Meteosat Third Generation: Data Handling Architecture of a State-of-the-Art GEO Meteorological Satellite

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Abstract—**This paper presents the architecture of the Data Handling Subsystem of the Meteosat Third Generation Imager satellite (MTG-I), with an emphasis on unique or challenging aspects, as well as an assessment of in-orbit performance.**

Keywords—Meteosat, MTG, Data Handling, Avionics, OBSW

I. 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 satellite (MTG-I1) was launched on 13th December 2022 by an Ariane 5 launch vehicle. The commissioning of the complete system is expected to span over most of 2023.

This paper presents an overview of the MTG-I Data Handling Subsystem, highlighting its design challenges, unique aspects and in-orbit performance.

II. MTG-I MISSION DESCRIPTION

The objective of the MTG System is to provide continuous high-resolution observations and geophysical parameters of the Earth System derived from direct measurements of its emitted and reflected radiation using satellite-based sensors from the geo-stationary orbit.

The MTG space segment supports the following missions, services and associated payloads:

- Flexible Combined Imager (FCI) mission; allowing to scan either the full disc in 16 channels every 10 minutes with a resolution of 0.5-1km, also known as Full Disc High Spectral resolution Imagery (FDHSI) in support of the Full Disc Scanning Service (FCI-FDSS) or a quarter of the Earth disc every 2.5 minutes, known as High spatial Resolution Fast Imagery (HRFI) in support of the Rapid Scanning Service (FCI-RSS).
- Lightning Imager (LI) mission, detecting continuously over almost the full Earth disc the lightning discharges taking place in clouds or between cloud and ground with a resolution around 4.5km at sub-satellite point.
- Search and Rescue (SAR) Relay Service allowing the continuation of the MSG geostationary search and rescue (GEOSAR) service as part of the Cospas-Sarsat international system, whose aim is to provide distress alert and location information to appropriate rescue authorities for maritime, aviation and land users in distress.
- Data Collection System (DCS) mission which involves, as a continuity of the MSG mission, the collection and transmission of observations and data from surface, buoy, ship, balloon or airborne Data Collection Platforms (DCP).

III. MTG-I DATA HANDLING ARCHITECTURE

All the satellite management functions are centralized within the Satellite Management Unit (SMU), which embeds all required resources for MTG-I command control, including in particular:

- Dual 1553 MilBus (Platform and Payload)
- Reconfiguration module, including mass memory and master onboard time
- Command authentication
- PUS TM/TC management and distribution
- Direct I/O acquisition and commanding
- All drivers for solar array and antenna motors, propulsion valves, AOCS sensors and actuators management

All mission data handling is performed by a dedicated Data Distribution Unit (DDU), part of the Payload Data Downlink (PDD), which includes:

- Acquisition of all data through SpaceWire links (up to 140 Mbps)
- Redundancy and multiplexing management thanks to SpaceWire routers,
- ECSS frame formatting with dedicated virtual channels per data source
- AES encryption
- Memory buffering sufficient to provide 163.89 Mbps constant through 8 parallel LVDS data flows to the PDD OQPSK modulators for MTG-I Ka band downlink.

The DH architecture allows to decouple as much as possible platform and payloads with a limited amount of DH interfaces thanks to the use of:

- A Payload 1553 MilBus for PL command-control
- A Payload SpW network for Mission data distribution (image data, auxiliary data, scan law data)
- Limited discrete interfaces for power-up, initialization and ultimate FDIR investigation

