

THE SENTINELS FOS AND ITS CONTINUOUS EVOLUTION: FROM THE WHITEBOARD TO TESTING FOR THE NEWER GENERATIONS

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Abstract

The Sentinels Flight Operations Segment (FOS) at the centre of ESA operations in ESOC, Darmstadt, continues its evolution.

Two decades ago started the journey: the common conception, development and implementation of a single Flight Operations Segment to support a first series of Sentinels missions, that would soon expand in number.

Today, while successfully executing flight operations of the Sentinel-1, Sentinel-2 and Sentinel-5p missions – with their numerous challenges, such as for instance the altitude lowering campaign of Sentinel-1B and the recent launches of Sentinel-1C and Sentinel-2C – the FOS continues preparation activities for more launches in 2025 and 2026: Sentinel-1D, Sentinel-6B and Sentinel-3C. The so-called Sentinels First Generation.

Following the provisions of the Copernicus Long Term Scenario jointly defined by the European Commission and the European Space Agency, the Sentinels FOS and the teams continue its technical evolution initiated five years ago towards the integration, verification and validation of the deltas required to operate the new generation of Sentinels missions (the so-called Sentinel Expansion missions), including among others:

- the adoption of the CCSDS Space Data Link Security protocol for the authentication of the uplink communications;
- the incorporation of file-based transfer of data between ground and the satellite, making use of the CCSDS CFDP protocol;
- the adoption of the Ka radiofrequency band for the communications in the area of scientific data downlink;
- the push for more automation and for lights-off operations (i.e. without man in the loop);
- the support to investigation of Artificial Intelligence based tools and plug-ins that may bring further capabilities and benefits to satellite operations.

This paper will present the major achievements after the preliminary designs and first procurements were triggered in 2023, the current status and the lessons learned. As a matter of fact, the Sentinels FOS has already seen:

- the completion of its Design Review;
- the consolidation of the core internal and external interfaces required to satisfy the evolutions of the missions;
- decisions concerning the strategy towards the Mission Control System baseline to be used at start and potentially evolve during the lifetime of the FOS;
- the increased awareness of security in all processes, also in FOS;
- the early integration activities of the main evolutions, such as SDLS authentication, Distributed CFDP architecture and File Based Operations – the previous for the first two Sentinels Expansion missions, CO2M and CRISTAL;
- and the completion of the Critical Design Review for the Flight Operations Segment instance of the CO2M and CRISTAL missions.

The evolution continues, with both its pleasant surprises and its unplanned challenges, and with all ESA teams working to adapt to the future while maintaining the solidity of ESOC's proven and flying Sentinels Flight Operations Segment.

Keywords: Copernicus, Sentinels, expansion, flight operations, evolution, ground segment

Acronyms/Abbreviations

Back-Up Control Centre (BUCC)
Collision Avoidance Manoeuvre (CAM)
CFDP File Reconstruction System (CFRS)
Consultative Committee for Space Data Systems (CCSDS)
Control Centre Distributed CFDP System (CC-DCFDP)
CCSDS File Delivery Protocol (CFDP)
European Cooperation for Space Standardization (ECSS)
European Ground Systems – Common Core (EGS-CC)
European Space Agency (ESA)
European Space Operations Centre (ESOC)
European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)
File-Based Operations (FBO)
Flight Dynamics System (FDS)
Flight Operations Control Centre (FOCC)
Flight Operations Segment (FOS)
Ground Systems Test and Validation Infrastructure (GSTVi)
Mission Control System (MCS)
Main Key Management Facility (MKMF)
Mission Planning System (MPS)
Mission Control Core based on Common Core (M4C)
Protocol Data Unit (PDU)
Satellite Control and Operation System 2000 (SCOS-2000)
Space Data Link Security (SDLS)
Space Debris Office (SDO)

1. Introduction

Since the early 2000s and as part of the European Global Monitoring for Environment and Security (GMES) programme, ESA implemented and started operating a first generation of Sentinel satellites to provide accurate, timely and easily accessible information to improve the management of the environment, understand and mitigate the effects of climate change and ensure civil security [1]. The first generation of Sentinel missions is providing information in various domains:

- all-weather, day and night radar imaging
- high-resolution optical imaging
- ocean and global land monitoring
- atmospheric composition monitoring

This effort materialised in a fully operationally proven and flying Flight Operations Segment, which today is executing operations of six Sentinel spacecraft (Sentinel-1A, 1C, 2A, 2B, 2C and Sentinel-5p) and which was in charge of flight operations during the initial flight phases of Sentinel-3A, 3B and Sentinel-6 MF, until handed over to EUMETSAT.

As part of the same programme, since 2012 renamed as Copernicus Programme, the European Space Agency (ESA) is implementing a series of Sentinel Expansion missions including the required ground segment system evolutions from the already available and operationally validated Copernicus Ground Segment (including the Flight Operations Segment, FOS), together with their post launch operation, i.e. the CHIME, CIMR, CO2M, CRISTAL, LSTM and ROSE-L spacecraft and their payload, throughout the post-launch mission lifetime of the first and second satellite of each mission family.

The main evolutions required within the FOS to support the operations of the above-mentioned Sentinel Expansion missions were presented in SpaceOps 2023 [2]. This article presents the major achievements, challenges and lessons learned in the transition from the design whiteboard to the integration testing phase of the FOS for the Sentinel Expansion missions.

2. Overview of the Flight Operations Segment and the major evolutions driven by the Sentinel Expansion missions

The FOS, as part of the overall Copernicus Space Component, provides capabilities for the satellite monitoring and control, including execution of all platform activities and the commanding of the payload schedules, during all mission phases. Several facilities and services are already deployed and fully operational, while others required evolutions and delta-developments to cover for new requirements stemming from the Sentinels Expansion missions' needs.

