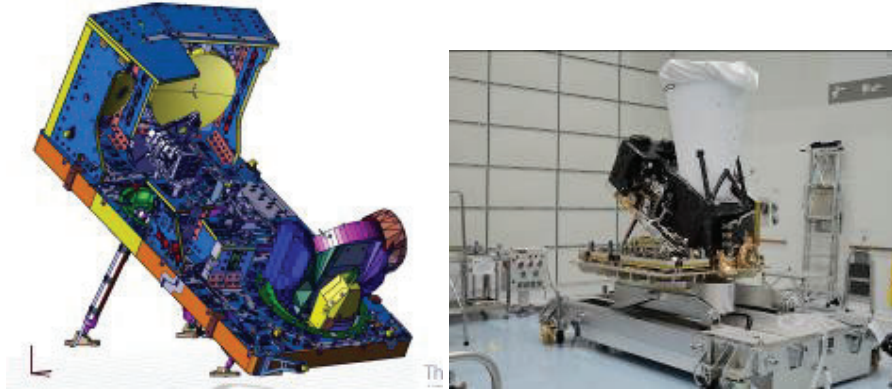


Figure 4: The FCI telescope is designed and developed by OHB Systems in Oberpfaffenhofen under an ESA/Thales Alenia Space contract. On the left CAD view without baffles, and on the right the FCI Telescope first flight model, after delivery to Thales Alenia Space Cannes facilities

The design of the telescope has reached full maturity: qualification close-out planned early 2021.

### 1.4.3 Spectral Separation

The 16 spectral channels, extended from the visible part of the spectrum to the thermal infra-red, have been split in five groups of spectral bands with a pure spectral separation performed by dichroic beam-splitters. The separation type minimizes the in-field separation which contributes significantly to the scanning law error budget. The selected polarization-oriented design leads to the current three dimensional arrangement offering a perfect polarization balancing between in-plane and out-of-plane polarization states.

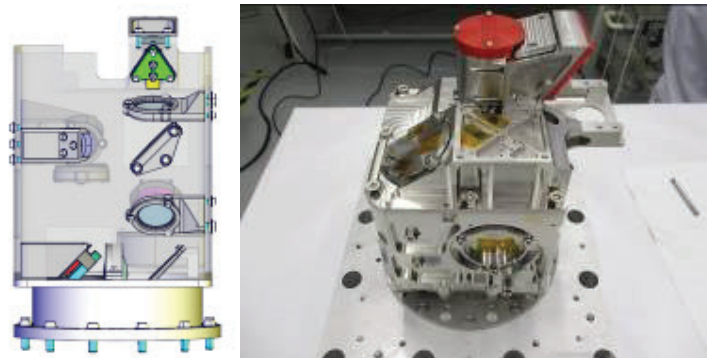


Figure 5: Spectral Separation Assembly is designed and developed by Safran-Reosc, under an ESA/Thales Alenia Space Contract. Picture on the right side: credit Romain Berruée – Safran Reosc

SSA qualification level has made a large step forward in 2020 after the successful test of the coating robustness under sun intrusion. Formal qualification closure is expected by the first quarter of 2021.

#### 1.4.4 Cold-Optics

There are 1 NIR and 3 IR spectral groups, each of them having its camera. These cameras offer at the same time high image quality at cryogenic temperature, low distortion and high throughput.

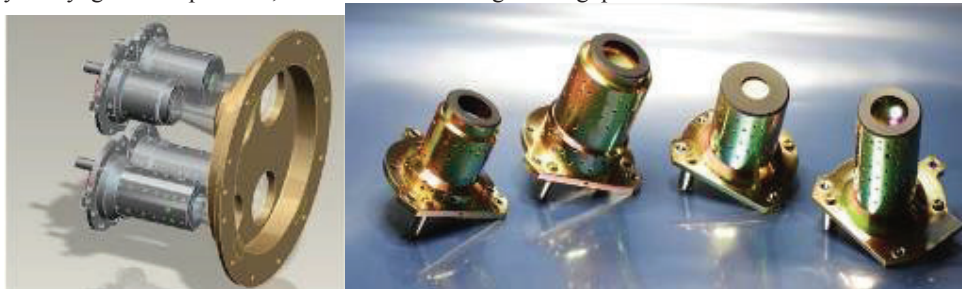


Figure 6: schematic view and as-built picture (Cover image © 2018 Thales SESO®) of the CO-I elements. These elements are designed and manufactured by Thales SESO®, under an ESA/Thales Alenia Space contract.