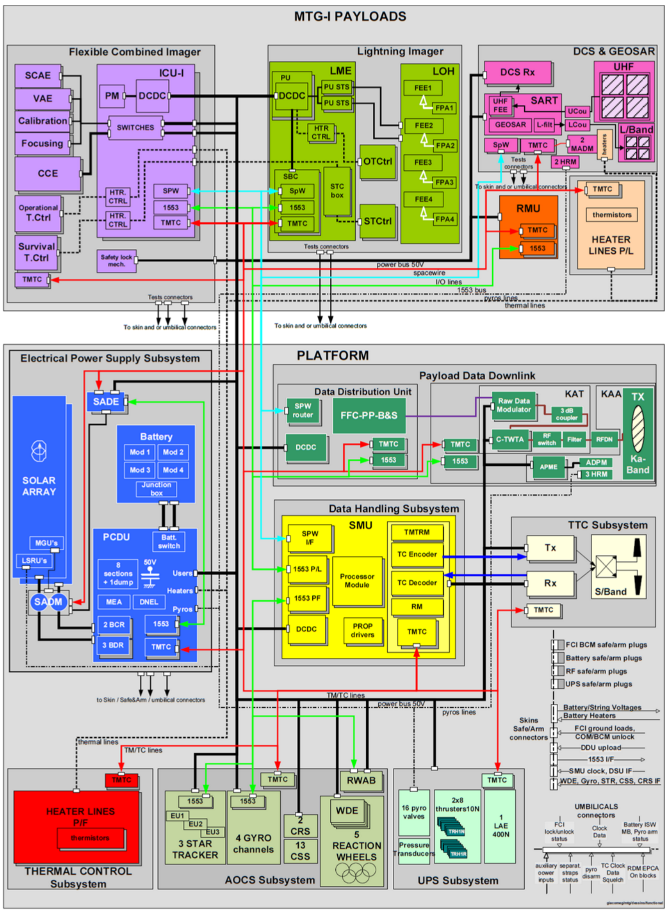

Figure 1: MTG-I satellite data handling architecture

IV. Data Handling Features

Some features of the MTG-I Data Handling Subsystem (DHS) deserve mentioning for various reasons, either being challenging, unique or innovative. The next sections highlight some of them, and the full paper will present them in detail.

A. *PUS Command and Control Design*

The ground command-control of the satellite is performed with Packet Utilisation Standard (PUS) TM/TC packets, as well as most of the acquisitions and commands between the platform and the instruments through the 1553 payload MilBus.

The MTG DHS includes three PUS terminals: the SMU, the FCI Instrument Control Unit (ICU) and the LI Main Electronics (LME) simulator. This is made possible by making use of the Thales Alenia Space PUS library, which ensures easy integration and full compatibility between all three PUS systems.

The standardized PUS TM/TC, used for both the command-control of the satellite for both space-to-ground interface and internal on-board exchange between platform and payloads:

- Allows for a unified interface that reduces validation and operation effort.
- The Thales Alenia Space France PUS library is implemented in both on-board software (OBSW) of the platform control software and FCI ICU-SW to minimize SW development.
- It allows simple, reliable and flexible definition of satellite FDIR with standardized platform and payload exchange between three pieces of OBSW for monitoring, event detection and action sequence for both failure isolation and recovery, and mode configuration management.
- The PUS capability to add or modify autonomous action as FDIR has proven very useful to fix in-orbit anomalies or even failure without the need to compile, patch or uplink OBSW, since it allows to add periodic tasks for monitoring functions and units and for commanding them via action sequences.

B. *A-Priori Compensation (APC)*

Taking images from 36,000 km with a resolution of 0.5km requires a highly stable satellite pointing. To improve the already high stability of the platform developed for MTG, a feed-forward mechanism was designed and implemented that uses the reaction wheels to compensate for the disturbances of the SCAN mechanism in the FCI instrument while they happen. This requires knowledge in the platform of the activities performed by the instruments, and a high level of synchronization between both.

In order to allow to operate FCI in observation without ground intervention, the satellite has in its memory a number of mission scenarios that contain:

- Table of angles for the instrument scan mechanism movement, with angles for Full Disc Coverage and three different Local Area Coverages, associated transitions from one coverage to the next and rally phase, so that each coverage starts from the canonical position. The table contains the start and end angles for each swath, which allows for the computation of scan angles at 1kHz SCAN SW at 1kHz in real time.
- A Priori Compensation (APC) tables for AOCS sampled at 10Hz. Those tables allow to compensate precisely scan

disturbances and to help achieve fine pointing mode requirements.

The onboard APC table is used by the reaction wheel management function to compensate the scan movement by adding the scan compensation torque from the APC table, used in open loop, to the torque commanded by the AOCS controller. This computed torque is then used for commanding the reaction wheels.