A simplified view of the FOS context within the Copernicus Space Component is shown in Figure 1. In terms of colour coding, yellow are mission specific systems and green are generic services provided to the mission. In orange are externally procured ground station services.

The principal FOS components are:

- The Ground Station and Communications Network performing telemetry, telecommand and tracking operations within the S-band frequency. A network of S-band ground stations will be used throughout all mission phases.
- The Flight Operations Control Centre (FOCC), including the following main elements:
 - The Mission Control System (MCS), providing the satellite monitoring and control functions, incl. commanding, housekeeping telemetry (HKTm) data archiving and processing.
 - The Distributed CFDP functions, supporting the real-time CFDP protocol closure and the file reconstruction for the S-band.
 - The Master Key Management Facility (MKMF) which, together with the SDLS Facility integrated in the Mission Control System, will be responsible for the generation, storage, and distribution of cryptographic cipher keys and for their own monitor and control.
 - The Mission Planning System (MPS), supporting the planning and scheduling of satellite operations.
 - The satellite operational simulator, supporting procedure validation, operator training and the simulation campaign before each major phase of the mission.
 - The Flight Dynamics System (FDS), supporting all activities related to attitude and orbit determination and prediction, preparation of slew and orbit manoeuvres, spacecraft dynamics evaluation and navigation.
 - A general-purpose Communication Network, providing the services for exchanging data between FOCC and the S-band ground stations, and with any other external systems during all mission phases.
 - The ESOC Space Debris Office (SDO), providing collision risk assessments and supporting the preparation and execution of Collision Avoidance Manoeuvre (CAM).
- A Back-Up Control Centre (BUCC), not shown in the picture, which implements the subset of functions that are needed to ensure satellite safety.

The major evolutions required in these components were presented in [2] and are recalled here in a brief manner:

1. Evolution from the ECSS Packet Utilisation Standard A to C (PUS-C) [5] which features, amongst others, new parameter types, services and an approach for commanding persistent activities to the spacecraft.
2. Adoption of File Based Operations for downlink of recorded housekeeping and science telemetry (from the On-Board Computer and the Payload Data Handling Unit, respectively), and for the uplink of data (e.g. telecommands, OBCPs or memory data) to the On-Board Computer.
3. Adoption of the CCSDS File Delivery Protocol (CFDP) [3] as underlying protocol for file transfer.
4. In the area of security, adoption of the CCSDS Space Data Link Security protocol [4].
5. Potential need for commanding support to science downlink operations in the Ka-band, should an acknowledged CFDP mode (class-2) be required to fulfil the system requirements.
6. Evolutions to support the new common platforms developed by the key European satellite primes, particularly in the area of operational simulators and flight dynamics monitoring and commanding activities.

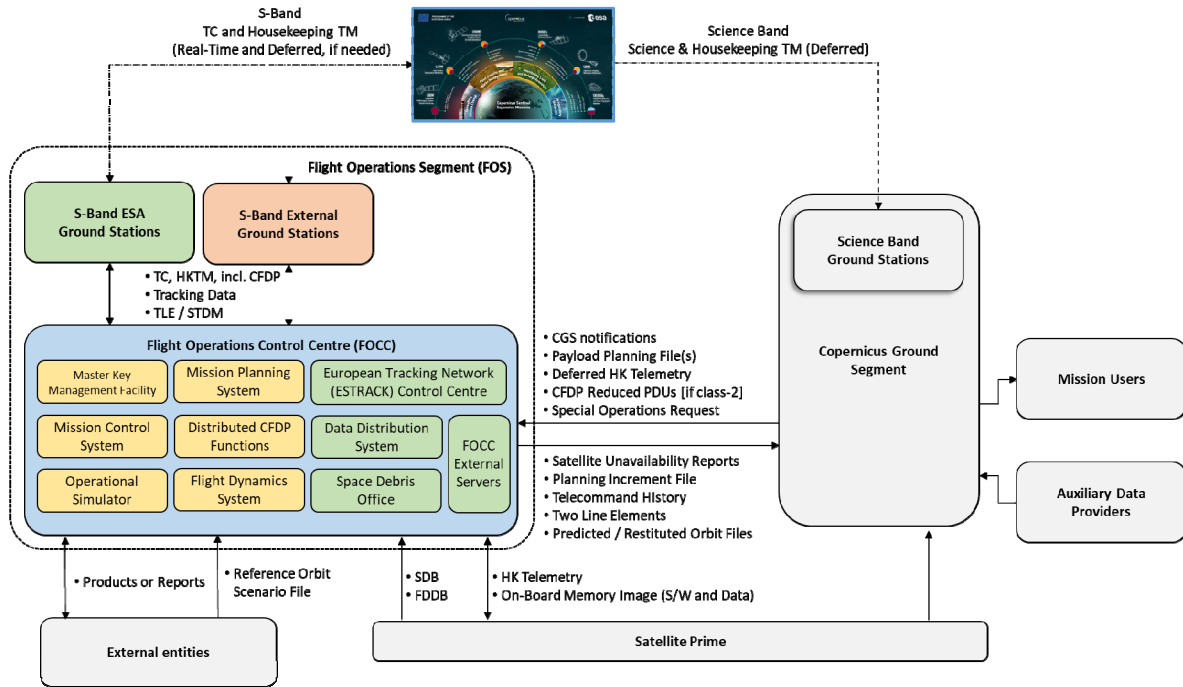


Figure 1 – Sentinel Expansion system overview (FOS centric view)

3. Programmatic status: where is the FOS at the moment.

At ground segment level the commonalities amongst the Sentinel Expansion missions are so large that:

- the FOS systems are being designed and implemented following generic principles aiming at maximising re-usability through extensive use of modular and configurable components.
- a common review and integration approach was conceived that ensures the validation of both the common and the mission-specific elements of the FOS in an efficient manner.