All qualification activities are now finalized, and the closure is planned Q1 2021

#### 1.4.5 Detector Assemblies

The 16 spectral channels have been grouped in 5 Detector Assemblies (VIS, NIR, IR1,IR2,IR3)

Each Detector Assembly is based on a CMOS image sensor die mounted in a package that incorporates optical filters, a permanent window and a ribbon flex terminated with a custom 61 way Deutsch connector. In order to ensure full image over lifetime and be robust to any pixel operability evolution, a four pixel redundancy is implemented on each sensor.

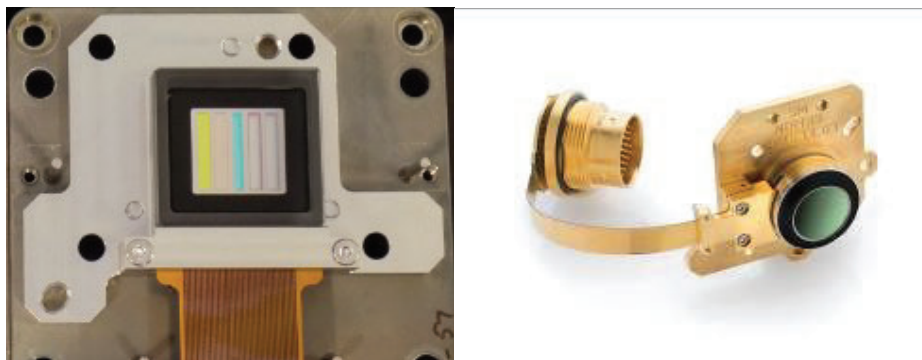


Figure 7: The VIS Detector Assembly (on the left) is developed by Teledyne e2V, while the NIR/IR Das (on the right) are developed by Lynred, both under ESA/Thales Alenia Space contracts..

The VIS detector Assembly is located at the Telescope focal plane, and operated at ambient. The NIR/IR detector Assemblies are located at Cold Optics foci, inside the cryostat. They are operated at 58K.

This new generation offers a wide field of view of about 200km, which, associated to the scan speed, offers the MTG short revisit time of a Full Earth Disc in 10min.

The VIS detector Assembly design is qualified.

The NIR/IR Detectors qualification will be pursued all along 2021. This late qualification has been properly anticipated in the development plan, with risks covered by early validation tests on representative samples.

#### 1.4.6 Video Chain Unit (VCU)

MTG-FCI Video Chain Unit function is developed by Thales Alenia Space. It is composed of 5 Front-End Electronics (FEE), one for each detector assembly, and one Video Acquisition Electronics (VAE), which performs the Analogic to digital conversion. The time tagged video data are sent to the Instrument Control Unit.

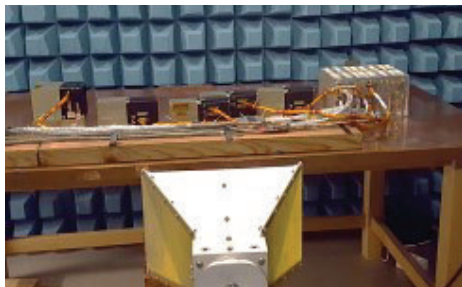


Figure 8: VCU Protoflight Model, during its EMC tests.

The qualification process is under finalization ,with formal closure planned early 2021.

#### 1.4.7 Cryo-Cooler Unit (CCU)

The Large Pulse Tube Cooler brings the 4 FCI NIR/IR detectors down to 58K with limited microvibration generation.

