SpaceOps-2025, ID # 379

Preparation for Routine File-Based Operations using CFDP for the Copernicus CO2 Monitoring Mission

E. Valido Cabrera[a*], F. Di Loreto[a], N. Larrea[a], K. Davies[b], A. Loretucci[a], M. Pantaleoni[a], C. Putignano[a], S. Tarquini[a]

[a] *European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), Darmstadt, Germany*
[b] *Terma GmbH, Darmstadt, Germany*
* Corresponding Author: Eduardo.Valido@eumetsat.int

Abstract

As part of the Copernicus component of the EU Space Programme, the European Space Agency (ESA) and EUMETSAT are preparing for the expansion of the Copernicus Space Infrastructure with new observation capabilities including the development of an Anthropogenic CO2 Monitoring mission (CO2M).

Through a Contribution Agreement with the European Union, EUMETSAT was entrusted to contribute to the development of a significant part of the CO2M ground segment and is responsible for the routine operations of the CO2M mission. It will be the first mission operated by EUMETSAT to make use of fully file-based operations and the CCSDS File Delivery Protocol (CFDP), for spacecraft data management and transfer between the spacecraft and ground systems.

File-based operations have been gradually introduced in space missions over the last 20 years or more, initially as bespoke mission-specific implementations (e.g. as a derivation of the Large Packet Transfer Service S13 of the ECSS Packet Utilisation Standard combined with mission specific services), and later evolving towards standards in efforts to reduce development and operations costs. The CFDP is part of this evolution.

File-based operations and CFDP are already in use for several space missions, such as ESA's Euclid mission. However, CO2M is the first large system that will use CFDP for both data upload and data download in the context of an Earth observation mission using low-Earth orbiting (LEO) spacecraft.

Keywords: CO2M, CFDP, File-based Operations (FbO), Onboard File Reconstruction

Acronyms/Abbreviations

AOS	Acquisition of Signal
CADU	Channel Access Data Unit
CFDP	CCSDS File Delivery Protocol
CFS	CADU File Segment
CLTU	Command Link Transfer Unit
FbO	File-based Operations
FM	Flight Model
ISP	Instrument Source Packets
LOS	Loss of Signal
OBC	On-Board Computer
OBCP	On-Board Control Procedures
OGS	Operational Ground Segment
PDHU	Payload Data Handling Unit
PDU	Protocol Data Unit
PFM	Proto-Flight Model
SLE	CCSDS Space Link Extension
SLE-RCF	Space Link Extension Return Channel Frames

1. Introduction

The CO2M satellites will feature fully File-based Operations (FbO) and will implement the CCSDS File Delivery Protocol (CFDP) [1] for the exchange of files between the space and ground segments both in S-Band (monitoring and control) and Ka-Band (payload data). The satellites will be able to support transactions in both unacknowledged and acknowledged mode and will implement the functionality to operate in both CFDP service classes:

- Class 1, providing unreliable delivery of data files from the source to the destination over simplex connection, without retransmission of corrupted data.
- Class 2, providing reliable delivery of data files from the source to the destination, over a duplex connection, with retransmission of missing or corrupted data.

In preparation for the routine operations of the CO2M satellites, EUMETSAT has completed the critical design phase and is well advanced with the development phase of the Operational Ground Segment (OGS) for CO2M. The CO2M OGS will implement the CFDP entities responsible for the exchange of files with the On-Board Computer (OBC) in S-Band (uplink and downlink) and with the Payload Data Handling Unit (PDHU) in Ka-Band (downlink only) for the reception of Payload Data. To support the implementation of the CFDP protocol on ground, the OGS will rely on the *Ground Station Distributed CFDP* (*GS-DCDFP), Control Centre Distributed CFDP (CC-DCFDP)* and *CFDP File Reconstruction System (CFRS)* software components developed by the European Space Agency (ESA) [2] plus a newly developed component, the *CFDP Front-End Processor and File Reconstructor (CFEP)*, responsible for the reconstruction of the on-board files downlinked by the PDHU as a stream of CADUs over the Ka-Band link.

The CFEP will feature an interface with ESA's Copernicus Space Component (CSC) Ground Segment for the collection of CADUs made available by ESA's Copernicus Ground Segment through the CADU Interface Point (CADIP). Additionally, not only will the CFEP reconstruct the onboard files but will also maximise the data return in case of missing or corrupted Protocol Data Units (PDUs) when operating in Class 1 (operational baseline for payload data) as explained in section 4.

CO2M is the first of a series of CFDP-based satellites to be operated by or with contribution from EUMETSAT that will benefit from this development.

2. High-level CFDP Implementation in CO2M

CFDP is an integral part of the File-based Operations concept and will be used to exchange the following file types between the CO2M space and ground segments:

- TM-FILE: Files containing Telemetry (TM) packets
- TC-IMM-FILE: Files containing Telecommand (TC) packets for immediate execution
- TC-DLY-FILE: Files containing TC packets for Delayed (later) execution
- OBCP-FILE: Files containing On-Board Control Procedure (OBCP) byte code
- RAW-FILE: Files containing raw data (unformatted Byte value) for e.g. on-board software maintenance
- TM-FILE-COMP: compressed Files containing TM packets (when file compression is available)

Two independent CFDP Entities hosted by the OBC and PDHU respectively aboard each one of the CO2M spacecraft, and one on ground (hosted by the MCOS and implemented across the FbO and CC-DCFDP components) will deal respectively with the exchange of files between the On-Board Computer (OBC) and the Mission Control and Operations Sub-Segment (uplink and downlink in S-Band), and between the Payload Data Handling Unit (PDHU) and the Mission Data Processing Sub-segment (downlink only in Ka-Band). The following table shows the different CFDP entities defined for the CO2M System:

