SpaceOps-2025, ID # 506

Overcoming adversity – Operational concept changes to ensure Europe's next Prime GEO imaging instrument mission

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Abstract

Meteosat Third Generation (MTG) is Europe's most advanced geostationary meteorological system composed of two series of satellites designed with ESA and European manufacturers to operate and deliver meteorological products and data for climate monitoring over the next 20 years. The first of four MTG-Imagers was launched in late 2022 and the first of 2 MTG-Sounders will be launched in mid-2025.

During the system commissioning phase of MTG-I1 imaging mission, the Calibration and Obturation function of the Prime Flexible Combined Imager (FCI) instrument developed an anomalous behaviour that required intensive and delicate investigations, both in flight and on ground models. Without detailing the elements contributing to the anomaly, the paper develops the necessary reactions and the decision path leading to the selection of an innovative and unusual operational approach for such an imaging Mission.

In particular, the article explores the complex trade-offs conducted to reach the need of a drastic reduction of the calibration use to the very minimum acceptable to maintain the high performance of the mission on one side, while ensuring that the obturation capability (i.e. shutter position) of the unit would still be available for the instrument safety against the risk of sun intrusions. This significant reduction of the instrument on-onboard calibration is a departure from the instrument initial operational concept that will be inspiring next missions.

The core part of the article focuses on two other major operational changes that have been designed, tested and implemented on board in a staggered approach, reaching the goals pertaining to the new operational concept. Both the novelty and the unusual complexity of the solutions selected is emphasised, introducing significant benefits for the next MTG models as well as improvements for future Meteosat missions.

Driven by the need to resume the instrument and system commissioning as soon as possible, the first stage of the operational changes introduced allowed the instrument to keep its imaging mode with the scanner moving during the regular station keeping manoeuvres.

Finally, the article describes the implications of the operational concept changes driven by the need to reach all FCI modes for maintenance and regular tuning. A complex solution with changes at instrument on-board software levels, and beyond with implications at satellite level, was implemented. The paper describes the implications of the many changes applied to the FCI mode management to allow keeping the instrument in free beam, while maintaining the protection mechanism for its safety.

As a conclusion the paper emphasises the overall experience and benefits gained from the collaborative approach from the satellite manufacturers and the European agencies though the resolution of the many challenges faced, leading to major improvements brought to this critical European meteorological mission.

Keywords: On-board Calibration, FDIR, OBSW, Operational task force,

Acronyms/Abbreviations

AOCS	Attitude and Orbit Control Sub-system
CCU	Cryo-Cooler Unit
COM	Calibration and Obturation Mechanism
COM-I	COM implementation for FCI mission
DDU	Data Distribution Unit
DHS	Data Handling Sub-System
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCI	Flexible Combined Imager
FDC	Full Disc Coverage
FDIR	Failure Detection, Isolation and Recovery
FMEA	Failure Modes and Effects Analysis
FMON	Functional Monitoring
GSICS	Global Space-based Inter-Calibration System
HW	Hardware
ICU	Instrument Control Unit
ICU-SW	ICU Software
IDPF	Instrument Data Processing Facility
IR	Infrared
LAC	Local Area Coverage
LEOP	Launch and Early Orbit Phase
LI	Lightning Imager
MFW	Multifunctional Wheel
MND	Metallic Neutral Density
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
OBSW	On-Board Software
OTF	Operational Task Force
PMON	Parameter Monitoring
PUS	Packet Utilisation Standard
SCAE	Scanner Electronics
SCAN	Scanner
SCA-I	Scanner assembly for the FCI mission
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SKM	Station Keeping Manoeuvre
SOR	Switch-Off Request
SPEIO	Specific Input-Output
SCSW	Spacecraft Control Software
SMU	System Management Unit
SW	Software
VNIR	Visible and Near Infra-Red

1. Introduction

Meteosat Third Generation (MTG) is a series of six geostationary satellites developed and procured by the European Space Agency (ESA) on behalf of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), consisting of four MTG Imager satellites (MTG-I) and two MTG Sounder satellites (MTG-S). The objective of the MTG mission is to provide Europe and, by extension, the International Community, with an operational satellite system to support accurate prediction of meteorological phenomena and provide monitoring of climate and air composition through operational applications for a nominal period of twenty years following the conclusion of the preceding MSG mission.

For MTG-I, Thales Alenia Space is the prime industrial contractor and supplier of the Flexible Combined Imager (FCI), with OHB as the sub-contractor for the satellite platform, and Leonardo S.p.A the supplier of the Lightning Imager (LI), the first European instrument in Geostationary orbit designed to detect and monitor lightning activity continuously.

The first satellite (MTG-I1) was launched on 13th December 2022 by the Ariane 5 launch vehicle. MTG-I1 was declared operational on 04th December 2024 and renamed Meteosat-12, adding its operational services to the Meteosat fleet, initiated in 1977 and currently composed of three operational MSG satellites (Meteosat-9 operated over the Indian Ocean, Meteosat-10, -11 operated over Europe and Africa).

While approaching a major milestone allowing the MTG-I1 satellite to be relocated from its commissioning longitude towards its nominal longitude, in view of entering the operational service, the Calibration and Obturation function of the Prime Flexible Combined Imager (FCI) instrument developed an anomalous behaviour that affected the MTG-I1 prime imaging mission.

This paper aims at offering a detailed presentation of the comprehensive work conducted by ESA, Thales Alenia Space France and EUMETSAT throughout the phases of the initial reactions, investigations, technical trade-offs, adaptations and innovate solutions and their operational implementation to counter the anomaly and restore the MTG-I1 prime mission.

2. The MTG system, the main players and the missions

2.1. European Space Agency (ESA)

The European Space Agency (ESA) is a leading intergovernmental organization committed to the peaceful exploration and utilization of space, with a strong emphasis on Earth observation and meteorological research. Since its establishment in 1975, ESA has developed a comprehensive programme of satellite missions that support climate monitoring, weather forecasting, and environmental management. In close partnership with EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites), ESA has played a central role in the development and deployment of key meteorological satellites, including the Meteosat series with the Meteosat Third Generation (MTG) system as its latest addition. Additionally, ESA's Copernicus Sentinel missions provide high-resolution, long-term datasets that are critical for understanding atmospheric dynamics, monitoring extreme weather events, and informing policy responses to climate change. Through these initiatives, ESA significantly contributes to both European and global capacities in operational meteorology and climate science.

2.2. Thales Alenia Space France

A Joint Venture between Thales (67%) and Leonardo (33%), Thales Alenia Space is a global space manufacturer delivering, for more than 40 years, high-tech solutions for telecommunications, navigation, Earth Observation, environmental management, exploration, science and orbital infrastructures. Thanks to their diversity of skills, talents and cultures, TAS's customers (governments, institutions, space agencies, telecommunications operators) are given "Space to Connect, Secure & Defend, Observe & Protect, Explore, Travel & Navigate". Thales Alenia Space have teamed up with Telespazio to form the Space Alliance, which offers a complete range of solutions including services. Thales Alenia Space have a corporate culture to always provide a win-win approach, shared both with partners and customers.