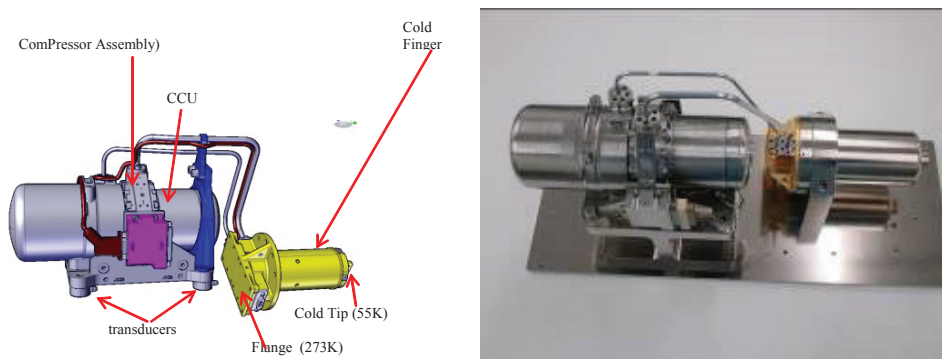


Figure 9: The MTG Large pulse-Tube cooler is developed Air-Liquide Advanced Technologies under an ESA/Thales Alenia Space contract

This cooler has already a strong flight heritage and its qualification for use on MTG is closed.

#### 1.4.8 Elastomer Suspension Elements

In order to filter the remaining microvibration, the cryo-cooler is suspended on elastomer elements. This technology has been developed by Thales Alenia Space under MTG contract. Its design, and in particular its cut-off frequency, is tuned to both

- Ensure an efficient attenuation of the main remaining compressor microvibrations, occurring after the fundamental harmonic at 56 Hz.
- Be stiff enough to avoid any need of a launch-lock, securing the in-flight operations



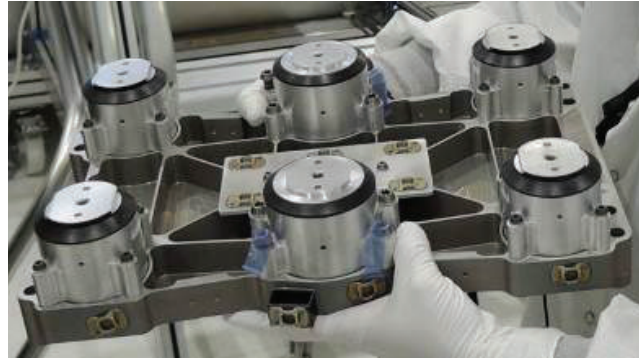


Figure 10: FCI elastomer Suspension Elements (ESE), a Thales Alenia Space technology

ESE have recently successfully passed ageing test, and qualification close-out is planned to be formally close early 2021.

#### 1.4.9 Instrument Control Unit (ICU)

The ICU is the central computer in charge of instrument operating modes management and merges the main FCI interfaces with the platform. It is responsible for :

Beyond the classical instrument management functions (Modes Management, Telecommand/Telemetry and Failure Detection and Isolation, Power Distribution and Thermal Control), this ICU also includes the mechanisms drive electronics.

On top of its multiple functions, one of its key performances is to monitor the internal blackbody (used for IR channels gain in-flight calibration) to a few mK accuracy.

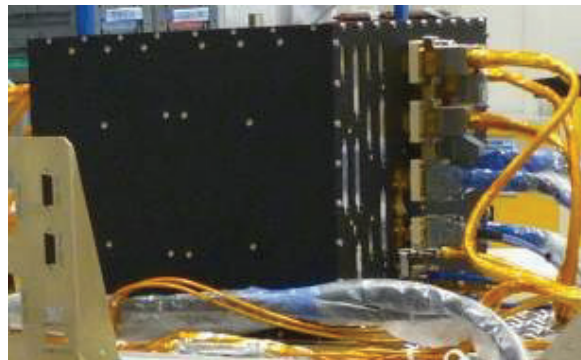


Figure 11: Instrument Control Unit is developed by Thales Alenia Space.