CFDP entity ID (mnemonic)	Values dec (Hex)	Description
OBC_PFM_ENTITY_ID	**48** (0x30)	OBC PFM (CO2M-A)
PDHU_PFM_ENTITY_ID	**49** (0x31)	PDHU PFM (CO2M-A)
OBC_FM2_ENTITY_ID	**50** (0x32)	OBC FM2 (CO2M-B)
PDHU_FM2_ENTITY_ID	**51** (0x33)	PDHU FM2 (CO2M-B)
S_BAND_GROUND_ENTITY_ID	**58** (0x3A)	For MCOS (Monitoring and Control)
KA_BAND_GROUND_ENTITY_ID	**59** (0x3B)	For MDPS (Payload Data)

Table 1: CFDP Entity IDs for CO2M

Note: CO2M-C has been recently approved, and the baseline documentation is under review to include the CFDP Entity IDs for FM3.

The operational baseline for CO2M is:

- ✓ **CFDP Class 2** (Reliable Transfer) for transactions in S-Band, i.e. between the CFDP entities *OBC_PFM/FM2/FM3* and *S-Band Ground*, for the exchange of monitoring and control data (TM-FILE, TC-IMM-FILE, TC-DLY-FILE, OBCP-FILE, RAW-FILE and TM-FILE-COMP)
- ✓ **CFDP Class 1** (Unreliable Transfer) for transactions in Ka-Band, i.e. between the CFDP entities *PDHU_PFM/FM2/FM3* and *Ka-Band Ground*, for the transmission of payload data (TM-FILE and TM-FILE-COMP).

It is important to note, however, that both CFDP Entities aboard the CO2M satellites can operate in Class 1 and in Class 2, and it would be thus possible to evolve the CO2M system and the operations concept at a later stage to operate the CO2M satellites in CFDP Class 2 also for payload data, should the need arise. Yet, the baseline for the design of the CO2M OGS is CFDP Class 2 for monitoring and control data (S-Band) and Class 1 for payload data (Ka-Band).

The figures below show the CFDP transactions between on-board and ground CFDP entities for uplink in S-Band and downlink in S-Band and Ka-Band, indicating the relevant CFDP PDUs (M=Metadata, FD=File Data, EOF=End Of File, NAK/ACK=Negative/Positive Acknowledgment, FIN=Finished) encapsulated in CCSDS TM / TC packets:

