

## FROM THE FIRST TO THE NEXT SENTINELS GENERATION: FOS EVOLUTIONS WITHIN A FULLY OPERATIONAL GROUND SEGMENT

E. Zornoza<sup>a\*</sup>, P. Choukroun<sup>a</sup>, J. Morales<sup>a</sup>, J. Pineiro<sup>a</sup>, I. Shurmer<sup>a</sup>, F. Marchese<sup>a</sup>, D. Mesples<sup>a</sup>

<sup>a</sup> *European Space Operations Centre (ESOC-ESA), Darmstadt, Germany*

\* Corresponding Author, [eduardo.zornoza@esa.int](mailto:eduardo.zornoza@esa.int)

### Abstract

During the first decade of this twenty first century, the European Space Operations Centre (ESOC) was tasked with the development, implementation and operation of a Flight Operations Segment (FOS) to support a first series of Sentinels missions, i.e. Sentinel-1, Sentinel-2 and Sentinel-3. Despite the existing differences at satellite and mission level between the various missions, and in view of their common programmatic management it was decided to approach these in a common manner, making an effort to identify synergies, to envisage common procurements of ground segment elements (such as Mission Control System, Network Data Interface Units, Main Key Management Facility) and services, such as external ground station services.

This effort materialised in a fully operationally proven and flying Flight Operations Segment, which today is executing operations of five Sentinel spacecraft (Sentinel-1A, 1B, 2A, 2B 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.

But challenges do not stop for this fully operational FOS. Preparation activities are progressing fast towards the launch of the C and D models of the first three Sentinel missions and of Sentinel-6B. And on top of this, the FOS has started preparing for the arrival of the six Sentinel Expansion missions, a new family of missions that intends to cover the gaps and expand the current capabilities of the Copernicus Space Component.

This paper presents the variety of technical challenges that the adoption of this set of modern missions represents for a fully operational FOS, as new satellite and/or ground technologies are required, such as:

- the adoption of the Ka radiofrequency band for the communications in the area of scientific data downlink;
- the incorporation of file-based transfer of data between ground and the satellite, making use of the CCSDS File Delivery Protocol (CFDP);
- the adoption of the CCSDS Space Data Link Security protocol for the authentication of the uplink communications;
- and last but not least the evolution of the ground infrastructure, the most major change being the adoption of a new mission control system baseline, departing from the SCOS-2000 software system used during over two decades into a more modern system based on EGS-CC, to be deployed while the previous infrastructure needs to be maintained for some years still.

The push for evolution is undoubted, but so is the need to maintain safe and efficient operations, while maintaining the established external interfaces, of ESOC's proven and flying Sentinels Flight Operations Segment.

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

## Acronyms/Abbreviations

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)  
ESA Ground Operation System – Common Core (EGOS-CC)  
European Space Agency (ESA)  
European Space Operations Centre (ESOC)  
European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)  
Flight Dynamics System (FDS)  
Flight Operations Control Centre (FOCC)  
Flight Operations Segment (FOS)  
Ground Station Distributed CFDP System (GS-DCFDP)  
Mission Control System (MCS)  
Main Key Management Facility (MKMF)  
Mission Planning System (MPS)  
Mission Control Core based on Common Core (M4C)  
Network Data Interface Units (NDIU)  
Protocol Data Unit (PDU)  
Satellite Control and Operation System 2000 (SCOS-2000)  
Space Data Link Security (SDLS)  
Space Debris Office (SDO)  
Variable Coded Modulation (VCM)

## 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 five Sentinel spacecraft (Sentinel-1A, 1B, 2A, 2B 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 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.

This article presents the main evolutions required within the FOS to support the operations of the above mentioned Sentinel Expansion missions together with the constraints imposed by existing ground segment, the available and planned facilities and by the needs for cost effective operations.

## 2. Overview of the Flight Operations Segment

The FOS, as part of the overall Copernicus Space Component, will provide 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 require 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).