2.3. European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)

EUMETSAT is the European operational satellite agency for monitoring weather, climate and the environment from space, operating satellite fleets both in geostationary and polar orbits, providing processed satellite data, products, and services for nowcasting, numerical weather prediction, and climate monitoring to national meteorological services, research institutions and international partners. EUMETSAT plays a key role in the Meteosat Third Generation (MTG) programme and system in partnership with ESA, which develops and builds the satellites. EUMETSAT has defined the user and system requirements, leads the development and procurement of the ground segment and infrastructure, and is responsible for the operational management of the satellites after launch, the data reception, processing, and distribution to users in Europe and worldwide. EUMETSAT also supports users with technical assistance and training to make the best use of MTG data.

2.4. The MTG-I1 prime mission, the FCI instrument

The MTG-I 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 at least 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 transmits data to the ground station at full resolution and for all spectral channels in both nominal (FDC) and reduced scan (LAC) modes, as illustrated in Figure 3, allowing HRFI and FDHSI missions to be fulfilled simultaneously also for LAC coverage.

The full operational capability is based on the use of two imager satellites (MTG-I). One satellite performs the full Earth-disk scanning (FDC mode) in a 10 min basic repeat cycle, while the second covers the northern quarter of the full disk over Europe in 2.5 min.

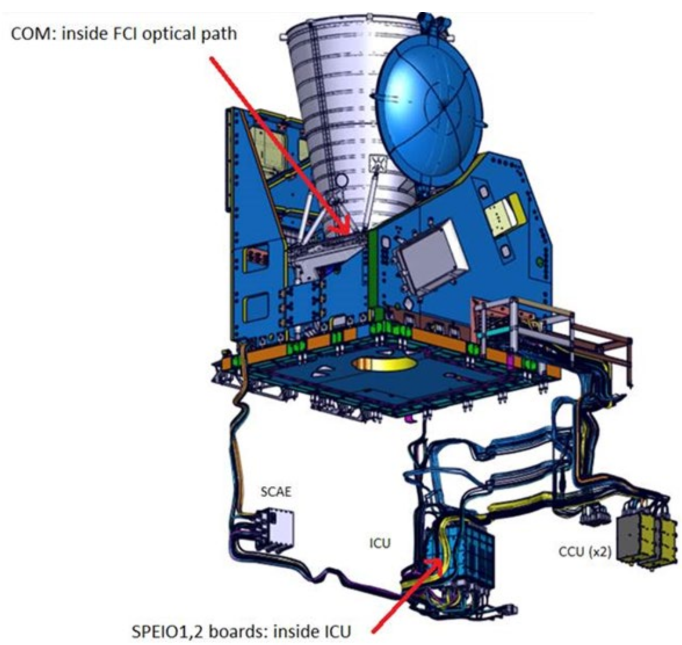

Fig.1 The Flexible Combined Imager - overview

Compared to the Imaging service from the SEVIRI instrument onboard Meteosat Second Generation (MSG) satellites, the FCI instrument significantly enhances weather forecasting accuracy in several ways that enable meteorologists to monitor and predict severe weather events with greater accuracy, improving early warnings and helping to protect lives and property:

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- Higher Temporal Resolution: The FCI provides full Earth images every 10 minutes (and high-resolution images of Europe every 2.5 minutes), compared to the 15-minute intervals (and 5 minutes) of the previous generation. This allows for more frequent updates and better tracking of rapidly changing weather conditions

- Improved Spatial Resolution: With a spatial resolution ranging from 500 meters to 1 kilometre, the FCI offers more detailed observations, enabling meteorologists to detect smaller-scale weather phenomena.

- Enhanced Spectral Coverage: The FCI operates across 16 spectral bands, covering visible, near-infrared, mid-infrared, and thermal infrared wavelengths. This broad spectral range improves the detection and analysis of various atmospheric components, such as clouds, aerosols, and moisture.

- Better Radiometric Performance: The FCI's improved radiometric resolution allows for more precise measurements of atmospheric properties, leading to more accurate weather models.

- Synergy with Lightning Imager (LI): The combination of FCI data with the Lightning Imager (LI) on the same satellite enhances the monitoring of severe thunderstorms and lightning activity, providing critical information for nowcasting and early warning systems.

3. The Calibration and Obturation Mechanism (COM)

The COM is a dedicated mechanism inserted in the FCI optical path, designed to fulfil several different functions of the instrument. The COM allows the acquisition of the maximum possible flow of information by the different optical channels in a "free beam" position, but also allows to perform some on-board IR (Infra-Red) and VNIR (Visible and Near Infra-Red) calibrations. It finally allows the setting of the system in a position safe for the optics in case of possible failure detected and managed by the Failure Detection, Isolation and Recovery (FDIR) system embedded on-board.

Purely a hardware mechanism, the COM is handled by the FCI software located inside the Instrument Control Unit (ICU) of the FCI (see figure below). It has two different nominal and redundant interfaces, handled by two different Specific Input-Output (SPEIO) boards of the ICU.

3.1. COM Mechanism Description

The figure.2 describes the schematic configuration of the light path and the surrounding equipment in the proximity of the COM embedded in FCI payload (COM-I).

The labels P1 and P2 indicate the positions in the light path where the Multifunctional Wheel (MFW) can locate the optical elements. The COM-I can place different optical elements in these positions depending on the function to be performed.

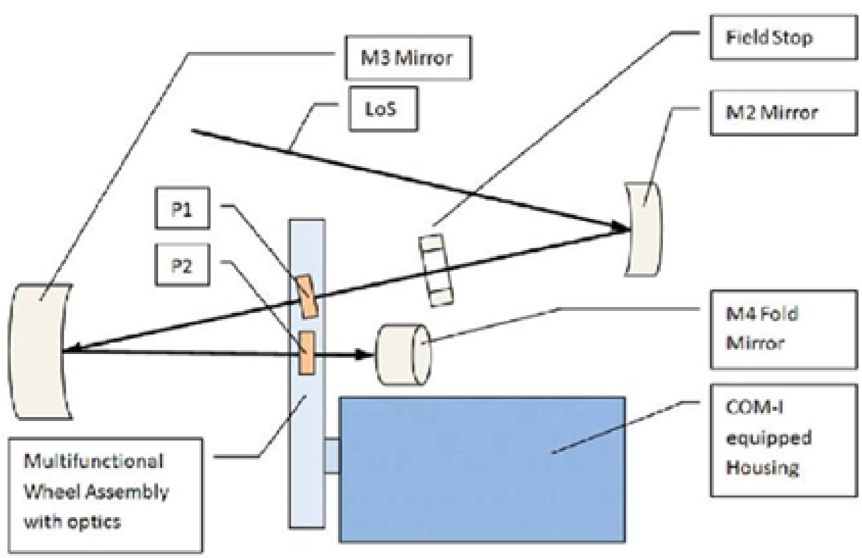
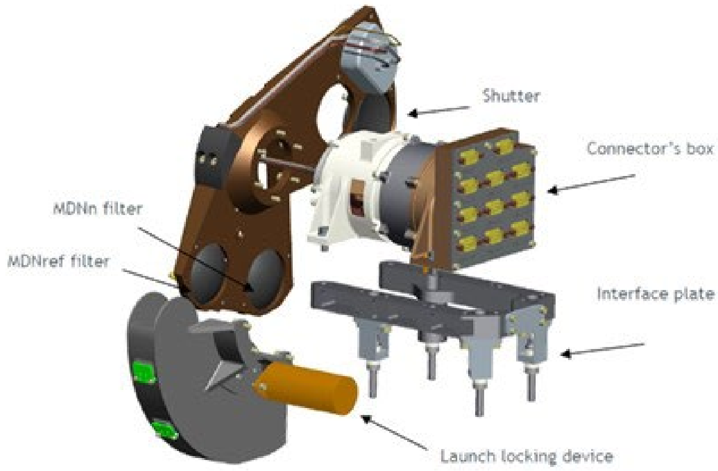