Today, the Sentinels FOS has undergone successfully the following review milestones:

- In 2022, Preliminary Design Review of the FOS for the CO2M mission (this mission was ahead in schedule)
- In 2023, one single common Design Review of the FOS for the other five Sentinel missions.
- In 2024, Critical Design Review of the FOS for the CO2M mission.
- In early 2025, Design Checkpoint of the FOS for the CRISTAL mission (end of phase C, equivalent to CDR).

The Design Checkpoints for the remaining four missions are currently planned in 2026 and beyond and are dependent on the evolution of the space segment activities and the completion of their phase C activities.

In terms of verification and validation, an efficient yet robust approach was conceived thanks to the fact that most of the FOS main systems and facilities required in support of the Sentinel Expansion missions are already operational and have been exhaustively validated by numerous pre- and post-launch activities of several Copernicus and other Earth-Observation missions. It consists of:

- Verification at component and subsystem level of all delta functionality stemming from the evolutions required by this generation. Examples of these campaigns are acceptance testing of the Mission Control System and Operational Simulators of the CO2M and CRISTAL, and acceptance testing of the DCFDP systems.
- Validation of the whole FOS through the execution of all FOS system-level testing campaigns. Examples of these campaigns are the System Validation Tests campaign, whose first slot for CO2M was executed in January 2025; and the Radio-Frequency Compatibility Tests, planned for CRISTAL in May 2025 and for CO2M in September 2025.

4. Main achievements, challenges and lessons learned.

4.1 ECSS Packet Utilisation Standard C (PUS-C) and mission control system baseline

In the area of Mission Control System, the original plan was [2]:

- To incorporate all the required evolutions into the SCOS-2000 software system used during over two decades in ESOC, to be used to operate the first of the Sentinel Expansion missions (CO2M).
- To operate the other five missions with a more modern system based on the European Ground Systems – Common Core (EGS-CC). The functional scope of this system, Mission Control Core based on Common Core (M4C), would have been very similar to the SCOS-2000.

However, at the time when the Sentinel Expansion missions needed to start defining the tailoring of their Mission Control Core, the system based on EGS-CC was considered not fully mature for adoption by the missions. It was thus decided that the back-up solution, which was the SCOS-2000 system developed for CO2M, would be also used to operate the other five Sentinel Expansion missions, at least for their initial operational phase.

The more technical evolutions brought by the new PUS-C standard have been very successfully implemented. Special mention could go to the following two cases:

- a) The new parameter type relative CDS time format was chosen for implementation by the satellite manufacturer of one of the six missions (CO2M), while the other five remained with CUC format. However, PUS-C mandates now that in all cases the reference epoch is 1958. This created unexpected problems because this date is earlier than UNIX reference time, and further changes were needed to cope with this.
- b) Parameters of type unsigned integer and signed integer of 64 bits were not supported by the previous versions of SCOS-2000 systems at ESOC but were now implemented in the space segments. The same was soon identified for UINT and INT parameter of 48 bits. Measures were then taken to implement these parameter types in the Mission Control System. Today UINT64 and INT64 are supported by the core MCS applications (not yet UINT48 and INT48), but several Software Problem Reports were raised and implemented in relation with this functionality.

It remains to be tested and verified that these parameters are also fully supported in other data management applications, such as data dissemination. The integration of these applications corresponds to future phases of FOS integration, currently planned for early 2026 in the CO2M and CRISTAL missions.

- c) The introduction of the Message Type Counter (MTC), planned to be used for the monitoring of the telemetry gaps instead of the Source Sequence Counter (SSC), was very smooth.
- d) The implementation of Request Sequencing (PUS 21), Position-based Scheduling (PUS 22, supporting the commanding of persistent activities) and File Management (PUS 23) was carried out very quickly. However, testing activities so far have made use of integration and testing tools only. Full verification of correct implementation will only be achieved when the first on-board SW versions implementing these services are received from the satellite primes and integrated in the Operational Simulator (planned for both CO2M and CRISTAL during 2025).