This feed-forward compensation torque is loaded from tables corresponding to the payloads scan law (one table for each scan scenario). The table can be updated by ground TC depending on the mission needs. The compensation torque is computed on ground knowing the desired profile for the scan law and the inertia of the scan mirror and fork. A fine synchronization in the order of a millisecond between the scan movements and the a-priori compensation torque is realized on board to be sure to apply the correction simultaneously to the scan disturbances.

C. High Rate Diagnostics Mode

MTG includes a High-Rate Diagnostic Mode (HRDM), intended to be used for investigations in case of anomaly. The HRDM allows the DHS to acquire a subset of parameters at a higher rate than standard House-Keeping (HK), up to 1kHz. The HRDM service has the following characteristics:

- one parameter at 1kHz for at least 4 minutes, or
- up to 10 different parameters for at least 4 minutes such the product of number of parameter(s) and the sampling frequency is constant (= 1000)

The HRDM acquisitions are performed in hardware (not depending on SW intervention while running), with temporary on-board storage through PUS packet store in mass memory before downlink to ground via S-band telemetry or, optionally, Ka-band for faster availability on ground.

There are in total five HRDM sources within the satellite:

- Two of them in the satellite platform for high-rate monitoring of the currents of the power distribution and for the DH parameters
- Two in the FCI for ICU (Instrument Control Unit) and CCE (Cryo-Cooler Electronics)
- One in the LI instrument

The SW PUS provides three packet stores, one for the HRDM data of each element (platform, FCI and LI), allowing ground to download or not data when needed without impacting the TTC link for each acquisition sequence.

In the knowledge of the authors, this was the first mission for which it was required to provide diagnostic telemetry with such high frequency, through demanding requirements coming from the MSG lesson-learnt where power current monitoring was helpful to investigate FDIR impacts from in-flight single event transients (SET).

D. LI architecture using a PowerPC

The instrument uses four cameras covering Europe, Africa, the Middle East and parts of South America. Each camera has a 1Mpixel resolution, acquiring 1,000 images per second. This high data volume needs to be processed in the instrument itself to reduce this data to a manageable volume that can be downlinked within an allocated budget of 30Mbps, including only the events identified as lightning, instead of full images for on-ground analysis.

The Single Board Computer (SBC) is the core of the Main Electronics equipment that interfaces the Optical Head Front-End (OH-FE) of the Lighting Imager (LI). It manages continuously an OH-FE data rate up to 480Mbps made of multiple images to be processed and filtered in near real-time, to reduce any lightning false event (false alarm rate) that could be introduced by micro-vibrations. Data output is made of a flow of CCSDS TM packets up to 80Mbps peak. Both input and output data are exchanged using SpaceWire links up to 150Mbps (four OH-FE plus one Nominal and one Redundant towards the DDU), making use of two AT7910 routers.

A typical microprocessor used in space (for example the processor of a Satellite Management Unit, SMU), like one of the Sparc series sold by CAES, is not able to carry out all the calculations involved in the above data processing.

For this reason, the LI instrument main electronics (LME) is built around the Thales Alenia Space Italy Single Board Computer (SBC) that makes use of a Freescale PowerPC PC7448 CPU running at 960MHz supported by 1GiB of SDRAM (with a throughput capability more than 3Gbps), and two Microchip FPGAs RTAX2000: one mainly devoted to C&C and PowerPC supervisor (to manage reset, watchdog, non-volatile memories and MIL15553) and the other devoted data acquisition and storage from FE, DMA implementation (input and output) and to manage PowerPC Bus (called 60x).

To reach an average processing rate of 650000 DTs (Detected Transients) per second, an extensive use of parallel calculation has been done exploiting the 4 vector units AltiVec® embedded in the PowerPC.

PowerPC (PC7448) is produced by Freescale in 90 nm CMOS SOI Technology, which prevents by design any latch-up (SEL) and provide a radiation hardness of 100Krad.