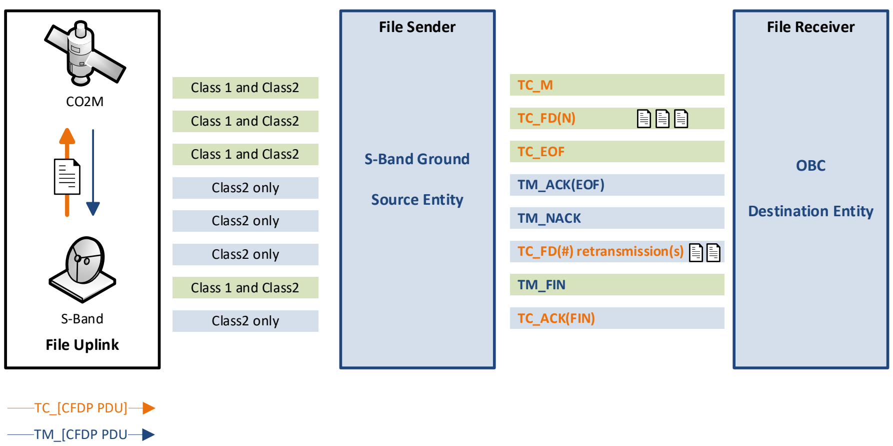


Figure 1: CFDP PDUs File Uplink in S-Band

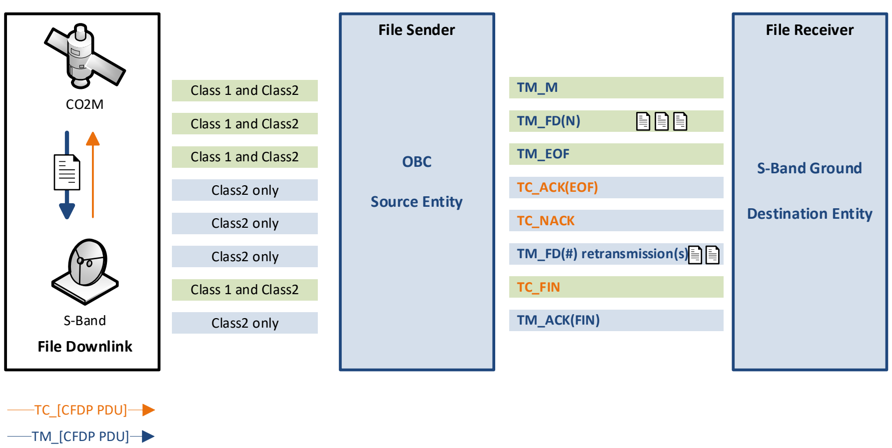


Figure 2: CFDP PDUs File Downlink in S-Band

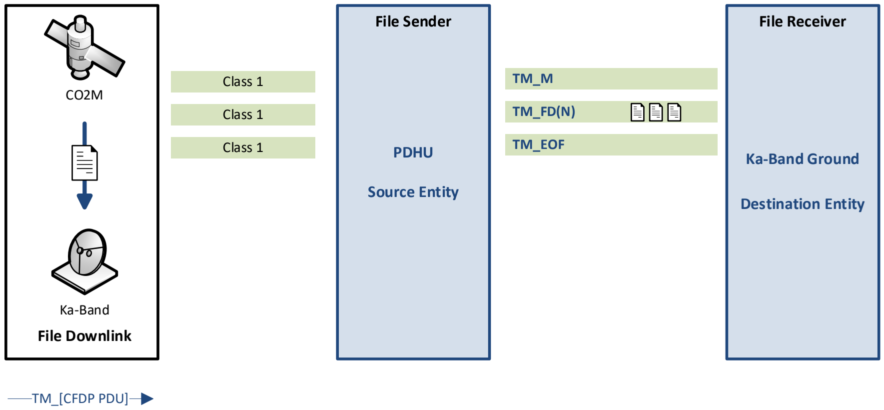


Figure 3: CFDP PDUs File Downlink in Ka-Band

CFDP PDUs are encapsulated into dedicated CCSDS Space TM or TC packets for being transferred between the file sender and receiver as indicated in the figure below. It should be noted that the satellite implements two different version of the CFDP Standard [1]: B4 for the OBC, and B5 for the PDHU. The different versions of the standard have implications in the format of the CFDP PDUs and packet formats (for example, the CFDP PDU header has a length of 12 and 8 bytes for the OBC and PDHU, respectively) to be managed by the CO2M OGS.

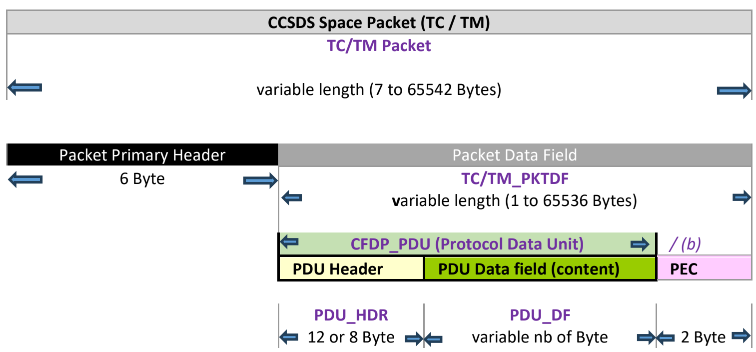


Figure 4: CFDP PDU Encapsulation into CCSDS Space Packet

3. Distributed CO2M CFDP Architecture

The CO2M Operational Ground Segment (OGS) comprises the four major blocks, split between EUMETSAT and ESA organisations, depicted in *Figure 5*:

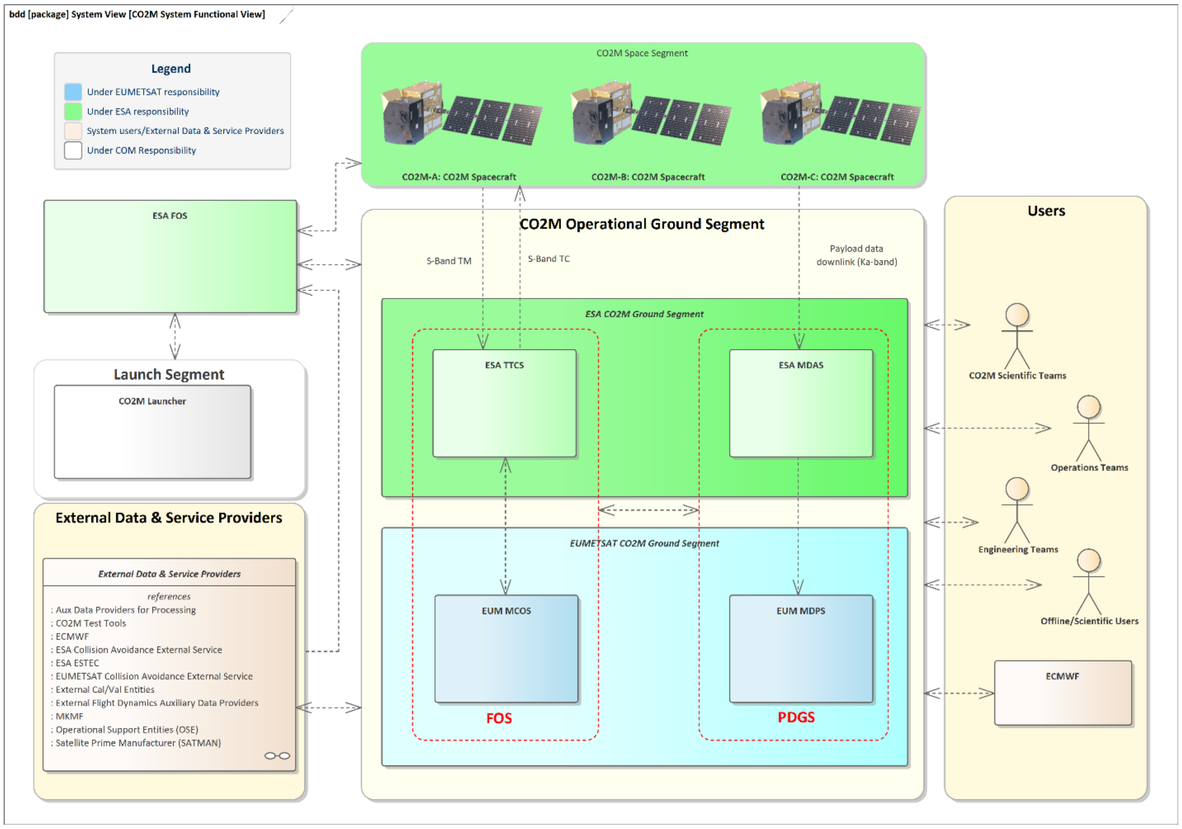


Figure 5: CO2M Operational Ground Segment

Telemetry Tracking & Commanding Sub-Segment (TTCS) ensuring space to ground communication link in S-Band for the acquisition of housekeeping telemetry data, uplink of telecommands and provision of ranging measurement data. The TTCS will be a service provided by ESA during the CO2M mission lifetime.