Fig.2 COM-I insertion in the FCI optical path

The COM-I mechanism (Fig.3) is based on a rotating multifunctional wheel (MFW) directly driven by a stepper motor to stable predefined positions. The MFW links the different optical and calibration elements to the optical bench by two pair of bearings mounted in a housing which allow by rotation the positioning of the elements in the optical path. The MFW is locked during launch by a pin puller that is retracted in orbit leaving the MFW free for rotation.



The IR calibration function is provided by a black body which is placed at intermediate focal plane (P1 - Field Stop level) oriented toward detectors. It provides a controlled radiance source with the provision of high accuracy thermometry. The VNIR calibration function is provided by two MND filters (nominal and reference), located at FCI-TA exit pupil level (P2).

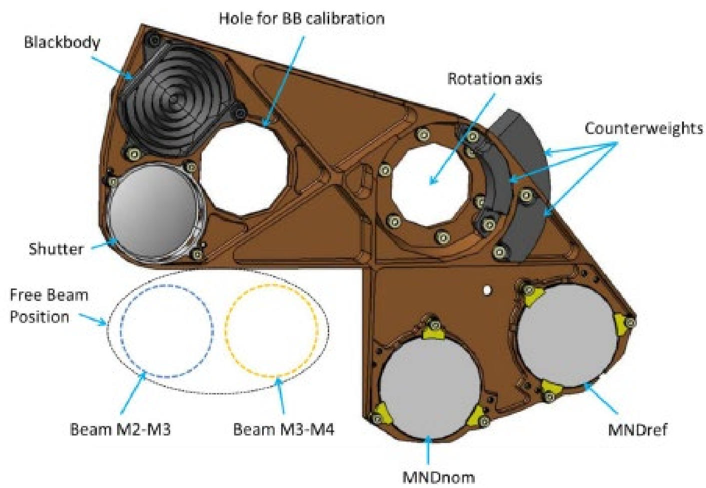


Fig.3 COM-I mechanism - Equipment overview (top)
- MFW positions in the optical path (bottom)

3.2. The COM Nominal Operations

Whilst the FCI is fully operational, the observed scene by the instrument detectors can be:

- The Earth (Observation): the COM is put in free-beam position by the ICU. The FCI Scanner is in an Operational mode. The FCI is fully operable and provides observation data to Platform Data Distribution Unit (DDU).

- The Black Body (BB) IR Calibration: calibration of IR channels is obtained by putting the COM into the Black Body position by the ICU during the retrace(*) of the scan patterns. IR Calibration data are sent to Platform DDU as for the mission data. The IR calibration can be performed either autonomously on-board (time based execution) or on ground TC request.

- The MND (VNIR calibration): calibration of VNIR channels is obtained by putting the COM into its MND positions (Nominal or Reference Metallic Neutral Density positions) by the ICU-I to capture the Sun (with MND attenuation) at Earth periphery. The VNIR calibration mode is relative to a particular Local Area Coverage "LAC4_4" (summer) or "LAC4_1" (winter) scan pattern ("Blind" LAC4_4 or LAC4_1 when MND is in place, Earth still undetectable). VNIR calibration data are sent to Platform DDU as for the mission data. The VNIR calibration can only be performed on ground TC request.

(*) In a dedicated Mission Scenario, a Scan Law is defined by a rally phase (to go from a reference canonical position to the start of a swath), a repetition of swathes, "U-turns", and retraces (to go from an end-pattern to the beginning of a new one) that can be repeated indefinitely.

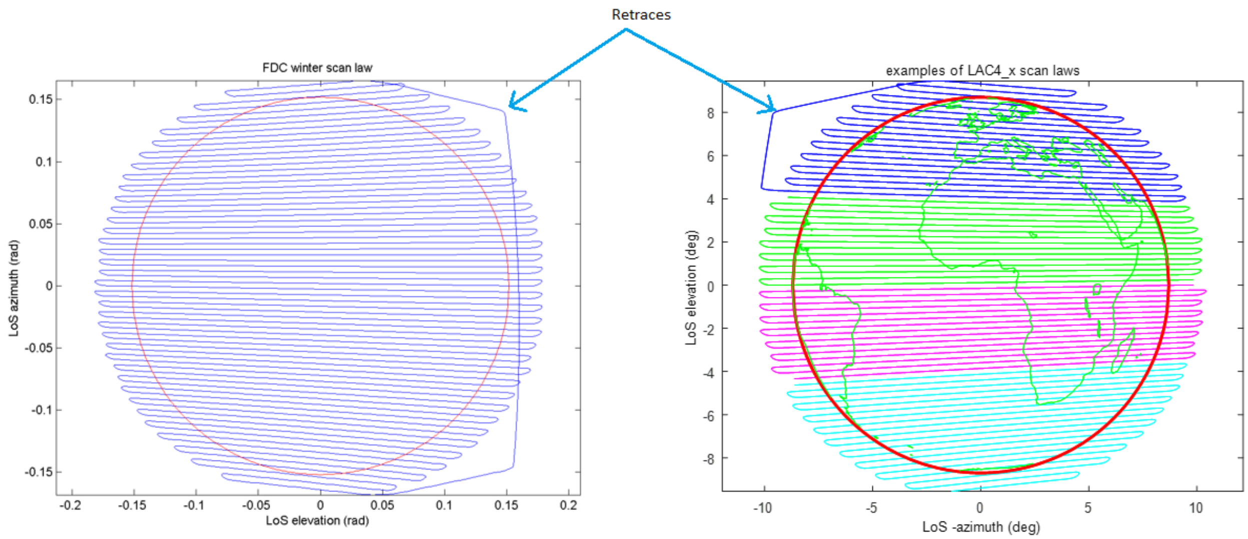


Fig.4 Typical FCI Scan Laws : *Full Disc (left), a Local Area Coverage (LAC) (right)*

In the FCI nominal Full Disc mission definition, the COM is programmed by the ICU-SW to perform automatic on-board BB IR calibration during each retrace, while the FCI Scanner is looking over the "Deep Space".