Qualification tests have been completed end 2020, and qualification review is planned Q1 2021.

#### 1.4.10 Envelope and engineering budgets

The FCI mass is below 470kg, which is well within the platform capability.

Its envelope is about 1.55mx1.4mx2m, and is accommodated to allow, on the same platform side, the accommodation of the Lightning Imager instrument (developed by Leonardo under an ESA/Thales Alenia Space contract).

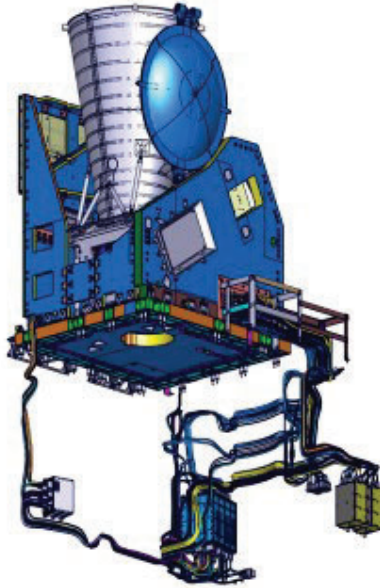


Figure 12:MTG-FCI overview. Note that three electronics (Instrument Control Unit, Cryo-Cooler electronics and Scan Electronics) are located inside the platform.

## 2. FCI DEVELOPMENT STRATEGY

The development risks mitigation is mainly based on 3 non-flight development models:

1. The Functional Chain Validation test bench validates the data handling and software, derisking the functional behavior of the instrument, as well as internal and external electrical interfaces,
2. The Detection Control and Electronics Assembly (DCEA) Engineering Model validates
  - a. the Warm Assembly: the common Spectral Separation Assembly and Visible detector integration & performance,
  - b. the Cold Assembly: the cryostat and NIR/IR detectors integration, the cryostat thermal performances and combined detectors and cold optics performances in a representative thermal environment,
3. The Structural and Thermal Model (STM) validates the thermal control performance, the mass properties, and the robustness of the instrument against launch loads and sun intrusion (unavoidable in geostationary orbit). In addition, and because of the severe pointing requirements applicable to the satellite, the micro-vibrations propagation inside the instrument are characterized on this development model. Then this development model is also used to validate the EMC shielding efficiency.

To complete the development plan, the first-flight model is following a so-called “proto-flight approach” meaning that it is submitted to qualification environments harder than the ones predicted in flight.

### 2.1 Detection Control Electronics Assembly (DCEA) Engineering Model

#### 2.1.1 Configuration of the specimen under test

The DCEA Engineering Model is built from the following equipments, having flight representative interfaces and performances:

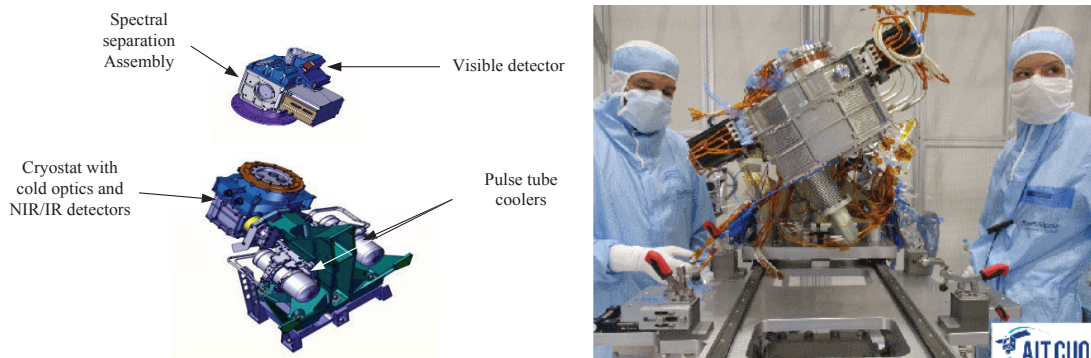


Figure 13: Detection Control Electronics Assembly: the heart of the MTG FCI Image acquisition

Together assembled, these units form the heart of the instrument, where the key optical and radiometric performances are generated.