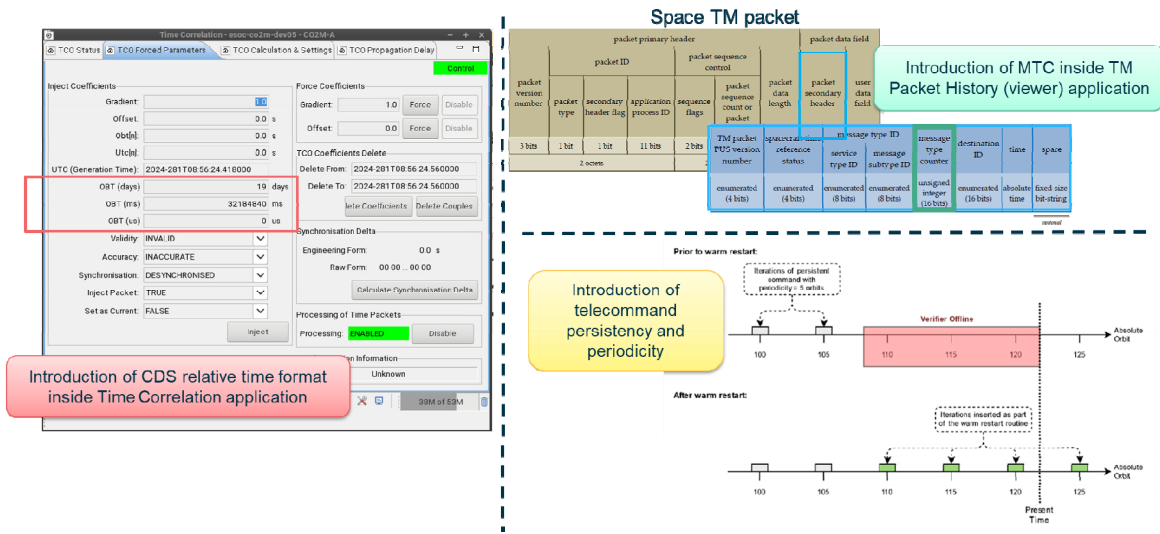


Figure 2 – Three of the main achievements in the evolution of the MCS towards PUS-C

4.2.1 File Based Operations

The capability to manage and transfer data of various types via files (telemetry, telecommands, raw software data, on-board control procedures) is planned for the Sentinel Expansion missions.

In order to support File-Based Operations (FBO), it was decided that enhanced visibility of the on-board file stores of the On-Board Computer (OBC) and the Payload Data Handling Unit (PDHU) was required in the FBO application of the Mission Control System. This application was specified to ingest the TM reports from the satellite representing the current content of the on-board directories and represent them in the form of a file explorer.

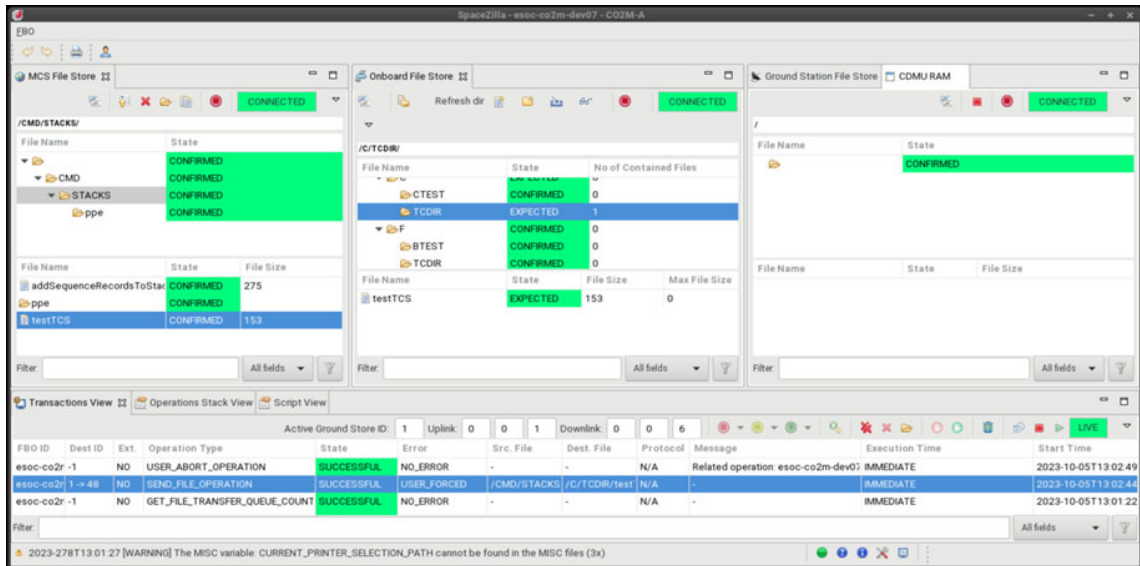


Figure 3 – File-Based Operations application display (similar to FileZilla)

The main challenge, not initially identified, is linked to the combination of:

- 1) The structure that the PUS-C standard dictates for the TM reports which represent the contents of the on-board file systems.
- 2) Together with the fact that PUS-C provides full flexibility in the definition of the lengths for directory and file names.