3.3. Use of calibration data for image production

During the course of a day the temperature of the FCI telescope varies, particularly when the sun is illuminating the telescope aperture. Thus, the instrument background signal for the thermally sensitive (infrared) channels varies during the day and presents a variable offset that needs to be subtracted from the detected signal to obtain the radiance emanating from the Earth. The black body, together with views of deep space, provide two reference points on the radiance scale that allow the digital counts from the instrument to be converted into radiances in engineering units, i.e. the reference points provide the slope (gain) and offset (instrument background) of the digital count versus radiance line. The deep space views provide the offset estimation about every 4 to 10 seconds.

The gain of the instrument varies more slowly due primarily to water ice build-up in the cryostat – the infrared detectors are kept at 58K to ensure low noise levels. Additionally, the gains of individual pixels may vary due to aging effects, focal plane warming and cooling operations (decontaminations) and radiation events at detector level. As mentioned previously, the black body calibration measurements can be performed at every retrace. For a FDC scan law this implies a calibration every 10 minutes. Thus, the gain of the instrument and every pixel individually for the infrared channels is re-estimated every 10 minutes. Finally, as the black body is inserted part way into the FCI optical path, on-ground calibration data is used to extrapolate the black body measurement to the entrance of the telescope. To estimate if there is a change in the transmission of the front telescope, not included in the black body measurement, a third calibration point is acquired by heating the black body by ten degrees once per day.

Since the normal temperature of the black body lies at around room temperature the black body calibration is useful only for the infrared channels. The visible and near-infrared (VNIR) channels have a slower gain variation than the infrared channels and this is monitored using a metallic neutral density (MND) filter. The MND filter is a semi-silvered lens that allows a fraction of the light coming through the instrument aperture to pass and reflects the rest. The MND lens blurs any features present in the aperture image at the point where VNIR detectors register the signal. The MND calibration measurements are taken four times per year, when the sun is just above or just below the Earth disc and in the instrument field of view. The blurring effect of the MND prevents sunspots from effecting the calibration. As with the black body calibration the MND and deep space data are used to provide the two reference points for gain and offset calculation, allowing every pixel in the VNIR channels to be individually calibrated.

4. The adversity and the main investigations

4.1. The in-flight anomaly

One year after MTG-I1 Launch and Early Orbit Phase (LEOP), having successfully put the satellite into Geostationary orbit with an Ariane 5 launcher in December 2022, a major anomaly occurred in the FCI prime mission. The FDIR detected a critical anomaly of the COM position during the execution of a nominal scan law and triggered a switch-off of the instrument.

The preliminary events reported on ground indicated an error of the COM position during the commanding to the free beam position at the end of a retrace phase. This error being critical to the mission, the FCI ICU-SW issued a Switch-Off Request (SOR) to the Platform, which in turn issued an additional set of direct commands to the FCI hardware to move the COM to the shutter safe position via the redundant electronics and motor coils.

4.2. The investigations

Without going into too much detail, this anomaly required intensive and delicate investigations, using both in-orbit and on-ground models. Indeed, since the FDIR is designed to cope with all possible error cases (implemented in the numerous Failure Modes and Effects Analysis (FMEAs) reported by the different manufacturers at sub-systems and system levels), the combination of paths explored to determine possible root causes was particularly high.

Several tests were performed in-orbit, involving the FCI switch-on and retry of the COM commanding through the same nominal path and through all the other possible HW and SW redundant paths. The testing isolated the source of the problem to the nominal path and the COM could be commanded normally using the redundant path.

In parallel, possible workmanship issues in the manufacturing processes were explored, all the remaining on-ground COM models of MTG fleet of satellites were inspected and all other possible root causes of the anomaly (wiring to the ICU, ICU boards, etc) were considered. The detailed root cause analysis has not led to the identification of a unique cause for the anomaly, however a fish-bone analysis including all considered possibilities was created to propose recommendations.

Although the system was qualified to operate beyond the intended satellite lifetime, there was a fear that a premature ageing of the system could have occurred. This possibility would be due to the high number of COM movements performed since the start of the mission (the automatic BB IR calibration causes the COM to move from free beam to black-body and back to free beam every 10 minutes). Even if the activation of the redundant COM path allowed the recovery of the COM functionalities in-flight, the premature aging hypothesis could not be excluded and led to reconsider the use of the COM for MTG-I1 FCI as detailed in the following section.

5. The conceptual change of the FCI COM operations

During the investigation of the MTG-I1 FCI calibration anomaly, and while the root cause was investigated by the MTG Industrial team, one of the priorities was to resume FCI operations as soon as possible in a safe manner so that high-quality data products could be delivered to the MTG user base. An Operational Task Force (OTF) was established and tasked to determine the best way to operate the FCI on MTG-I1 minimising the use of the Calibration and Obturation Mechanism (COM) and to derive the operational inputs, such as operational procedures or recommendations, instrument and platform configuration and SW, to support an implementation in flight.

To understand the scope of the activities to be minimised, the movements of the COM can be grouped in three categories:

- <u>Commanded COM movements:</u> those performed to execute activities that are needed for the nominal use of the FCI instrument, but not necessary for spacecraft safety or orbital maintenance, namely the calibrations

- Mode-transition COM movements: those performed by the satellite while executing activities that result in FCI mode changes (e.g. manoeuvres), which are necessary for regular satellite activities

- Protective COM movements: those performed automatically by the satellite FDIR to protect the FCI detectors (by going to shutter position) from Sun intrusion

To achieve the minimisation of COM activations, it was agreed between all stakeholders to create a 3-phase strategy, defining short/mid/long term solutions to increase autonomy whilst ensuring the necessary protections are in place with the COM in free beam position, especially for Station Keeping Manoeuvres and Yaw Flips. Each of these solutions was rigorously analysed regarding their risks and benefits, including a trade-off analysis between the risk of number of activations and the risk of potential degradation of the COM-I1 over time and considering the need of operational data.

5.1. Short term solutions

The prime objectives of the OTF on the Short-term phase was to:
- minimise any time-based risk by bringing the COM in free beam as soon as possible
- stop all the commanded COM movements for calibrations, until a medium-term approach is agreed,
- minimise other risks by retaining SAFE mode, sun-intrusion and other FDIR-triggered movements to shutter.

The OTF agreed to implement a specific set of satellite and instrument configurations, using mostly the existing set of operational procedures and guides, complemented by operational recommendation when necessary to achieve a stable satellite and FCI set up:

- FCI in OBSERVATION mode, i.e. acquiring and generating science data
- No scan encoder calibration
- No VNIR and IR calibrations
- No tuning of repeat cycles or implementation of pending recommendations or other operations which would require moving the FCI into WAIT mode
- FDIR/SAFE mode protections active

5.1.1. Approach to next planned manoeuvre

As part of the short-term actions to minimize as far as possible the commanding of COM movements it became necessary to establish a strategy to avoid commanding the COM during the next important Station Keeping Manoeuvre (SKM), which has strong planning constraints to ensure a proper satellite orbital control. For this type of operation, the FCI operational baseline was to nominally put the COM in shutter position during the whole manoeuvre.