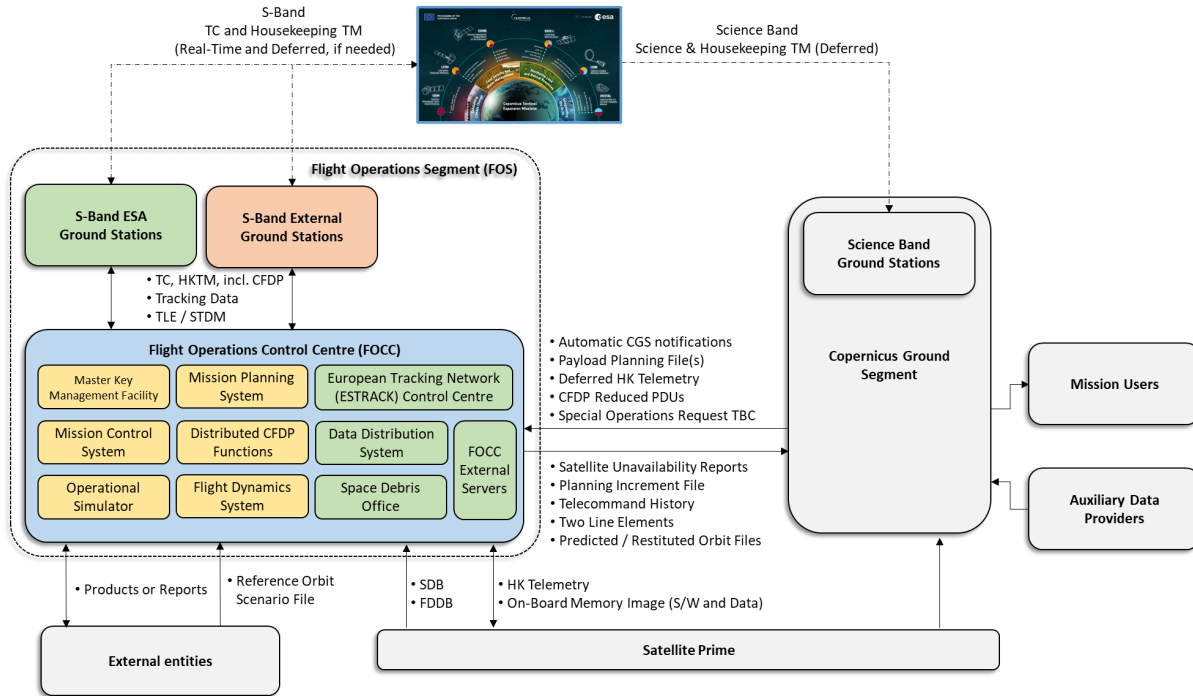


Figure 1 – Sentinel Expansion system overview (FOS centric view)

### 3. Main evolutions and developments driven by the Sentinel Expansion missions

ESOC is currently operating a number of Sentinel missions (among many other Earth Observation missions) and preparing, at the same time, for more to be launched. At ground segment level the commonalities amongst all these missions are so large that all FOS systems have been already designed and implemented following generic principles aiming at maximising re-usability through extensive use of modular and configurable components.

Most of the FOS main systems and facilities required in support of the Sentinel Expansion missions are therefore already operational and have been exhaustively validated by numerous pre- and post-launch activities. The delta functionality required in the Sentinel Expansion FOS stems from the following main evolutions:

1. 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.
2. Adoption of the CCSDS File Delivery Protocol (CFDP) [2] as underlying protocol for file transfer.
3. In the area of security, adoption of the CCSDS Space Data Link Security protocol [3].
4. Evolution from the ECSS Packet Utilisation Standard A to C (PUS-C) [4] which features, amongst others, new parameter types, services and an approach for commanding persistent activities to the spacecraft.
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.

#### 3.1 File Based Operations

The capability to manage and transfer data via files is requested for the Sentinel Expansion missions. The usage of files will guarantee the integrity of the transferred data, without any manual intervention from ground. Moreover, in the longer term, the usage of files will enable the pre-processing on-board files and remove the packet structure constraint when managing data.