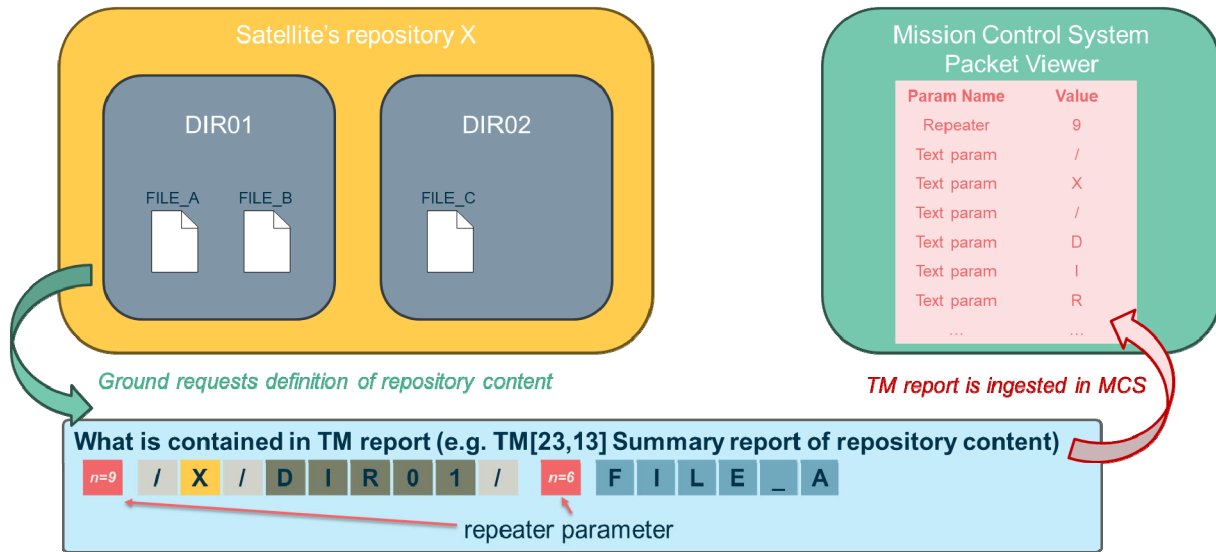


Figure 4 – Structure of PUS23 reports and how they are observed in MCS

Today, the design of the FBO application of the Sentinel Expansion Mission Control System, which is an evolution of the PUS-A Service 13 used in previous interplanetary and astronomy missions of ESA, expects (configurable) fixed values for the length of the directory name and file name. They can be different from each other, but they need to be constant for a given mission.

This may not seem like an important limitation and indeed it was very soon confirmed for the CO2M mission that the space segment configuration foresaw one same directory length and one same file length. However, it was later identified that, for the CRISTAL and LSTM satellites, the way the on-board software had been specified to implement telemetry compression meant that directories would have names of different lengths, e.g.:

- Directory HKTLM would contain non-compressed HKTLM data.
- Directory HKTLMZ would contain the same TM data but in the form of compressed files.

The preferred way-forward for this challenge remains to be identified. One option is the re-design of the FBO application, but there are others, such as the possibility of restricting this enhanced visibility functionality only to a subset of the directories. It shall be reminded that the telemetry data will be autonomously stored into files on-board and autonomously downlinked (both processes according to the configurable rules of PUS service 23). These files thus “come and go”. Instead, the other types of files (telecommands, raw data, OBCP data) will be created by ground or upon dedicated requests from ground. Maintaining on-ground a “reference” with enhanced visibility can therefore be considered needed only for the directories containing these data (TC, raw data, OBCPs).

4.3 CFDP and Distributed CFDP (DCFDP)

The protocol to be used for the transfer of files is based upon the CCSDS CFDP protocol. A summary of the distributed implementation of this standard inside the FOS can be found in [2] and is recalled in Figure 8.

At this stage of the FOS integration and testing phases, successful file reconstruction of telemetry files generated by FOS GSTVi system has been tested. More testing is planned in the short term, because ESA has recently received versions of the on-board software of the CO2M and CRISTAL missions implementing file transfer.

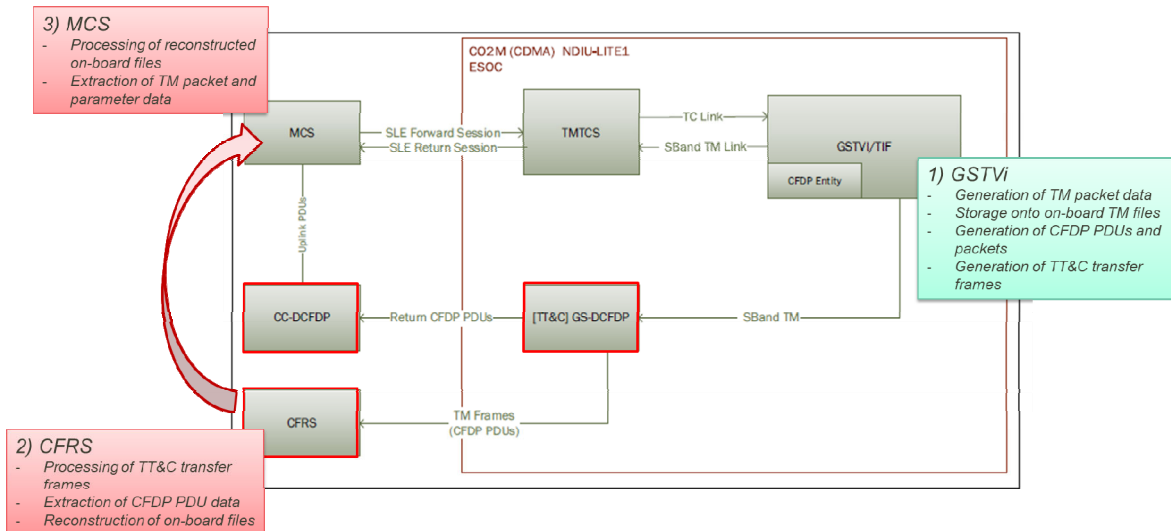


Figure 5 – Validation of file reconstruction with GSTVi

In the area of DCFDP, one of the main lessons learned in the transition from the while board to the implementation was the realisation that only the information in the S-band Transfer Frames would not be sufficient for the CFDP File Reconstruction System (CFRS) to place the frames, packets and CFDP Protocol Data Unit (PDUs) in the correct order as the first step in the reconstruction process. The previous was due to the short wrap-around of the Virtual Channel Frame Counter inside the Transfer Frames. With the data rates expected in S-band, this counter would repeat itself up to every second.

The solution to this problem was two-fold. On the one end, the format of the offline telemetry files stored at the various ground stations was reviewed, and it was identified that the stations include a header before each transfer frame and this header could be specified to include a time field. On the other end, additional requirements were placed in the file reconstruction system (CFRS) to process this time field and use it together with the Virtual Channel Frame Counter to place all the frames in the same order as they were downlinked. This additional functionality has been already verified in CFRS. Full validation with the TT&C ground station network will be performed as part of the next steps in the FOS IV&V campaign.