Mission Control and Operations Sub-Segment (MCOS), in charge of the monitoring and control of the satellites, through TTCS, during system commissioning, routine operations and disposal phases.

Mission Data Acquisition Sub-Segment (MDAS) ensuring space to ground communication link in Ka-band for the reception of the payload raw data as well as housekeeping telemetry data over the mission data link. The MDAS will be a service provided by ESA during the CO2M mission lifetime.

Mission Data Processing Sub-Segment (MDPS) in charge of the mission data retrieval from MDAS, reconstruction and processing, archiving and dissemination of the generated payload data products.

The implementation of the CFDP inside the EUMETSAT's CO2M Operational Ground Segment follows the distributed architecture depicted in *Figure 6* (only main elements involved in CFDP handling are shown):

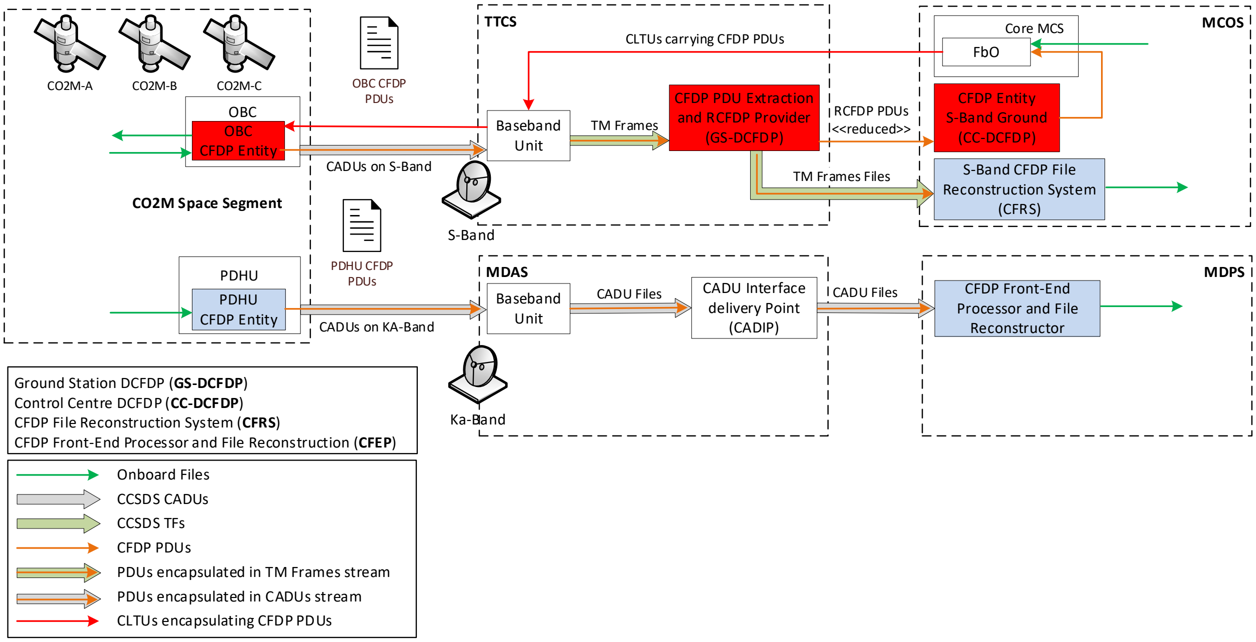


Figure 6: CO2M Operational Ground Segment - CFDP Distributed Architecture

The exchange of **monitoring and control data in S-Band** (uplink and downlink) is done across two CFDP Entities operating in Class 2, the on-board CFDP entity *OBC* and the CFDP entity *S-Band ground* in MCOS implemented with support of ESA's DCFDP components distributed across the TT&C Ground Stations (GS-DCFDP) and the Control Centre (CC-DCFDP):

<u>For the downlink (class 2)</u>

- The onboard CFDP Entity inside the **OBC** initiates the downlink of files and generates the necessary CFDP PDUs (as per *Figure 2*) which are encapsulated into CCSDS TM Packets, TM Frames and eventually into CADUs downlinked in S-Band.
- The TTCS ground stations acquire the CADUs and forwards the TM Frames to the **GS-DCFDP** responsible for:
    - Reception of TM Frames from GS demodulators
    - Writing the frames to disk
    - Extracting CFDP PDUs
    - Generation of reduced CFDP PDUs
    - Provision of reduced CFDP PDUs to CC-DCFDP through R-CFDP
- At the MCOS, the **CC-DCFDP** is responsible for:
    - Receiving Reduced CFDP PDUs through R-CFDP
    - Monitoring CFDP transactions
    - Generation of uplink CFDP PDUs (file downlink response) and provision to the **FbO** component (as per *Figure 2*) for uplink of information about corrupted PDUs that need to be re-transmitted to ground, or to finish transactions
- At the MCOS, the S-Band File Reconstructor - **CFRS** is responsible for:
    - Ingestion of TM Frame files
    - Extraction of CFDP PDUs from frame files
    - Reconstruction of the on-board files from CFDP transactions

<u>For the uplink (class 2)</u>

- The CFDP Entity **S-Band ground** hosted by MCOS (**FbO** component) initiates the uplink of TC Files and generates the necessary CFDP PDUs (as per *Figure 1*) which are encapsulated by the Mission Control Subsystem into CCSDS TC Packets, TC Frames and eventually into Command Link Transfer Units (CLTUs) to be provided to the TTCS stations for uplink in S-Band.
- The OBC entity receives the CFDP PDUs and generates the CFDP PDUs (positive / negative acknowledgements and finished directive as per *Figure 1*)