For commanding activities, the FOS will mainly uplink the following types of file to the space segment:

- TC Files for immediate execution, e.g. in order to populate an on-board schedule.
- TC Files for delayed execution, e.g. standalone and self-contained satellite configuration activity to be executed at a given time or at a given PSO.
- Raw Files, to uplink software patches.
- OBCP Files, to upload new or updated definitions of On-Board Control Procedures.

As an example, Figure 2 presents the on-board schedule uplink use case (TC file for immediate execution). It assumes that the corresponding commanding product is already available (i.e. output from the mission planning activity).

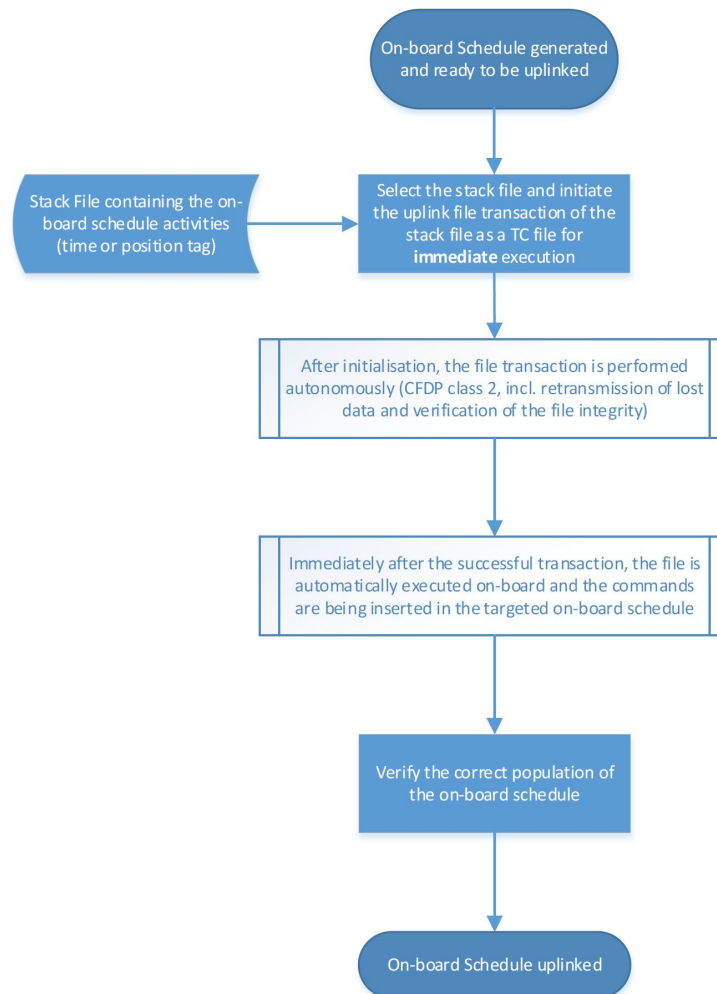


Figure 2 – On-board Schedule uplink via File Based Operations

For what concerns monitoring activities, files will be mainly used to downlink recorded telemetry data. Telemetry packets will be stored within files, which will be subsequently transferred during a pass. An on-board autonomous function, referred to as “downlink manager”, monitors a set of directories in the on-board file system(s). When activated, a downlink manager resumes all suspended file transactions it initiated (if any) and initiates if possible new file transaction(s) based on file downlink priority and age. Figure 3 presents the operational use case whereby on-going file transaction are suspended at the end of a ground station pass and resume at the beginning of the subsequent one.