However, the Single Event Effects (SEE) are required to be tested to verify the effectiveness of both the device mitigation features and also other mitigation techniques implemented at board level (e.g. periodical microprocessor reset), in the MTG application. For this reason, Thales Alenia Space Italy itself developed and conducted two radiation test campaigns in 2016 and 2018 at TAMU facility in Texas (USA) that demonstrated that the architecture was fit for purpose.

Thales Alenia Space Italy started to develop this board in the mid-2000s, exploiting an internal R&D activity funded by ASI. MTG's Lightning Imager is the first project to use the results of this R&D activity.

Another challenging design aspect was related to the thermal need to release about 7W of thermal dissipation from the PowerPC core, through a contact area of only $57mm^2$. The design solution involved the use of an aluminium cold finger and a high-performance thermal pad, to be installed on the core with a high-precision mechanical integration. In collaboration with ESA, the assembly was qualified, and its performance verified.

E. Use of a SpaceWire (SpW) network

The high volume of data acquired by the MTG instruments is handled via the SpW network.

MTG-I makes use of a unique type of link for all mission data with flexible, scalable and standardized SpW links and routers. MTG-I implement a satellite network with heterogeneous data flow in rates and format thanks to the encapsulation of SpW, CPTP and PUS protocols and format allowing for both:

- acquisition of mission data from the various sources of the satellite up to its distribution to ground, and
- sending mission configuration data to the payload for programming the scan movement based on a user-defined scan law.

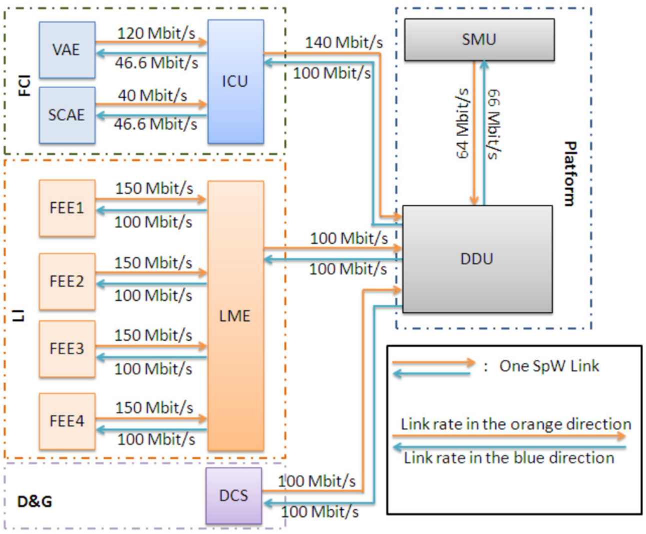

Figure 2: SpaceWire network on MTG-I

The choice of the SpW standard allows for:

- use of the same link and protocol in a transparent way, independently of the actual data rate,
- prevent development and qualification of specific high data rate link components,
- have same technology within all satellite parts and units developed by subcontractors for platform and payloads, EGSE included,
- and minimize the development and validation effort.

F. SpW and data regulation in LI

All data acquired by the LI instrument four Optical Heads (LOH) is transferred to the Main Electronics (LME) via an internal SpaceWire network, which is also used by the LME to send TCs to the LOHs (LI Optical Heads); this TC/TM architecture is handled by LI custom PUS services. Each Optical Channel (LOC) has a fully redundant SpW interface with the LME for a total of eight SpW cables:

- SpaceWire I/F for LOC1 TM/TC exchanging (N+R)
- SpaceWire I/F for LOC2 TM/TC exchanging (N+R)
- SpaceWire I/F for LOC3 TM/TC exchanging (N+R)
- SpaceWire I/F for LOC4 TM/TC exchanging (N+R)

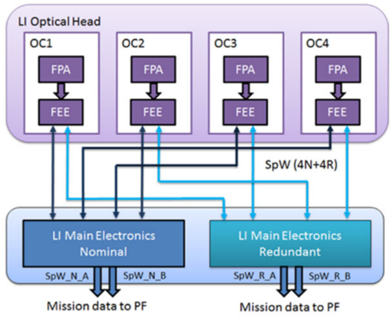

Figure 3: LI SpW internal network

LOC SpW cables conform to the ECSS standard, with an additional external overall shield granting the connection of the shields to both sides.