- The TTCS ground stations acquire the CADUs and forwards the VC4 TM Frames including CFDP PDU directives to the **GS-DCFDP** component responsible for:
  - Reception of TM Frames from GS demodulators
  - Writing the frames to disk
  - Extracting CFDP PDUs
  - Generation of reduced CFDP PDUs
  - Provision of reduced CFDP PDUs to CC-DCFDP through R-CFDP
- At the MCOS, the **CC-DCFDP** is responsible for:
  - Receiving CFDP PDUs through R-CFDP
  - Provision (forwarding) of CFDP PDUs (as per *Figure 2*) related to uplink transactions (file uplink response) to the **FbO** component
- At the MCOS, the **FbO** component of the Mission Control Subsystem is responsible for:
  - Receiving CFDP PDUs through SLE RCF from CC-DCFDP
  - Extracting the CFDP PDU directives (ACK/NACK/FIN) and monitoring CFDP transactions
  - Generation of uplink CFDP PDUs (including retransmission of missing PDUs) and provision to the TTCS ground stations for uplink

The reception of **payload data in Ka-Band** in class 1 is done with the on-board CFDP entity in the *PDHU* operating in Class 1 and the CFEP extracting from CADU File Segments (CFS - files composed by a sequence of acquired CADUs) prepared at MDAS, the CFDP PDUs and reconstructing the onboard files:

<u>For the downlink (class 1)</u>

- The **PDHU** initiates the downlink of TM Files and the PDHU CFDP Entity generates the necessary CFDP PDUs (as per *Figure 3*) which are encapsulated by the PDHU into CCSDS TM Packets, Advanced Orbiting Systems (AOS) Transfer Frames and eventually into CADUs downlinked in Ka-Band.
- The MDAS ground stations acquire the CADUs and forwards them as CFS to the CADU Interface delivery Point (CADIP).
- At the MDPS, the **CFEP** is responsible for:
  - Collection and Ingestion of CFS from the CADIP
  - Extraction of CFDP PDUs from AOS frames
  - Reconstruction of the CFDP Files from transactions
  - Distribution of onboard ISP RAW Files to the PDP for the nominal mission data processing
  - Distribution of onboard HKTM files to MCOS

3.1 Justification of the Architecture

The Distributed CFDP architecture has been developed [2, 3] considering the high data rates on the Space to Ground link and the nature of low earth orbiting satellites, with short ground station visibilities requiring real-time protocol closure spanning across different passes and even across different ground stations. The concept relies on reduced CFDP PDUs generated at the ground station that will provide all the necessary information for detecting missing segments on the downlink, thus avoiding the forwarding of the actual file data to the control centre. The protocol closure will be naturally centralised at the MCS in the control centre, that will be in charge of issuing any uplink PDUs required (for retransmission requests or file directives to finish transactions). The reconstruction of the on-board files takes place in an off-line fashion: the transfer frames are transferred after the pass to the control centre for further reconstruction and utilisation.

4. CFDP Front-End Processor and File Reconstructor (CFEP) for Payload Data

CFEP is a major element of the CO2M Mission Data Processing Sub-Segment (MDPS). It is concerned with the extraction of mission payload data sensed by CO2M satellites and made available as CFS via ESA's MDAS CADIP. The component reconstructs the received on-board instrument telemetry data (TM-files containing ISPs) and provides them to CO2M Payload Data Processing (PDP) production chain and to the Multi-Mission Elements Data Access Services (MME DAS), according to the required interface needs of these systems.

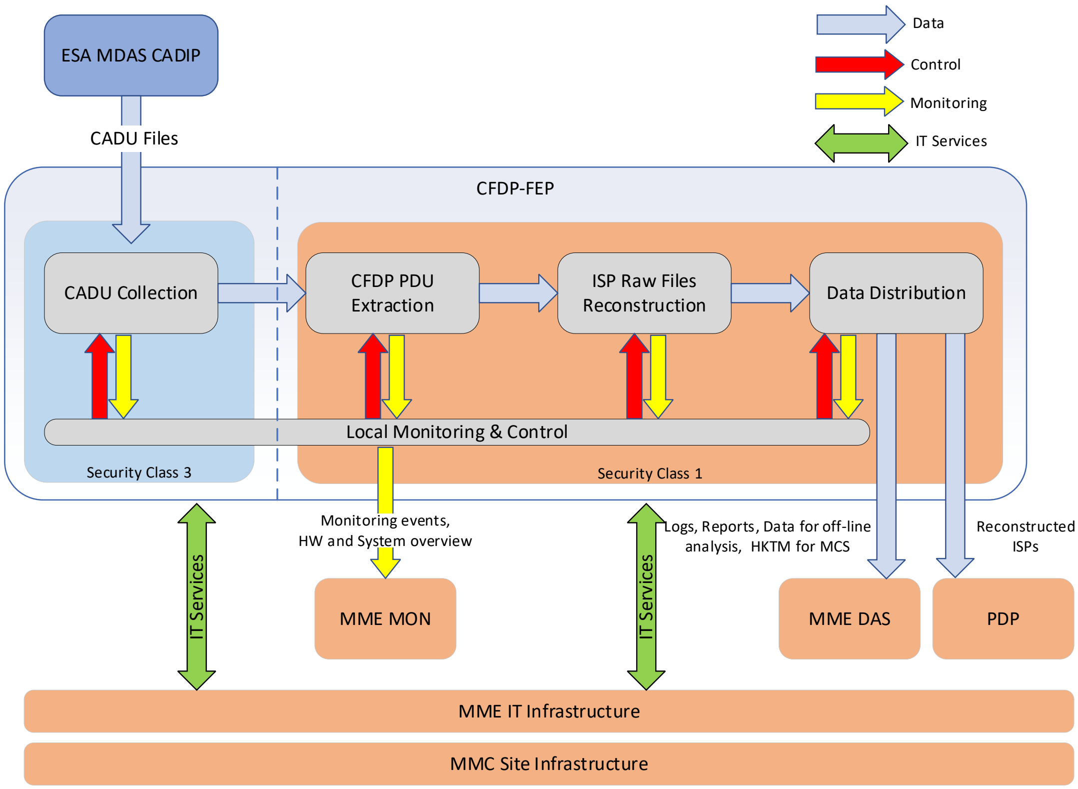


Figure 7: CFDP Front-End Processor and File Reconstructor (CFEP) for Payload Data