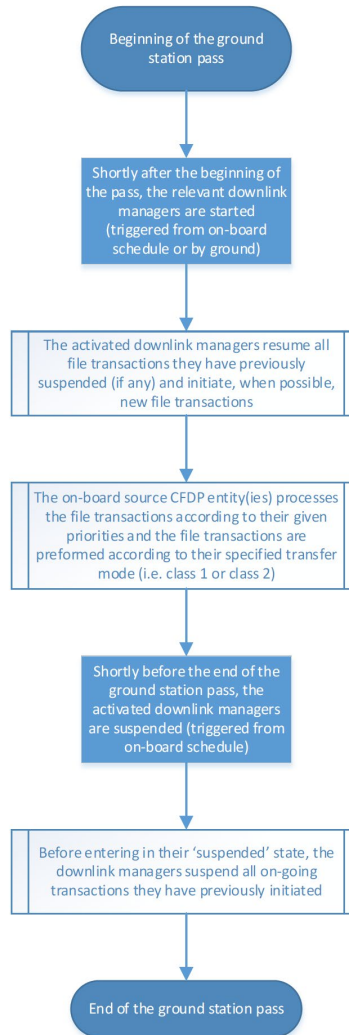


Figure 3 – Data downlink via File Based Operations

### 3.2 CFDP and Distributed CFDP (DCFDP)

The protocol to be used for the transfer of files is CFDP. But the system architecture differs depending on whether one considers the uplink or the downlink transactions.

- Because of their asynchronous nature and the relative low data rate and volume of data to be transferred, uplink transactions can be performed ‘point-to-point’. The Mission Control System will implement a CFDP source entity that will send data to a CFDP destination entity, which is a function of the satellite’s On-Board Computer software. These transactions can be performed in unreliable (class-1) or reliable (class-2) mode, the latter being the baseline for transactions over the S-band link.
- For the downlink, however, to be able to support higher data rates and transactions spreading over different ground stations, a distributed architecture will be implemented.

This architecture is depicted in different levels of detail in Figure 4 and Figure 5. The concept is that ground CFDP destination entity handling the downlink of files is distributed over the Flight Operations Segment (FOS). This approach allows to drastically reduce the real-time data traffic between the Flight Operations Control Centre (FOCC) and the TT&C ground stations.

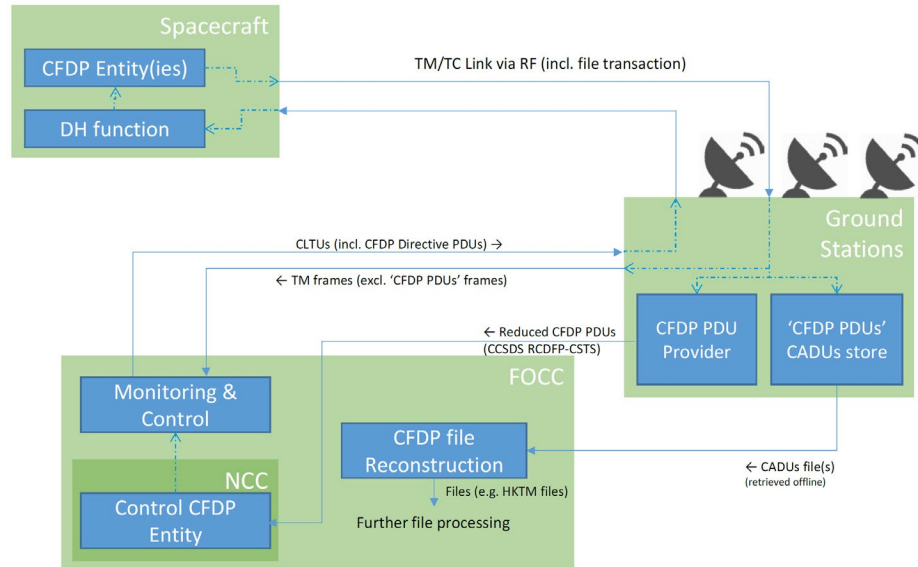


Figure 4 – Flight Operations Segment with Distributed CFDP systems (in red)

The architecture introduces three new systems with respect to the previous architecture of the Sentinels Flight Operations Segment (see Figure 5):

- A Ground Station Distributed CFDP System (GS-DCFDP) which receives transfer frames from one or several (high-rate) modems or demodulators, re-constructs the CFDP Protocol Data Units (PDUs), “reduces” them in size and forwards them to the CC-DCFDP thanks to a ‘Return CFDP PDU Service Provider’ [5].
- A Control Centre Distributed CFDP System (CC-DCFDP), which contains a ‘Return CFDP PDU Service User’, receives the “reduced” CFDP PDUs, detects gaps in the file data due to losses on the space link and generates the required directive PDUs to close the transaction.
- And a CFDP File Reconstruction System, which retrieves the TM stored at the ground station in an off-line manner and reconstructs the on-board files before making them available to the Mission Control System.