In this aim, three strategies were identified with the objective of keeping the COM in free beam during the Manoeuvre:
- Strategy 1: perform the manoeuvre while FCI in observation, scanning nominal pattern
- Strategy 2: perform the manoeuvre with the FCI in observation, scan Earth Pointed (new scan law to be developed)
- Strategy 3: perform the manoeuvre with the FCI in WAIT mode, but with the COM in free beam (FCI modes management to be revised)

A trade-off based on feasibility, outcomes, risks and implementation duration allowed to retain the first strategy, that was successfully implemented in the frame of the Operational Task Force (OTF) set up.

Indeed, from the table below, it was shown that the implementation of the 3rd strategy was not compatible with the need date of the SKM, the 2nd solution required updating the mission scenario with a particular scan law and its associated FDIR, while the 1st strategy was based on simpler analysis and update of a few operational procedures compatible overall with the implementation time constraint.

Table 1. Strategies analysed to keep the COM in free beam during next SKM

		Strategy 1	Strategy 2	Strategy 3
FCI and SCAN Configuration	FCI mode for manoeuvre	OBSERVATION	OBSERVATION	WAIT
	Scan	Scanning	Controlled - Earth Pointed	Baseline (canonical Earth Pointed)
Impacts on sub-systems and operations	DHS/Software	None	None	Very significant, driven by the transition from WAIT to OBS
	AOCS	None	None	None
	Scan	Potential Control error overpass and motor saturation to be checked	Need of new scan law + Simplified scan law (FDIR)	None
	Operations	A Priori Compensation to be disabled. Small test manoeuvre needed for validation	None	None

5.2. Medium-Term solutions

During the second step of the 3-phase approach, the OTF considered an extended set of possibilities:

- change of the FCI and satellite operations approach to minimise risk (e.g. manoeuvres approach to minimise sun intrusion risk)
- enable/disable/adjust FDIR reactions where they are not justified in comparison to COM risk
- possible patches to the FCI ASW or the platform SCSW
- assess the image data processing quality from permanent free beam without onboard calibrations, assess other/vicarious calibration approaches

to achieve the following Objectives:

- FCI mode transition without COM activation
- Keep satellite and FCI FDIR active with COM in free beam, but still move COM to shutter for Sun intrusion protection (FDIR)
- Change FDIR so that COM remains in free beam in modes lower than FCI Observation mode, and perform all operations with FCI always in free beam
- Adaptation of the Ground based processing to use cross-calibration of FCI with the IASI instrument on-board the EUMETSAT Low Earth Orbit (LEO) MetOp-B and -C satellites.

To replace the black body and MND calibrations as sources for derivation of gains for each channel, EUMETSAT teams have developed and validated an innovative solution at image data processing level. The solution is based on an external inter-calibration system originally planned for calibration monitoring. This has formed the cornerstone in the strategy for reducing the COM movements as it allows the overall Image radiometric performances to be maintained solely based on image data processing and production on ground. More details on the approach and tools used for this purpose can be found in another SpaceOps-2025 paper [1].

5.3. Long term solutions

The Failure Detection Isolation and Recovery (FDIR) design on board MTG is one of its great assets: it ensures the automatic protection of the various satellite subsystems when faults are detected. It is a complex system that considers a very large number of possible failures, prevents their propagation to other parts of the satellite and performs recovery actions autonomously.

In view of the presented anomaly, which was correctly detected and acted upon by the satellite FDIR, the aim of the OTF long term activities is to identify all necessary actions to setup the best long term solution using reduced COM movements but keeping the instrument in safe conditions, and to increase the robustness of the satellite operations by including modifications to the OBSW and the FDIR definitions both at satellite and FCI instrument level. These modifications affect the autonomous mode transitions triggered by the satellite FDIR system. More detailed information on the objectives attached to the long term solutions are presented in the section §7 dedicated to the protective commanding (FDIR) of the COM, and in particular in chapter §7.4.

This activity is still on-going, with an outcome targeted in mid-2025.

6. Reducing the Mode-Transition COM Movements

As the second step of the 3-phase strategy (see §5.2), a high-level approach for the OTF medium term implementations to keep COM in free beam in all FCI modes was defined, with the aim to:

- Tune the FDIR to allow COM in free beam for all the FCI modes when commanded from Ground, i.e. not when commanded by FDIR.

- Implement a solution to allow the transition from WAIT to OBS with COM in free beam, to be validated on representative test benches before uploading on the satellite.

The analysis of all possible FCI transitions by ground and FDIR was done, identifying the need to tune both ICU-SW and SCSW implementations for FCI controlled mode transition in free beam, and led to the upload of the new SW configurations after successful validation on HW models on ground.

6.1. COM positions and commanding reduction implemented by the OTF Medium term

The detailed FCI modes diagram and transitions is available in Appendix A.
The outcome of the OTF Medium term changes is summarized in the table below.

Table 2. Commanded COM positions per FCI modes – Baseline Design Versus OTF Medium term

FCI MODES	*Commanded COM Movements* **FCI baseline design**			*Commanded COM Movements* **OTF Medium term target**	
	FDIR based	***Mode transition***		***FDIR based***	***Mode transition***
SURVIVAL (OFF)	Shutter	Shutter		Shutter	Shutter
STAND-BY REFUSE	Shutter	-		Shutter	-
CONFIG REFUSE	Shutter	-		Shutter	-
STAND-BY HEATER WARM-UP CONFIGURATION	-	Shutter	➔	-	**Free Beam**
WAIT	-	Shutter		-	**Free Beam**
OBSERVATION	-	**Free Beam**		-	**Free Beam**

As depicted in the table above, as per the FCI baseline, the COM in free beam is only associated to the FCI in OBSERVATION mode. Whereas, thanks to the implementation of the OTF Medium term changes of both definitions of some FDIR and some FCI mode transitions (executed autonomously on-board), the COM will stay in free beam for four additional FCI modes (WAIT, CONFIGURATION, HEATER WARM-UP and STAND-BY).

This allows to operate the FCI for all routine operations without commanding the COM to shutter, including advanced instruments configuration settings requiring lower modes to be activated.

7. Reducing the Protective COM movements: Re-visiting the FCI FDIR

7.1. The FDIR concept of the MTG spacecraft and the main payloads

The FDIR concept implemented at instrument level is built to ensure the FCI integrity, and then, to avoid as far as possible to lose the instrument thermal stability in order to reduce as much as possible the mission unscheduled outage.

To keep its autonomy with regard to the platform, the instrument performs its own monitoring, and it is able to autonomously change mode to put itself in a safe condition, waiting for ground recovery actions. However, as the power supply line switching is under MTG Platform responsibility, the FCI ICU shall inform the Platform SMU in case of automatic FDIR transition: this is achieved by the transmission on the Payload 1553 Bus of specific events that are monitored by the platform Spacecraft Control SW (SCSW).

The autonomous reconfigurations have been limited to the failures for which the expected occurrence could lead to not complying with the availability requirements.