Figure 7 provides a comprehensive overview of the high-level decomposition of CFEP into the major sub-components (presented in grey colour), being:

- CADU Collection (named CCS in the remainder of this document). CCS is responsible for collection of the CFS data the Ground Station made available at MDAS CADIP.
- CFDP PDU Extraction (named PE in the remainder of this document). PE obtains the CFS files from CCS, inspects the content and assembles information to allow extraction of the whole set of PDUs composing each single TM file as provided in the content of the CFDP Transactions.
- ISP Raw Files Reconstruction (named RIRF in the remainder of this document). RIRF obtains the extracted PDUs in which each single onboard TM file has been chunked, and re-builds and provides it forward for dissemination. The RIRF is also taking care of:
    - (re-)profiling TM files like for instance, creating small overlaps between contiguous granules, filtering-out packets of certain type/subtype combination, changing the granule size according to the needs of the MDPS production chain.
    - TM Packets recovery in case of corrupted and missed data.
- Data Distribution (named DD in the remainder of this document). DD obtains the reconstructed TM files outputs from RIRF and disseminates these to the PDP and MME DAS systems.
- Local Monitoring & Control (named LMC in the remainder of this document). The operation of CFEP sub-components is controlled and monitored by the local M&C (LMC) sub-component which is also the access point to CFDP-FEP for the user interface (HMI).

The operational baseline for the payload data dumped in Ka-band is to use the CFDP protocol according to Class 1 – unreliable transfer, without the possibility of re-transmitting corrupted data. In this scenario, it is important that the CFEP can continue the TM file reconstruction process also in case of missed / corrupted data in the input CADUs stream, discarding corrupted / incomplete ISP packets, while continuing the reconstruction process and recovering from non-nominal situations. The CFEP component has been designed to be robust against input data corruption and can continue reconstructing the TM files, going beyond CFDP Entity nominal behaviour that would discard a corrupted file.

4.1 CFDP-FEP: Recovery of Corrupted and Missed Data

The approach is based on the concept of preservation of anomalous data present in CFS file fragments alongside good data during PDUs extraction. The ISP Raw Files reconstruction sub-component (RIRF) receives PDUs extracted from the CFS files. In the nominal case this data is the content of the complete set of CFDP file-data PDUs which have been extracted from CADUs, transfer-frames and CFDP TM encapsulation packets, each of which were fully and correctly formed.

In the non-nominal cases, data present in CFS file fragments might have been corrupted during the space to ground transmission and the data received by RIRF will contain a combination of PDUs extracted from well-formed CFDP TM packets plus one or more of the following:

- file-data PDU content extracted from packets affected by some kind of anomaly.
- fragments from the CFS file containing data which could not be extracted due to some anomalous condition.

Figure 8 describes the situation in which few CADUs are either lost or corrupted affecting two CFDP PDUs. In the first case, the header of the packet encapsulating PDU 3 is affected such that it can't be identified as a packet. In either case the remaining packet content are retained as malformed packet data. The RIRF transaction scanning & repair function initially discovers the first part of ISP 7 and identifies it as a corrupted packet. The algorithm then searches for the first legal packet (ISP 10). The file has already been marked as 'corrupted' at the extraction stage. Each ISP is checked for legality by CRC.

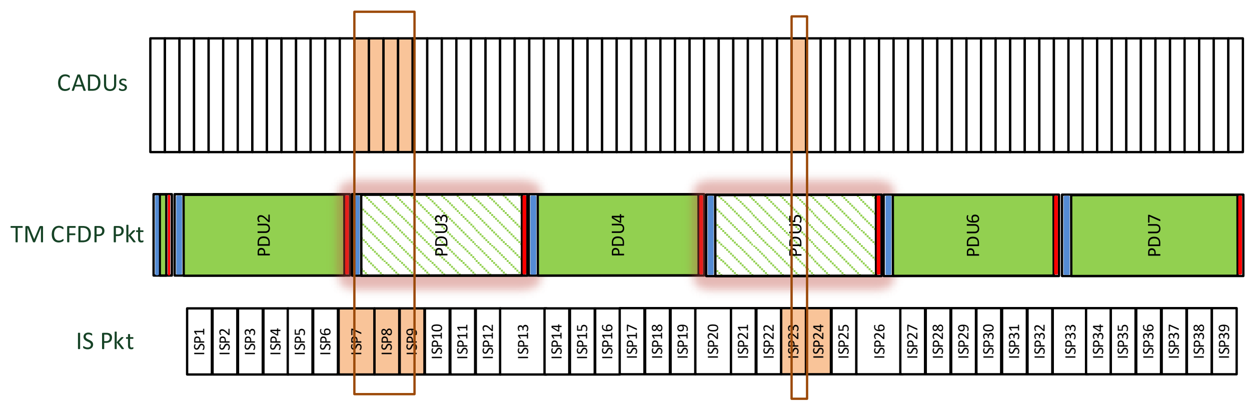


Figure 8: Few CADUs are either lost or corrupted affecting two CFDP PDUs

In *Figure 9*, corruptions affected two complete PDUs (3 and 5) and partially the PDU 4. This implies that PDUs 3 and 5 are entirely missing from the CFS file. Again, file has already been marked as 'corrupted' at the extraction stage. Each ISP is checked for legality by CRC. Upon encountering ISP 7 as invalid the algorithm searches for the next legal packet, ISP 16, then encounter another corrupted packet at ISP 18 and start again searching until arriving at ISP 28.