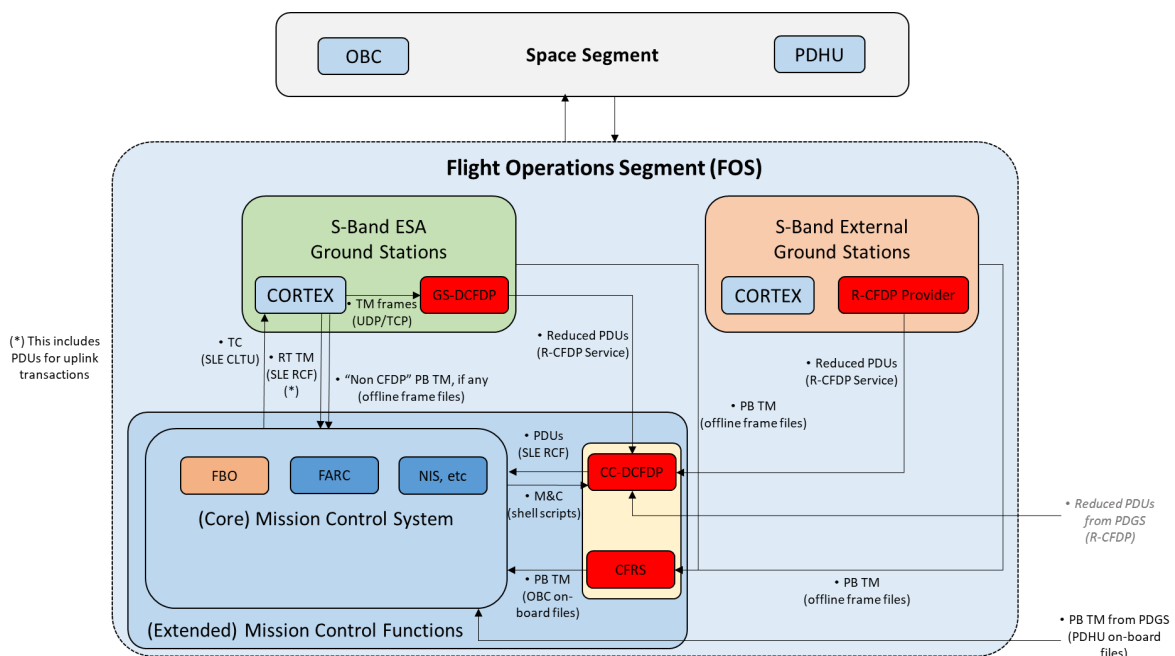


Figure 5 – Flight Operations Segment with Distributed CFDP systems (in red)

It shall be noted that the Distributed CFDP concept is “data and communication channel agnostic” and can be used in principle to manage any transaction of files from the space segment to any ground segment. However, the architecture presented is that of the Sentinel Expansion Flight Operations Segment, and its scope is only the TT&C frequency band (S-band).

### 3.3 CCSDS Space Data Link Security protocol

In order to adapt to the upgrades in the area of authentication and in particular to the new CCSDS SDLS standard ([3]), the Sentinel Flight Operations Segment will require 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), which is integrated in the Mission Control System, and which will be responsible for generating the Authentication Field for all telecommands and for encrypting the Packet Data Field of those telecommands identified in the Operational Data Base as requiring it .

The main changes are:

- Length, number and format of keys.
- TC and TM transfer frame structure (Figure 6 and Figure 7).
- The concept of Security Associations, which govern the secure communications parameters (pairs of Global Virtual Channel Identifiers, GVCID and Global MAP Identifiers, GMAP IDs) to be used by both the sending and receiving ends of a communications session.
- Support to the new Key Verification functionality (Figure 8).
- Export format to the various suppliers of Authentication Units, satellite primes and the Mission Control System.