The FCI FDIR strategy is based upon a layer breakdown with several failure levels defined according to the severity of the failure, the functions (Hardware or Software) involved in its detection and its potential effect, as specified by the MTG system team. The different failure classification defined at MTG satellite level are shown in the table below.

Table.3 Satellite Failures Hierarchical Classification Synthesis

FAILURE			FUNCTIONAL APPLICATION	DETECTION PERFORMED BY	RECOVERY TRIGGERED BY	IMPACT ON MISSION CONTINUATION
LEVEL	DESCRIPTION	SEVERITY				
LEVEL_0	Internal Failure	4 – Negligible	Platform Unit	Platform Unit	Platform Unit	No Outage
			Payload	Payload	Payload	No Outage
LEVEL_1A	Invalid Health Check	4 – Minor	Platform Unit	SMU OBSW	SMU OBSW	Possible limited outage
			Payload	SMU OBSW	SMU OBSW	Possible limited outage
LEVEL_1B	Internal Failure	4 – Minor	Instrument	Instrument H/W or OBSW	Instrument H/W or OBSW with the support of SMU OBSW	Possible interruption of the mission of the Instrument in failure
LEVEL_1C	Communication Interface Failure	4 – Minor	Communication with Platform Unit or Payload	Platform/Payload depending on the Communication Link	Platform/Payload depending on the Communication Link	Possible limited outage
LEVEL_2	Vital Function Malfunction or Performance Anomaly	3 – Major	Vital Satellite Function	SMU OBSW	SMU OBSW	Possible limited outage
LEVEL_3A	SMU H/W or OBSW Failure (1st occurrence)	3 – Major	Satellite Management Unit	SMU H/W or OBSW	SMU H/W or OBSW Alarm (1st occurrence)	Mission interruption
LEVEL_3B	SMU H/W or OBSW Failure (2nd occurrence)	3 – Major	Satellite Management Unit	SMU H/W or OBSW	SMU H/W or OBSW Alarm (2nd occurrence)	Mission interruption
LEVEL_4	Global Satellite Malfunction or Safety Endanger	2 – Critical	System Performance or Safety	Dedicated Platform or Instrument H/W	System H/W Alarm	Mission interruption

7.2. Use of PUS library for FDIR purpose

To support the FDIR scheme the FCI SW (ICU-SW, SCAN-SW) embeds proprietary implementations of PUS services, in line with the PUS standard [2]. The FCI on-board SW FDIR is based on the use of the followings PUS services:

- The Event Reporting Service (service 5)
  The service generates all the event reports in case of failure with "low severity" (5,2), "medium severity" (5,3) or "high severity" (5,4). Those reports will be used to trigger isolation or recovery actions or to warn platform or ground of a failure.

- The On-Board Monitoring Service (service 12)
  The service allows defining monitoring with comparison of on-board parameters with expected values, limits, masks, filters, validity conditions and generating event reports.

- The Event Action Service (service 19)
  The service allows defining TC to be sent autonomously on board in response to an event report. This service does the link between service 12 and service 132 or any other action TCs.

- The Action Sequences Management Service (service 132)
  The service allows to define action sequences, ie sequences of TCs and delays to ensure isolation or recovery process.

- The Functional Monitoring Service (service 142)
  The service provides the capability to monitor on-board functions (for example, SW applications or HW units) by managing associations of individual parameters monitoring, those parameters representing altogether the current health status of the function.

The Parameter Monitoring (PMON), and Functional Monitoring (FMON) definitions are designed to handle all possible error cases identified by the FCI FMEA, leading to the implementation of about 200 PMONs on the FCI.

7.3. Sun illumination failure detection

The failures leading to unprotected sun pointing are the most critical failures in terms of FDIR reactivity. If the SCAN is failing during the FCI sun illumination period, the shutter position shall be activated in less than five seconds to preserve detectors integrity.

As a consequence, the monitoring of the SCA-I movement is crucial for the FCI mission. The stop or a wrong pointing of the SCA-I can potentially lead to the sun illumination of the detector assembly and of the entrance cavity, which can cause irreversible damages of the FCI. The SCA electronics implement a Software in charge of controlling and monitoring the SCA Mirror according to a predefined scan law.

However, there are some specific failure cases that cannot be detected by the SCAE SW itself (typically as error in the SCA mirror position control loop, erroneous programmed SCA law angles…). To be robust to such critical failure that could lead to a too long sun illumination of detectors, it was decided to implement at ICU-SW level a monitoring of the SCA movement. This monitoring ensures that the SCA mirror does not remain blocked or does not move too slowly and guarantees that when the COM is in free beam position (Operational Mode) the detectors cannot be illuminated more than 5 seconds.

The FCI SW includes monitoring of the COM position telemetry, comparing the real COM position with the expectation of where it should be according to the FCI operational mode:

- The COM is commanded to be in shutter position in all modes except operational or refocusing modes,
- In operational mode, the COM can be either in free beam, Black Body or MND positions. The COM is monitored in free beam position with a large period to cover platform reconfiguration and the automatic IR calibration. In case of VNIR calibration, the free beam monitoring will be deactivated by ground operation procedure.

In case of a discrepancy between reported and expected positions, the FCI issues a SOR towards the platform and the FCI is switched off. Whenever FCI is in survival mode (i.e. ICU is OFF), the PF is then in charge of moving the COM to shutter position, using a dedicated interface using the redundant specific IO board in the ICU.

7.4. Analysis, Trade-off and Adaptations to the OTF targeted changes

As the last step of the 3-phase approach conducted by the OTF, a deep analysis of the on-board FDIR was initiated, with the aim to update all necessary monitoring and recovery actions to further minimize the movement of the COM but without endangering the safety of the mission, namely by keeping the on-board management of possible Sun intrusions in the FCI optical path when strictly necessary.

The strategies studied by the OTF to operate the FCI and the COM in the Long Term are elaborated with the guidelines and objectives listed below:

- Implementation of a solution to allow the FCI COM to remain in free beam position for an autonomous transition to CONFIGURATION-REFUSE mode for any period of the year.
- Analysis of the risk of sun intrusion damaging the FCI detectors associated with thruster activation during a transition to Sun Pointing or safe mode when the FCI is pointing at the Earth.
- Implement of a solution to allow the FCI COM to remain in the free beam position for an autonomous transition to STANDBY-REFUSE mode.
- Definition of mission rules, procedures and recommendations modifying operations to minimise the risk of unnecessary COM commanding depending on the time of year, e.g. differences between inside and outside of eclipse operations
- Definition of mission rules, procedures and recommendations to command the COM back to free beam in cases where the FDIR has put the COM in shutter. The purpose of this request is to minimise the time when the COM is in shutter.

7.5. COM positions and commanding reduction targeted by the OTF Long term

As summarized in the table below, the targeted implementation of the OTF long-term solutions will add as possible FCI modes with the COM in free beam the two FDIR cases entering CONFIGATION REFUSE and STAND-BY REFUSE modes, however for the later during specific periods over the year being under analysis and definition.