### 2.1.2 Tests

The DCEA EM has been submitted to the following main tests:

- “Plateau reconstruction”: this test allows to select the best sampling instant of the detectors, minimizing the dispersion with pixels
- Gain and offset characterization: this test allows to confirm the dynamic range covered by the detection chain, and also, especially in the infrared wavelength domain, the background. This validates the parameters of the video electronics and also the correct sizing of the detectors design
- Optical Performance : this tests validates the MTF, one the key contributor to the instrument performance, and also the efficiency of the shimming strategy put in place to fit with the as-measured optical interfaces of the detector assemblies and the cold optics
- Icing: this test validates how often the cryostat shall be decontaminated (i.e. heated above 200K) and enable to prepare the PFM AIT sequence accordingly

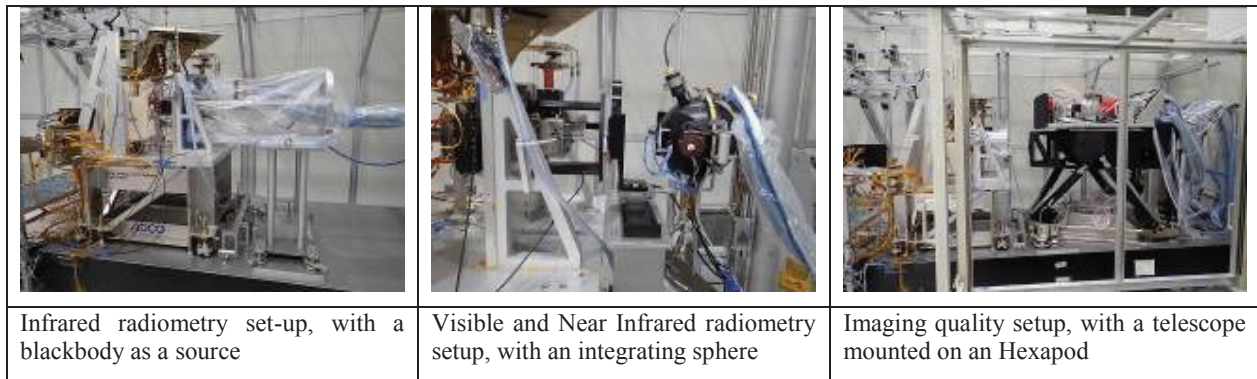


Figure 14: For these tests, several tests configuration have been developed, including custom made Optical Ground Support Equipments (OGSEs).

### 2.1.3 Lesson learnt

The DCEA EM demonstrated the suitability of the tests setup to

- characterize the radiometric adjustment of the detection chain,
- characterize the optical performance.

A side lesson learnt was that the polarization sensitivity measurement of the DCEA was degraded by test configuration straylight. The Proto-Flight model polarization characterization has thus been performed with a more suitable Ground Support Equipment.

Also, DCEA EM performances were measured as predicted, improving confidence in the FCI design:

- Shimming strategy and optical interfaces are validated,
- Radiometric chain dimensioning and adjustments are validated,
- Image quality is confirmed as-expected.

## 2.2 Structural and thermal Model (FCI STM)

### 2.2.1 Configuration of the specimen under test

The STM is composed of representative structure and thermal control (both passive, like multi-layer insulation and active, like the cryo-coolers and heaters). Also, all the mechanically representative mechanisms are included, and in particular the refocus mechanism, the calibration and obturation mechanism, and the scanner.

In order to get an accurate understanding of the behavior of the FCI under the critical space environments, the FCI STM is equipped with up to 400 thermocouple and 100 accelerometers.



Figure 15: FCI STM finalization, on the shaker.