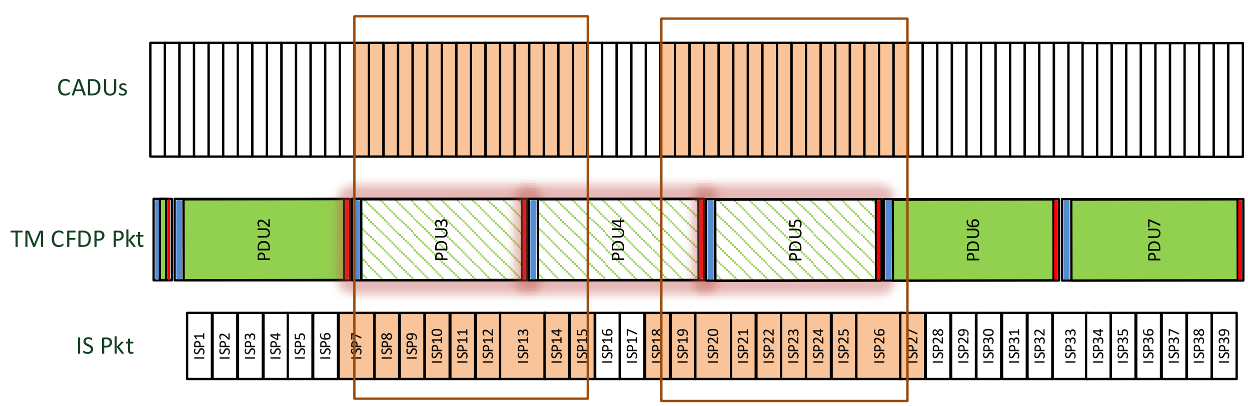
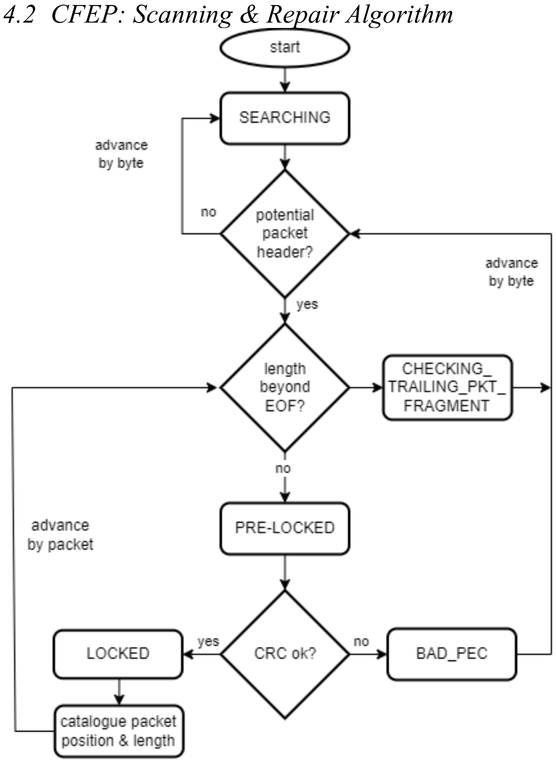


Figure 9: CADUs corruption affected two complete PDUs and partially a third one

4.2 CFEP: Scanning & Repair Algorithm



A scanning loop with 5 states is used to scan the entire file data assembling a 'catalogue' of the locations and lengths of packets which are declared legal by CRC check. Subsequently only these data will be considered during subsequent stages of reconstruction.

SEARCHING determines the occurrence of an 'acceptable' packet header (sequence of bytes containing values matching the expected fixed-field content for valid primary & secondary headers). Upon establishing this the PRE-LOCKED state is entered.

PRE-LOCKED proceeds with a CRC-check of the packet content, entering LOCKED if this is successful, and adding the position of the packet to the catalogue. Otherwise, the BAD_PEC state is entered, and the start position of the packet retained for possible subsequent use (see below).

If unacceptable packet header content is found following a BAD_PEC state the SEARCHING state is re-entered from the byte following the retained position, the premise being that the packet may have contained a corrupted length indication or may not have been packet-header data at all.

Where a prospectively legal packet header indicates a length extending beyond the end of file the CHECKING_TRAILING_PKT_FRAGMENT state is entered from the byte following this. Again, the premise is that the data encountered may have falsely indicated the length due to corruption and may hide subsequent packet data.

4.3 CFEP: Additional Input Data Corruptions

CFEP is also robust against other possible corruptions that might affect extracted PDUs like:

- Missed Metadata PDU: this PDU type contains the onboard folder and filename of the onboard file. In this case, the CFEP is able progress with the reconstruction of the target TM file identifying the original file type from the APID / TYPE/ SUB-TYPE of contained ISPs,
- Missed EOF PDU: this PDU type arriving as last PDU for each file and is signalling its end. If not received within a configurable timeout, the CFEP will close autonomously the file triggering its distribution to recipient components.

5. CFDP Operations Concept for CO2M

From an satellite operations point of view, it is important to understand that even if the CFDP standard co-exists with packet-based monitoring and control capabilities (where TCs can be sent directly to the OBC and real-time HKTM, high-priority telemetry and Critical Event log are still PUS-based), the use of DCFDP for the downlink of stored HKTM and science data from the instruments is a critical and novel function of the ground segment which deserves special focus.

File downlink operations will be performed routinely over the two daily S-Band TTC passes and once per orbit over one of the two Ka-band stations. The satellite will continuously store telemetry packets within files (both in the OBC and PDHU), which will then be downlinked during ground station contacts autonomously by on-board "downlink managers".