Table 4. Commanded COM positions per FCI modes – OTF Medium term versus OTF long term target

FCI MODES	*Commanded COM Movements* ***OTF Medium term***			*Commanded COM Movements* ***OTF Long term target***	
	FDIR based	***Mode transition***		***FDIR based***	***Mode transition***
SURVIVAL (OFF)	Shutter	Shutter		Shutter	Shutter
STAND-BY REFUSE	Shutter	-	➔	Shutter in specific periods for SCAN FDIR, **Free Beam otherwise**	-
CONFIG REFUSE	Shutter	-		**Free Beam**	-
STAND-BY HEATER WARM-UP CONFIGURATION	-	**Free Beam**		-	**Free Beam**
WAIT	-	**Free Beam**		-	**Free Beam**
OBSERVATION	-	**Free Beam**		-	**Free Beam**

8. The beneficial side effects for the MTG mission

Additionally to the direct outcomes received from the prime objectives to restore the MTG-I imaging missions for the EUM users community and to establish a safe approach for the COM operations to support the continuation of the mission, the MTG-I operations have also been enhanced with valuable and beneficial results from side analysis or trade-offs conducted in parallel of the prime anomaly investigations and resolution. These changes and evolutions are further detailed below.

8.1. Reduction of the FCI Mission outage:

Two factors contributed to reduce the overall duration of the FCI mission outages.

The first is directly inherited from the fact that the FCI is now kept in OBSERVATION mode during the Station Keeping Manoeuvres instead of being commanded to WAIT as per the initial baseline before the anomaly. This means that there is no interruption of the FCI science data acquisition and transmission from the satellite. There is however an outage at Image Data Processing Facility (IDPF) level, induced by the perturbated satellite attitude during the manoeuvre.

The second contributor to a significant reduction of the Payload outages (both FCI and LI) is the enhancement of the MTG-I1 station keeping strategy which was identified as a mid-term planned activity but that has been anticipated and initiated on the OTF request due to the potential reduction of the number of maneouvres and consequently of COM movements.

The EUMETSAT Flight Dynamics team, supported by the MTG industrial team and an academic work [3], developed, validated and implemented an optimized Station keeping strategy reducing the orbital control cycle from 3 manoeuvres every 8 weeks to 1 manoeuvre every 6 weeks. This is thanks to the addition of a small yaw bias to the burn direction of each North/South (NS) SKMs, which in terms of satellite orbital control is equivalent, within a single burn, to the combined control effects of both a North/South and an East/West manoeuvre. More details can be found in Appendix B and [3]. While the gain of such Combined NS + EW SKM is marginal in terms of propellant consumption, the overall impact on the total number of manoeuvres executed is significant in terms of planned mission outage reduction. It has therefore become, earlier than initially planned, the baseline for MTG routine operations.

8.2. Optimisation of some units operations

It is worth mentioning that a few valuable technical outcomes have indirectly emerged from the extensive investigation work conducted to establish the Root Cause Analysis, and are being implemented as improvements to the in-flight operations, noting moreover that those are not linked to the in-flight anomaly itself, i.e. not identified in the root cause list. For instance, the operating current of one equipment has been reduced with the aim, while fully keeping the motorization margin of the unit to improve its reliability over the operational lifetime. A benefit retained not only for MTG-I1 but also implemented on all the other models of the MTG programme (MTG-I and MTG-S).

8.3. Defining Mission rules supporting faster recovery if needed

The aim of establishing mission rules is primarily to gain time when executing satellite operations, in particular recovery operations as the rules will allow EUMETSAT to execute pre-defined sequence of operations in case of well identified events or configurations. Those cases would otherwise be considered as an anomaly and would require a longer process with an Anomaly Review Board to be organized and review the satellite status and events, some analysis conducted to elaborate on the root cause and propose a way forward.

The provision of mission rules to allow EUMETSAT to react rapidly in cases where the COM is commanded to shutter has been attached to the OTF Long-Term activities and is being prepared by Thales Alenia Space France. These mission rules are established to limit the time when the FCI COM stays in the shutter position after an FDIR triggering.

8.4. New scan retrace profile implemented

A consequence of not being able to use the COM for MTG-I1 black body and MND calibration, is the inability to use these sources for equalization of the gains for each pixel of a channel in the Image Data Processing Facility (IDPF). The default scan pattern for the full disc scan or rapid scan, from the flight operations manual, moves the scan mirror line of sight through deep space to one side of the Earth during the retrace between two scans (see fig.4).

Since for MTG-I1 the black body is no longer in the field of view during the retrace, the possibility to relocate the retrace such that all pixels move in a north-south direction through the same Earth target has been exploited by the EUMETSAT Instrument and science team. This north-south scanning was tested during MTG-I1 commissioning and allowed a good reconstruction of the relative pixel gains for each FCI channel. Dedicated scan laws for the summer and winter satellite orientations have been defined and implemented for MTG-I1 Routine Operations to allow the pixels to pass in a north-south direction through a Libyan dessert target. The data obtained is used to monitor any evolution of gain between pixels of a channel and perform equalization as needed.

8.5. Beyond MTG-I1: Operational implementation to other MTG models

Although the improvements above are benefiting primarily the MTG-I1 satellite in orbit, some topics will be made applicable and implemented to the next models of MTG-I (MTG-I2 to be launched as early as mid-2026) and MTG-S when applicable, ensuring that the entire MTG fleet is taking on board the opportunities gained from the COM anomaly to enhance the operational service delivered to the MTG user community.

9. The successful and results-oriented approach of an effective European cooperation

The presented resolution of the anomaly of the Calibration function in the Meteosat Third Generation (MTG) programme exemplifies the strength and effectiveness of long-term European cooperation in space-based meteorological missions. From the earliest phases of feasibility studies through to the operational deployment of the MTG-I1 satellite, this programme has demonstrated a cohesive, result-oriented collaboration among key European stakeholders.

- Central to this effort is the European Space Agency (ESA), which played a leading role in steering the investigations and overseeing the technical development and implementation of the identified solutions with rigor and vision.

- In parallel, Thales Alenia Space, as the industrial prime contractor that guided the end-to-end system development with a wide network of European subcontractors, proved once again their leadership and engineering expertise are critical in achieving the industrial team's successful resolution of the Flexible Combined Imager (FCI) anomaly, through a targeted system-level intervention, is a testament to their agility, depth of technical knowledge, and commitment to mission success.

- EUMETSAT, as the operational agency, holds the vital role of implementing and operating the MTG system for the benefit of European users. With a focus on long-term service continuity and operational excellence, EUMETSAT ensures that the MTG satellites deliver accurate, timely, and actionable data for weather forecasting and climate monitoring across Europe and beyond.

The seamless coordination between ESA, Thales Alenia Space, and EUMETSAT illustrates a mature and effective model of European space collaboration that is deeply rooted in shared objectives, complementary roles, and a sustained commitment to delivering value to society.