Figure 6 – TC transfer frame with SDLS

The security header contains the Security Parameter Index (SPI) and an Anti-Replay Sequence Number (ARSN). The SPI is used to uniquely identify a security association applicable to a transfer frame. The ARSN is used to detect and prevent unauthorized reception of previously transmitted data. The security trailer conveys the Message Authentication Code (MAC). The MAC is computed over the frame VCID, the segment header, the security header and the frame data field (i.e. the telecommand packet conveyed by the frame). It is used to perform the cryptographic authentication of the source of the telecommand.

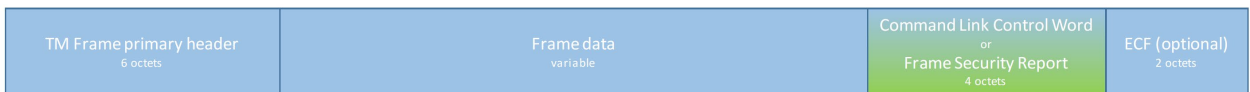


Figure 7 – TM transfer frame with SDLS

The FSR contains a brief report of the on-board authentication function:

- an Alarm Field which indicates if a TC transfer frame has been rejected by the security function
- Security Events Flags, which indicates whether the frame was rejected because of an invalid ARSN, an invalid MAC or an invalid SPI
- the SPI carried in the last TC frame received by the security function
- the 8 least significant bits of the ARSN carried by the last TC frame received by the security function

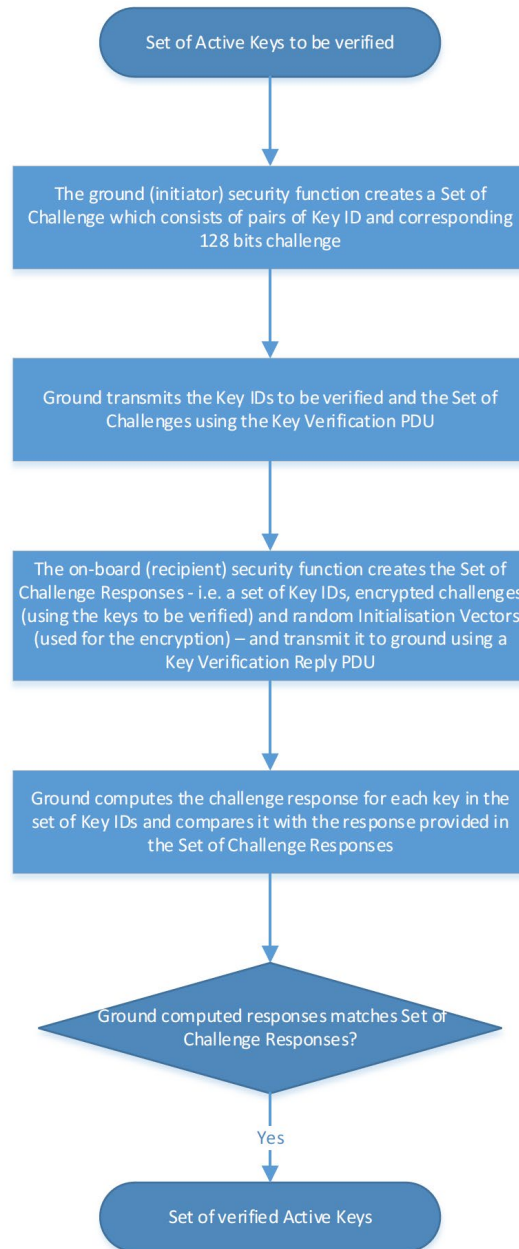


Figure 8 – Key Verification SDLS extended procedure

### 3.4 ECSS Packet Utilisation Standard C (PUS-C) and new mission control system baseline

These two evolutions, while independent in nature, are presented together as they primarily focus on the mission control system.