### 2.2.2 FCI STM Tests

In addition to the classical mechanical tests, qualifying the design against launch loads, the FCI STM has been submitted to very specific and complex tests: thermal solar vacuum tests at ESA/ESTEC and microvibration tests in Thales Alenia Space Cannes facilities. FCI STM was then delivered for satellite level testing (more details can be found in [2]).

### 2.2.3 Vibration tests

Mechanical vibration tests are quite classical for space borne instruments. What was particular for the FCI was the deep international cooperation set in place: Thales Alenia Space for the instrument, OHB for the Telescope Assembly and ADS-Spain for the structure. The risk associated to this complex responsibility chain has been mitigated by a modal survey (low level sine), which helped to anticipate, at structure level, the Instrument Finite Element Model correlation.

### 2.2.4 Thermal tests

As for all earth observation instruments located in geostationary orbit, the sun is illuminating the FCI aperture each day around midnight. Depending upon the day in the year and the phasing with the scan law, this sun intrusion goes more or less deep inside the instrument optical path illuminating, not only the mirrors and lenses, but also the baffles and surrounding structures and thermal control. Only a solar test with a space simulator could bring an environment representative enough to test the FCI.

This is why the FCI STM travelled from Cannes(France) to ESTEC (Netherlands) Large Space Simulator (LSS).



Figure 16: FCI STM entering the ESTEC Large Space Simulator

The main lessons learnt was the demonstration of the FCI design to withstand its thermal environment in space. More precisely, the temperatures in hot, cold with and without sun confirmed the expectations, validating the instrument thermal control design. This test also drove some design optimization applicable to the flight models: some heaters were added on loop heat pipes, and the thermal mathematical correlation led to adjust some regulation parameters of the thermal control software applicable to flight.

### 2.2.5 Microvibration and EMC tests

Back to Thales Alenia Space facilities in Cannes (France), the FCI STM completed its test campaign by microvibration and EMC tests.

A microvibration test has been held to quantify the level of FCI LoS jitter that the Cryo-cooler (CCU) Noise Source generates. This test qualified not only the FCI pointing performance (LoS jitter), but demonstrated also the efficiency of the cryo-cooler suspension (ESE).

For this test the FCI STM was attached to a Vibration Test Adaptor (VTA), suspended from the floor with pressurized Air Actuators. Critical Noise positions were excited (CCU & SCAN Noise Source Interface) with suspended  $\mu$ Shakers and exported vibrations were measured by accelerometers (placed on optical performance critical points). The generated Transfer Functions were used to verify (and if needed to correlate) the Numerical Model of the Test Setup. Moreover, the CCU Noise Source was activated and exported vibration were measured by accelerometers. To allow qualifying directly the FCI LoS jitter, these accelerometers were positioned in a way to be able to reconstitute the LoS jitter for each optic. The Total FCI LoS jitter could then be reconstituted, by combining all optics, with help of the optical sensitivity matrix.

The FCI STM was finally used to assess the EMC shielding efficiency which is of particular importance for the MTG-I mission. Indeed a Data Collection System & Geosar payload are co-passenger on MTG-I satellites to collect and distribute SAR data (Search & Rescue) and are sensitive to E-Field interference.

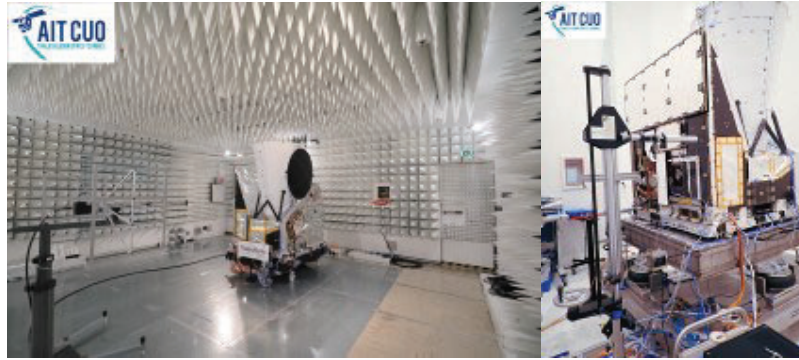


Figure 17: FCI STM in Faraday room for EMC tests (on the left), and during micro-vibration tests (on the right)

### 3. FCI FLIGHT MODELS STATUS

Since end 2010, a large team (currently 200 people in Thales Alenia Space) work together on the MTG-I development. MTG-I represents around 200 contracts, involving most of European countries and Canada.