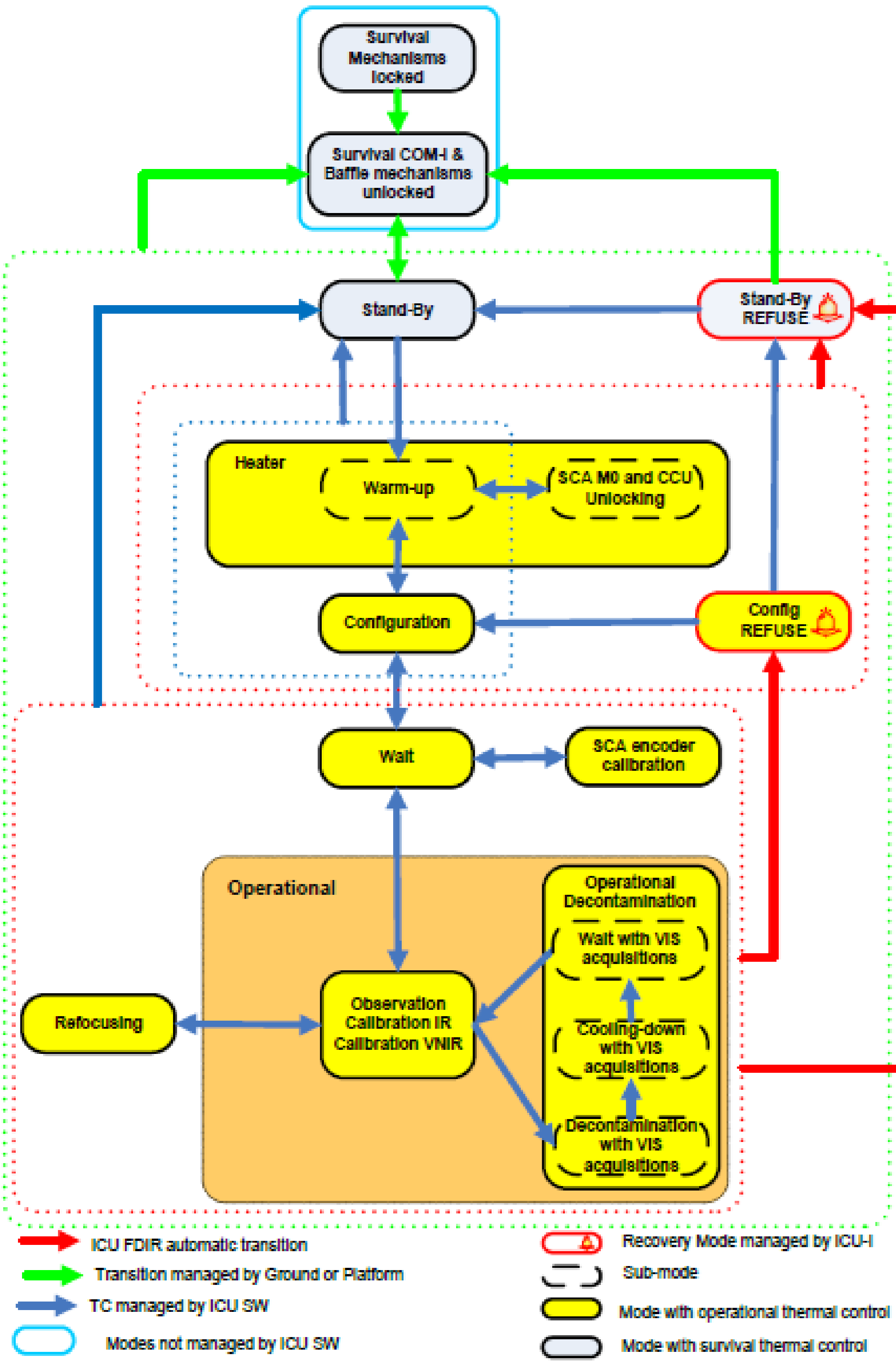
10. Conclusion

Although the next generation of European geostationary weather satellites, MTG, faced a significant anomaly in flight, the combined efforts of all stakeholders involved in the MTG programme has allowed to restore the MTG prime mission in an effective and reasonable time frame in view of the complexity of the failure root cause analysis on one side and of the operational adaptations developed and implemented on the other side.

The combination of the changes implemented on the satellite side and the ground side at image data processing level to resolve the FCI anomaly was a decisive and successful intervention that not only restored the satellite's image quality performance affected by the temporary loss of the FCI Calibration function but also enabled the MTG-I1 satellite to move forward safely into its routine operations.

The effectiveness and the dedication of all the teams involved from ESA, Thales Alenia Space France and EUMETSAT highlighted the resilience and the expertise of the actors and their ability to address the many technical challenges faced in identifying, addressing, and resolving the issue efficiently.

Appendix A (FCI modes diagram and transitions)



Appendix B - Summary of the enhanced station keeping strategy based on Combined NS and EW SKMs

The MTG three-axes stabilized platform allows to counterbalance deterministic disturbances by the AOCS software (e.g. solar arrays interference on exhaust plume) but also to compensate thrusters' cross-coupling effects and/or to perform combined orbit control within a single burn, via platform attitude biases, as described hereafter.

Roll bias: When in SKM, MTG is nominally oriented with its Y axis towards the out-of-plane direction in LOF. However, when the Reaction Control Thrusters (RCT) for NS control are firing, the resulting thrust vector is not perfectly aligned with the Y axis. Therefore, the Spacecraft must be tilted with a roll rotation to achieve a thrust vector aligned to the out-of-plane direction, if one wants to avoid radial coupling when performing NS burns. This effect varies along the mission according to the satellite Centre of Gravity shift and it has been tabulated against elapsed mission time. If one performs an equal number of North and South burns during a NS campaign, the radial coupling effect is naturally cancelled. However, North and South burns execution times are separated by 12 hours, meaning that this strategy can be implemented only if at least one burn is executed outside working hours, which is not optimal from an operational point of view. A more efficient way to cancel the radial coupling is possible if the three-axes stabilized platform of MTG is exploited to command the appropriate roll attitude bias.

Yaw bias: In addition to the radial coupling, if no attitude bias of the platform is commanded every NS manoeuvre is responsible for a coupling in the tangential direction as well. However, the tangential couplings are much lower in magnitude, thus they can be corrected through EW control without significant propellant cost increase; nonetheless, they can also be eliminated through yaw bias of the platform. A more relevant use of the yaw bias in station-keeping is to perform combined NS and EW control within the same burn: by tilting the platform with a yaw rotation, the required in-plane Δv for longitude control can be achieved through a burn commanded along the Y satellite axis, which should nominally be aligned to the out-of-plane direction, for inclination control.

The advantages of performing combined NS&EW manoeuvres are the decrease of total consumption and decrease of operational workload as well as service outages, due to the optimal burn direction and to the overall reduction of executed manoeuvres. If only a single burn is executed per cycle, the required roll and yaw biases must be commanded at the same time. A strategy taking into account a single burn with both biases is the current operational baseline for MTG-I1 routine operations.

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[3] Bertaboni, Filippo, Analysis of station keeping strategies for the co-location of geostationary satellites MTG-I1 and MTG-S1", Master Thesis, Politecnico di Milano University, academic year 2023/2024