The new PUS-C standard features, amongst others:

- new parameter types, such as relative CDS time format or packet fields (PTC=12).
- new telecommand and telemetry services covering functionality which used to be implemented via private services, e.g. Parameter Management (PUS 20), Request Sequencing (PUS 21), Position-based Scheduling (PUS 22, supporting the commanding of persistent activities) and File Management (PUS 23).
- Slight changes in packet structure, including 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).

These evolutions are being incorporated into the SCOS-2000 software system used during over two decades in ESOC, which will be used to operate the first of the Sentinel Expansion missions (CO2M) and which will remain as back-up solution for the other five. However, as prime solution for the latter missions, a more modern system based on the European Ground Systems – Common Core (EGS-CC) is being developed. The functional scope of this system, Mission Control Core based on Common Core (M4C), is very similar to the SCOS-2000. The majority of the functionality is provided by EGS-CC, but when a required functionality is outside of the scope of EGS-CC, it is provided by the M4C extension.

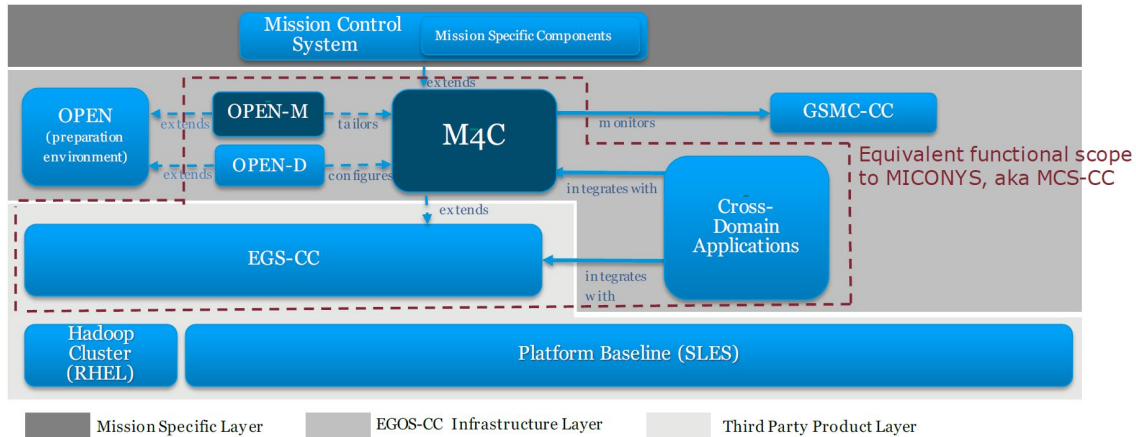


Figure 9 – Overview of ESOC’s new generation Mission Control System

### 3.5 Ka radiofrequency band for scientific data downlink

While the Flight Operations Segment continues to communicate with the satellites for TT&C using the S-band, the adoption of Ka-band for the downlink of scientific data has a set of implications in satellite operations:

- The higher directivity of communications in the Ka-band frequency with respect to X-band results in the need for the satellite to embark a steerable antenna, which needs to be pointed towards the target ground station.
- Depending on the pointing performance of the on-board antenna and the satellite itself, the needs will be analysed for ground’s orbit determination in terms of required time span, periodicity and accuracy.
- As a result of the higher sensitivity to atmospheric conditions, Variable Coded Modulation (VCM) [6] has been introduced to optimise the Ka-band link margin as a function of the ground station pass elevation profile.

## 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. Today this Flight Operations Segment:

- is executing flight operations of five Sentinel spacecraft (Sentinel-1A, 1B, 2A, 2B and Sentinel-5p),
- was in charge of flight operations during the initial flight phases of Sentinel-3A, 3B and Sentinel-6 MF, until handed over to EUMETSAT,
- is now preparing for the launch and flight operations of seven more models of the first Sentinel generation (Sentinel-1C, 1D, 2C, 2D, 3C, 3D and 6B),
- and is now adapting and incorporating the required evolutions, as presented in this paper, to support a full new generation of spacecraft, the six Sentinel Expansion missions.

The push for evolution is undoubted, but so is the need to maintain safe and efficient operations, while maintaining the established external interfaces, of ESOC’s proven and flying Sentinels Flight Operations Segment.

## 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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