Transfer Frame Primary Header										
Frame Identification				Master Channel Frame Count	Virtual Channel Frame Count	Frame Data Field Status				
Version	S/C Id	VC Id	OPCF Flag			Sec. Header Flag	Sync Flag	Packet Order Flag	Segm. Length Id	First Header Pointer
2 bits	10 bits	3 bits	1 bit	8 bits	8 bits	1 bit	1 bit	1 bit	2 bits	11 bits
0.1	2..11	12..14	15			0	1	2	3..4	5..15
2 octets				1 octet	1 octet	2 octets				

VCFC can take up to 256 possible values with transfer frames of ~ 1100 bytes at up to 2000 kbit/s => Wrap around every ~ 1 second

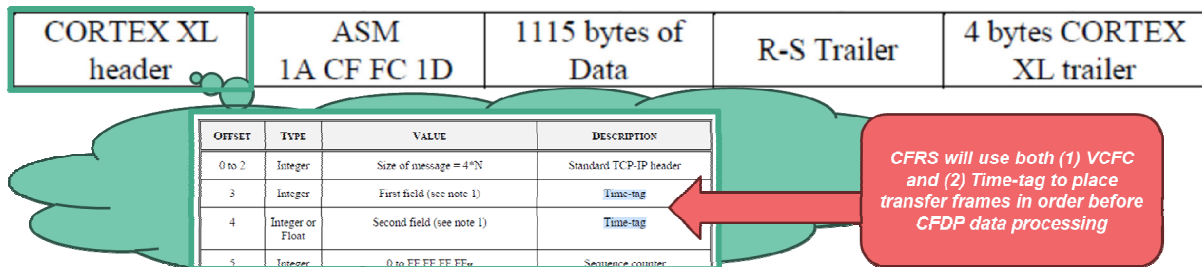


Figure 6 – Structure of S-band transfer frame and time-tag inside CORTEX header

The other main finding in the area of CFDP is the channelling of the satellite responses to CFDP uplink operations: while the FOS design expected the data in the real-time telemetry flow (Virtual Channel 0), the satellite primes implemented this flow together with the rest of CFDP data (i.e. from downlink transactions, in Virtual Channel 4). The divergence is considered to stem from the wording of the relevant requirements to the space segments.

In order to adapt to this situation, the Sentinels FOS team evaluated a series of possibilities, concluding in a streamlined solution that would leverage on the existing interfaces and would avoid the need for additional functionality at either ground stations or Mission Control System. In this solution, the CC-DCFDP system will be enhanced to expect CFDP PDU data not only related to downlink transactions (as originally foreseen) but also to uplink transactions. It will identify and split the two types of data, process them as needed for each case and forward the PDUs related to uplink transactions to the Mission Control System through the same interface originally foreseen for the PDUs related to downlink transactions. This new functionality is expected to be implemented in the course of 2025. In the meantime, the current FOS system design and implementation already supports validation of uplink and downlink transactions between FOS and space segment.

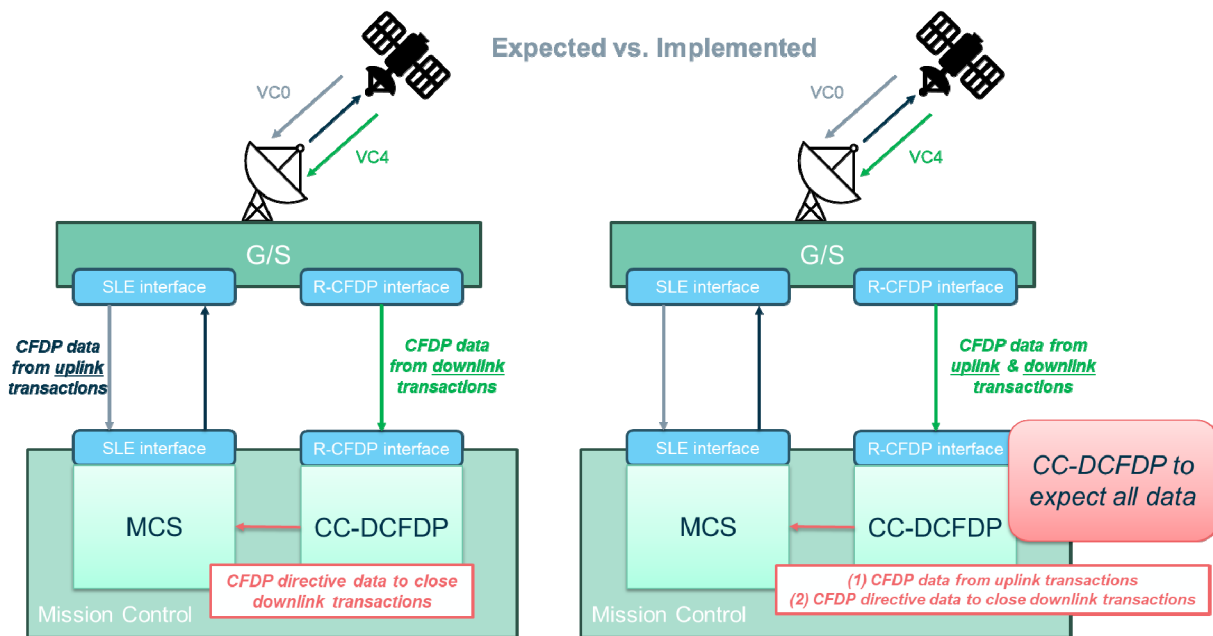


Figure 7 – Expected data flow vs real data flow.