The LME delivers the Mission Data to P/F DDU through two fully cross-strapped SpW interfaces (nominal and redundant). The Mission Data is encapsulated into PUS Service 201 TM Packets (one of the private MTG custom service). The LI provides data to MTG-I platform Data Distribution Unit (DDU) through SpaceWire during the OPERATIONAL and CALIBRATION modes.

Mission data includes:

- DT_DATA packets, containing the data on: coordinates of the Detection Transient (DT) event, 3x3 pixels radiance and reference background of detected events (available only in OPERATIONAL mode)
- IMG_DATA packets containing 10x13 pixels data (i.e. reference background in OPERATIONAL mode or radiance in CALIBRATION mode)
- TM_BASIC_CONF packets containing the information on current configuration which allow a monitoring of the correct configuration (available in OPERATIONAL and CALIBRATION modes)
- TM_AUX packets containing the information and housekeeping which allow to monitor the current status of the instrument (available in OPERATIONAL and CALIBRATION modes)

The LI starts the SpaceWire link (the DDU is in auto-start mode) through Platform SMU commands; the P/F SMU is in charge to select the SpW link (nominal or redundant), by means of the LI dedicated PUS svc236. In particular, the SpW selection with TC "SpW Selection (A/B)", and to start the link, by TC "SpW Start".

In case of SpaceWire link failure, LI OBSW does not perform an automatic switch to redundant SpW link; it is up to Platform to change the SpaceWire link.

Due to the nature of the LI instrument, detection of sporadic lightening events, the rate of scientific data generated by LOH to LME is not constant and it needs to be regulated to the allocated downlink budget of 30Mbps.

The mentioned adjustment is implemented through an Autonomous ''Data Regulation Algorithm'', one of the most innovative concepts implemented in the LI Instrument.

The Data Regulation Algorithm is implemented in the LME OBSW and consists of two steps:

- LOH DR: this step operates on the LME input and regulates the data flow from LOH based on the filling level of DT_DATA buffers implemented on both TX and RX sides of intra-unit SpW links. The algorithm operates at 10Hz performing a continuous configuration of the LOH detection electronics. Regulation can intervene on the parameters of both the detection algorithm and false event filtering algorithm to regulate the amount of DT_DATA transmitted from LOH to LME.

- LME DR: this step operates at the LME output and regulates the DT_DATA flow produced by the ASW based on the filling level of the mission data output buffer (i.e. TM_READY buffer). The algorithm operates at 10Hz, performing a continuous configuration of the Micro Vibration Filter (MVF) implemented to reject false events generated by potential platform Line of Sight instability. The regulation setpoint is defined to maximize the number of DTs transmitted on ground in any in flight condition.

The implementation of this algorithm simplified the activity on ground (e.g., during integration and AIT) giving the possibility to test the LI functionality and behaviour before the final flight scenario, visible only in flight.

As part of the in-flight instrument commissioning the data regulation algorithm is tuned in order to achieve the best Instrument Performance on the basis of real scenarios.

G. Use of a fully automated Separation Sequence

A fully automated spacecraft separation sequence has been designed with the objective to reach a safe and stable configuration after separation from the launcher, including deployment of the solar arrays and achieving a stable spacecraft Sun pointing. Thanks to the implementation on MTG-I, this is achieved without any need for ground operation, even in case of single failure.

The key driver for the autonomous sequence design was the need to operate on battery power until a sufficiently stable condition is reached, meaning limited time to complete the sequence, including possible recovery time.

The key aspects of the sequence design are:

- Fully autonomous spacecraft configuration and reconfiguration, with complete initialisation of propulsion subsystem and deployment of solar arrays.

- Extensive use of the redundancies available on-board for commanding and input signals acquisition, e.g., for pyro firing.

- SW filtering and validation of input signals, to ensure that autonomous decisions during the complex sequence are taken based on reliable inputs.