[3] and [4] present respectively the overall MTG development and the end-to-end performances status, at the last AMS/EUM Meteorological Satellite Conference (30 September – 4 October 2019).

End 2020, the FCI proto-flight model is now finalized, and some actual optical performances can already be estimated (refer to [5]).

The last weeks of 2020 have been dedicated to very intense and detailed Earth straylight characterization. This has been – here again – the occasion of a strong international and inter-organization cooperation: in a couple of days, the data went from generation by the Thales AIT in clean room, via processing by Thales Engineering and check by ESA, up to EuMetSat for detailed evaluation on final use products. This validated one of the critical aspects of the FCI design: its capability to reduce straylight to an acceptable level.

The FCI PFM is now being prepared for its mechanical test.

It will be followed by the optical vacuum testing. This will be the time when the critical detection chain adjustments will be performed, and the end-to-end optical performances (MTF) will be verified. Also, the instrument level calibration parameters will be characterized, for both radiometric (translation from counts to equivalent radiances) and geometric (line of sight, focal length, inter-channel coregistration) aspects.

The FCI proto-flight model delivery to the MTG satellite is planned in July 2021, for a launch end 2022.

In parallel, the second flight model is already being integrated in Thales Alenia Space clean rooms.

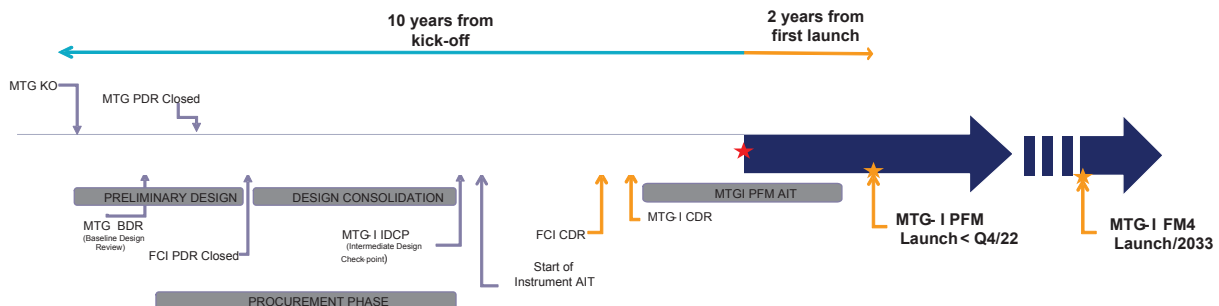


Figure 18: milestones of the FCI programme, with the FCI protoflight model at now less than 2 years from launch.

## ACKNOWLEDGMENTS

This work was performed at Thales Alenia Space, under a contract from European Space Agency (ESA). ESA implemented its Meteosat Third Generation Space Segment Development Program (MTG) to develop the proto-flight satellite (MTG-I). The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) implemented its MTG program, leading to a MTG System comprising a ground segment, the satellites, their launches and in-orbit commissioning, and operations of the system. ESA act as EUMETSAT's procurement agent for the recurrent MTG satellites. Thales Alenia Space constituted an industrial consortium with OHB System AG as Core team members for the Design, Development, Manufacture, Integration, Testing and Delivery for Launch of the MTG Satellites.

The author would like to thank ESA for the confidence put in Thales Alenia Space, as well as their strong support given in all domains. Also industrial partners shall be thanked, without which such a complex and demanding project could not be lead.

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