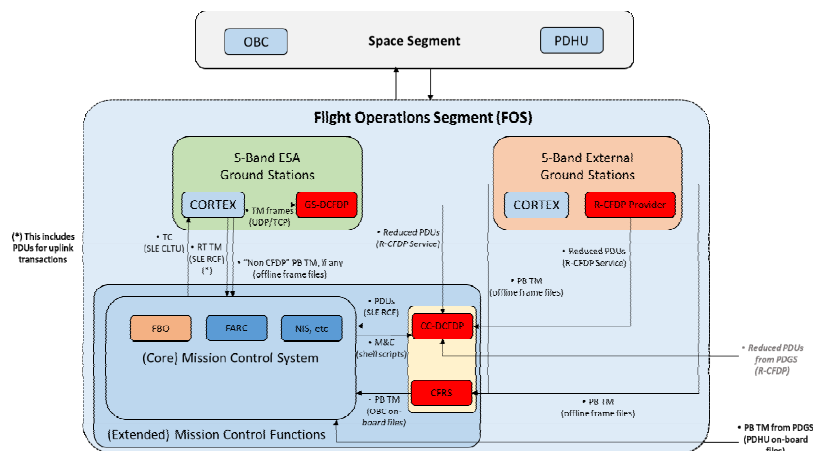


Figure 8 – Flight Operations Segment with Distributed CFDP systems (in red)

4.4 CCSDS Space Data Link Security protocol

The Sentinel Flight Operations Segment required an upgrade of the existing Master Key Management Facility (MKMF) and to the SDLSF (Space Data Link Security Facility, previously known as Key Management Facility) in order to adapt to the upgrades in the area of authentication and in particular to the new CCSDS SDLS standard ([4], [2]). These updates were specified to the various systems and, as soon as implemented, the following testing campaign were executed:

- a) Functional verification of the MKMF and MCS/SDLSF software.
- b) An E2E test with the Mission Control System and Operational Simulator of the Sentinel-1 mission was performed to confirm no regressions on the legacy functionality, with successful results.
- c) An E2E test with the Mission Control System and Operational Simulator of the CO2M mission was executed, with one issue identified on the Mission Control System, afterwards solved for a complete successful scenario.
- d) An E2E test with the Mission Control System and the actual CO2M satellite was executed as part of the first slot of the CO2M System Validation campaign (CO2M-A SVT-1), with successful results.

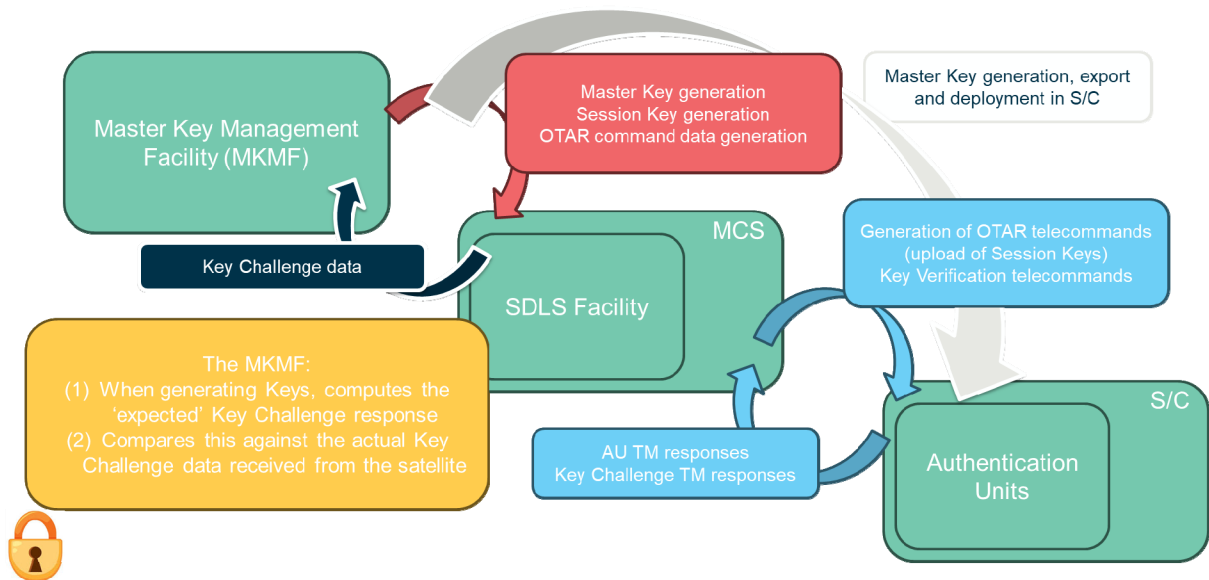


Figure 9 – Schematic of authentication end-to-end test, including SDLS Key Challenge functionality

Further tests will be executed for each satellite model of the Sentinel Expansion missions before the final generation and deployment of the flight keys to be used during the mission.

A curiosity identified during the design process of the MKMF and SDLSF software upgrades has been that the reuse of the solutions and concepts in place for the 1st generation does not necessarily imply full exploitation of all features of the new SDLS standard. For instance, the SDLS standard allows to consider the keys independently and allows the OTAR of any number of keys. However, the MKMF of the Sentinels treated session keys in “blocks” (for key import into KMF, for OTAR, etc) and this concept of “Key Sets” remains in the MKMF for the Sentinel Expansion missions.

4.5 Approach for validation of potential interfaces with a science ground scenario

The execution of science downlink operations in CFDP unacknowledged mode (class-1) implies that there is no interface between the FOS and the science ground station. This situation would be unchanged with respect to the design of the Sentinels FOS currently flying the first generation of Sentinel missions. However, as can be observed from the DCFDP architecture [Figure 8], a new interface would be needed between FOS and science ground stations should there be a need for science downlink operations in class-2.