- Single FDIR recovery independently of the failure cause, with reconfiguration to all redundant HW chains and redundant attitude control SW algorithm. This approach ensures that in the limited time available it is possible to recover the system and to autonomously continue and complete the sequence.

The autonomous separation sequence execution during the MTG-I1 launch proved the robustness of the concept, even with FDIR triggering and execution. In the figure below it is shown the battery voltage level up to sequence completion. Different phases can be observed:

- Spacecraft tumbling immediately after separation with the solar arrays not yet deployed. The battery charges when one solar array is exposed to the Sun and discharges when both solar arrays are in shadow.

- Discharge after propulsion subsystem initialisation and first spacecraft Sun pointing manoeuvre is performed. At this stage, when the Sun pointing is reached, the Solar Arrays not yet deployed are parallel to the Sun direction.

- Solar-arrays locks release and jump-out. The discharge stops and solar power starts being collected.

- Solar arrays deployment by deployment motor activation and final spacecraft Sun pointing. The collected solar power exceeds the consumption, so that the battery is charged to maximum level and stays in this condition.

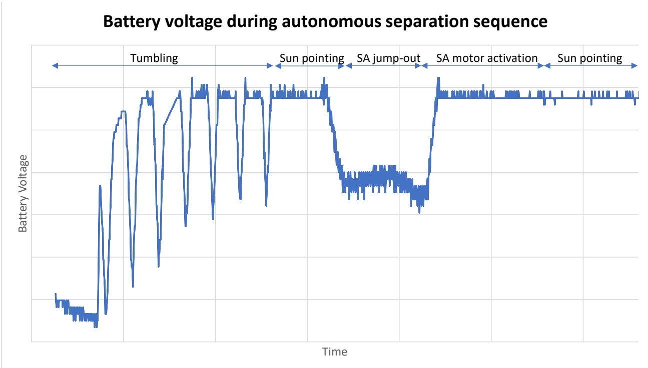

Figure 4: Battery voltage during execution of autonomous separation sequence, MTG-I1, 13th of December 2022

V. Conclusion

The MTG-I satellites include several unique features in its DHS. This paper has presented them in detail and included an initial in-orbit assessment based on MTG-I1 performance.

Acknowledgment

The authors wish to thank all the many people who have contributed to the MTG-I mission and have made it possible to create such unique, complex and successful series of satellites. All the people part of the European Space Industry involved in the MTG programme have worked tirelessly to achieve the incredible results we have already seen during the MTG-I1 commissioning phase, and for that you have our sincere gratitude.

A special mention to our colleagues at Thales Alenia Space, OHB, Leonardo, EUMETSAT and ESA for your support, professionalism and good humour over the last decade, always a pleasure working with you.

Finally, we wish to thank our families for their support, patience and enthusiasm for learning an unholy number of 3-letter acronyms.

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LIST OF ACRONYMS AND ABBREVIATIONS

AES	Advanced Encryption Standard
AOCS	Attitude and Orbit Control System
APC	A-Priori Compensation
CCE	Cryo-Cooler Electronics
CCSDS	Consultative Committee for Space Data Systems
CPTP	CCSDS packet transfer protocol
CPU	Central Processing Unit
DCS	Data Collection System
DDU	Data Distribution Unit
DH	Data Handling
DMA	Direct Memory Access
ECSS	European Cooperation for Space Standardization
FCI	Flexible Combined Imager
FDIR	Fault Detection, Isolation & Recovery
HRDM	High-Rate Diagnostic Mode
ICU	Instrument Control Unit
LI	Light Imager
LME	LI Main Electronics
LOC	LI Optical Channels
LOH	LI Optical Heads
MSG	Metetosat Second Generation
MTG	Meteosat Third Generation
OBSW	On-Board Software
OH	Optical Head
OQPSK	Offset Quadrature Phase-Shift Keying
PDD	Payload Data Downlink
PUS	Packet Utilisation Standard
RX	Reception
SAR	Search and Rescue
SBC	Single Board Computer
SDRAM	Synchronous Dynamic Random Access Memory
SEE	Single Event Effects
SMU	Satellite Management Unit
SpW	SpaceWire
TX	Transmission