In order to be ready to support this functionality, the Sentinels FOS team has worked on a streamlined approach that would allow the validation of this interface. It is based on the successful split followed in previous Earth Observation missions between FOS internal testing, System Validation Tests with the satellite and Data Flow Tests with the ground stations:

1. [FOS internal testing] All functional and performance verification and validation of the FOS components will be verified against the FOS operational simulator (which models PDU interface between science band G/S and the Flight Operations Control Centre).
2. [SVT] Verification of CFDP TM/TC packet interface between FOS and the on-board Payload Data Handling Unit (PDHU) during SVT with the PDHU configured in Class-1 and Class-2. This can be achieved without the real-time transfer of PDHU PDUs to FOS.
3. [Science G/S DFT] Should a science ground station implement CFDP functions, the interface to this ground station will be validated through the execution of a so called DataFlow Test. In this test:
 - a) a file stored during satellite AIT and containing satellite science TM is ingested into the ground station demodulator.
 - b) The ground station performs all required CFDP processing and sends the data to the Flight Operations Segment.
 - c) The Flight Operations Segment confirms good connection, verifies the correctness of the received CFDP data in terms of format and contents, and verifies successful processing on FOS side until readiness for uplink to CFDP directive data.

The following diagram represents the execution of this DataFlow Test and the involved data sets, systems and interfaces.

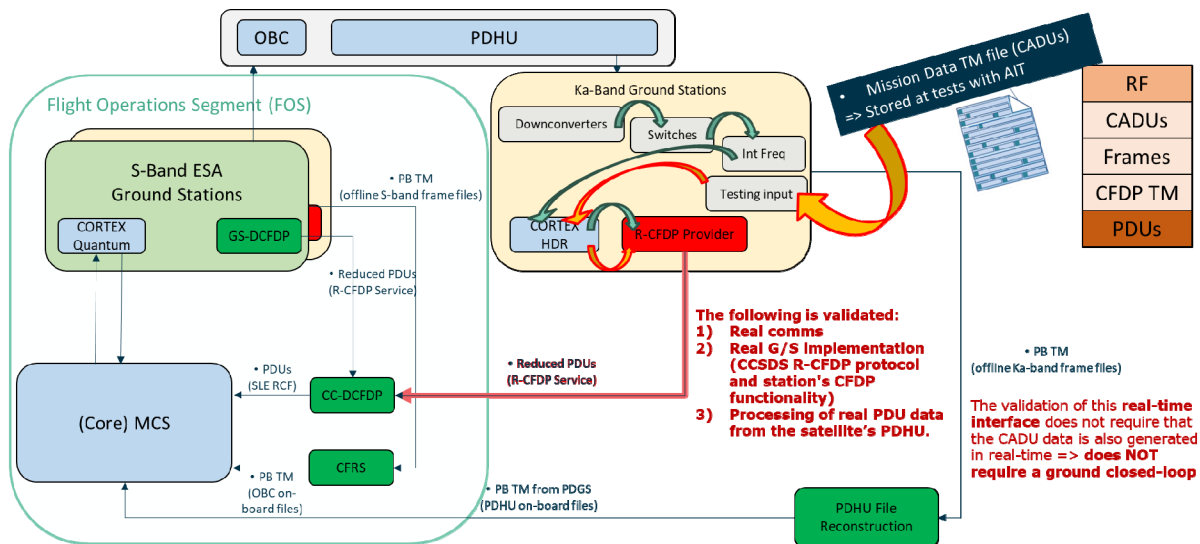


Figure 10 – Execution of DataFlow Test (DFT) between science ground station and Flight Operations Segment

4. Conclusions

The European Space Operations Centre (ESOC) in Darmstadt, Germany, successfully conceived, developed, implemented and validated over a decade ago a Flight Operations Segment for the first generation of Sentinel missions. The Flight Operations Teams at ESOC are now adapting and incorporating the required evolutions, as presented in this paper, to support a full new generation of spacecraft, starting with the six Sentinel Expansion missions.

The traditional complexity associated to the evolution (including some delta-developments) of a fully-functioning, 24/7/365 Flight Operations Segment, has required in parallel to adapt the FOS to new technologies, space segment enhancements (introduction of Ka-band, steering antennae, file-based operations, etc.) and associated changes in the operational concepts. That said, the biggest challenges we have encountered when moving from the white board to the reality remain in our opinion within the area of external interfaces. In particular, the very detailed technical specification of the TM/TC interface between the Flight Operations Segment and the satellite (e.g. PUS-C, CFDP) stands out as main contributor. This is fully justified by the great level of detail and the high technical complexity of such TM/TC interfaces.

Notwithstanding the good preparation of the Sentinels Expansion FOS “in paper” design, unforeseen challenges can always occur. The teams at ESOC continue addressing such inevitable unknowns with a combination of a very configurable and robust set of ground systems together with innovative and solid solutions. Thanks to all this, the Sentinels Flight Operations Segment continues its firm evolution, fully immersed in phase D activities, and well on track towards the readiness for the first Sentinel Expansion mission, expected to launch in 2027.

Acknowledgements

The authors would like to thank all actors of the GMES and Copernicus Space Component programme, in particular the European Commission and ESA Member States. Our particular gratitude goes to our colleagues in the Space Segment programme, in ESTEC, the Netherlands, and the Ground Segment, in ESRIN, Italy, for the close collaboration to make the Sentinels the extremely successful programme it is today. Finally, our highest appreciation to the members of all flight control, flight dynamics, data system and ground station, infrastructure and facilities teams in ESOC who have supported and taken care of the Sentinels Flight Operations Segment since its first steps until today.

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