On the space segment side, file downlink operations involve starting CFDP file transactions at the beginning of an S- or Ka-band pass and suspending them shortly before the loss of signal. The protocol ensures that file transactions that could not be completed in that pass can be resumed in the following one.

On the MCOS side, the required activities to support file downlink include the management of the links between the different DCFDP components and with the stations, repatriation of the S-band frame files for further reconstruction and replay, and management of the CFDP protocol closure in the CC-DCFDP. The operations concept foresees no manual intervention from the operations personnel in the nominal case, as all these activities are either executed autonomously (e.g. retransmission requests if CC-DCFDP detects missing segments) or are pre-programmed by the mission planning system.

To exemplify the use of DCFDP during a pass, we provide below the required operations at MCS, CC-DCFDP, GS-DCFDP, CFRS and Satellite to perform file downlink operations:

Before pass:

1. GS-DCFDP starts a satellite-specific Session to connect to the ground station modem; GS-DCFDP is prepared to receive VC-4 Frames and generate R-PDUs
2. MCS automatically opens SLE connections to the ground station modem (VC0/1/5 and F-CLTU) as well as to the CC-DCFDP, via Throw Events
3. MCS automatically triggers CC-DCFDP R-CFDP service connection to the GS-DCFDP

Close to AOS:

4. MCS triggers CC-DCFDP scripts to resume file transactions and open reception windows (resuming CFDP timers)
5. Satellite resumes Downlink Manager (OBC starts file downlink transactions)
6. GS-DCFDP receives VC-4 frames from ground station modem, generates R-PDUs and provides them to the CC-DCFDP. In parallel, all VC-4 frames are stored for further offline reconstruction
7. CC-DCFDP receives and processes R-PDUs. In Class-2, provides CFDP PDUs for uplink as required (retransmission requests, ACKs/NACKs)
8. MCS receives the CFDP PDUs via SLE, encapsulates them in telecommands and forwards them to the ground station via SLE for uplink to the satellite

Close to LOS:

9. MCS triggers CC-DCFDP scripts to suspend file transactions (reception windows are closed, CFDP timers paused)
10. Satellite suspends Downlink Manager (OBC pauses file downlink transactions)

After the pass:

11. MCS automatically disconnects SLE links to ground station and CC-DCFDP
12. MCS automatically triggers CC-DCFDP R-CFDP service disconnection from the GS-DCFDP
13. MCS automatically pulls VC-4 transfer frames and provides them to CFRS
14. CFRS performs file reconstruction and provides them to the MCS for replay
15. MCS replays the reconstructed on-board files

Regarding file uplink, it is important to mention that the operations concept foresees that the uplink of files with CFDP will be one of the most frequent activities executed during routine, with packet-based uplinks being used only in exceptional, non-nominal cases. The CFDP standard enables ground control to perform reliable file transfers to the satellite, guaranteeing the integrity and completeness of the uplink of a high number of telecommands encapsulated in a single file, thus simplifying greatly any uplink operations.

The operations concept will make use of the following file types on the uplink:

- TC-files for immediate execution, typically encapsulating the mission planning schedule of all time-tagged or position-tagged commands for the reference period.
- TC-files for delayed execution, typically encapsulating commands to perform routine or maintenance operations which need to be executed several times.
- Raw-files, used for uplink of software patches (for memories that support this format), greatly simplifying the critical operations required to perform on-board software updates.
- OBCP-files, to upload new or updated definitions of On-Board Control Procedures.

On the Mission Data Acquisition and Processing side (MDAS and MDPS), the required activities to support onboard ISP raw files downlink using CFDP Class-1 protocol include the acquisition of each orbit dump by the MDAS, the extraction of the CADUs stream and its split into multiple CADU File Segment (CFS) of configurable size, their upload into the CADU Interface delivery Point (CADIP) where the CFS are available for being downloaded by the CFDP Front-End Processor and File Reconstructor (CFEP). The CFEP is regularly querying the CADIP for the availability of new dumps, making MDPS operations concept fully data driven, triggered by the availability of new orbit dumps at CADIP. It is only at CFEP, where the onboard ISP Raw file reconstruction starts.

Dumped orbits are staged at CADIP for one week and, in case of issues, Operators can, from CFEP HMI, manually (re-)trigger the download of a given orbit still archived at the CADIP.

MDPS is also supporting Satellite Operations activities, providing the MCOS with a copy of the recorded HKTM files downlinked in Ka-Band and reconstructed by the CFEP. All other ISP Raw files containing Earth Observation or Calibration Data are provided to MDPS systems responsible for the processing of Mission Data and the generation of the relevant Mission Products and for their distribution.

6. Implementation Status

Preparation for spacecraft mission operations using CFDP-based file operations includes ensuring that the needed support functions will be available within the ground software systems at the Control Centre to users for monitoring and control of the spacecraft. The concepts for managing onboard data stores and the upload and download of data to and from them have evolved over many years, and the functions provided to operators today reflect the heritage of operations concepts and lessons learned over that period. Major drivers and concepts that have driven the design and implementation of the ground software are:

- The manner in which remote onboard files and filesystem are managed should ideally be independent of the underlying protocol, and the details of the protocol separated from the high-level operations performed, such as copying a file to the onboard storage. In this way, users and operators can move from one system to another and more easily understand how the file-based operations are to be performed, since the high-level functions are largely the same. Examples are moving from a spacecraft supporting the European ECSS Packet Utilisation Service 13 “Large Packet Transfer” for supporting file upload or download, to a mission such as CO2M using CFDP.
- Remote file-based operations build on concepts that have become everyday de facto standards to people familiar with working on computers, such as organising files in tree-structured filesystems, and performing operations on those files such as copy, move, rename and delete.
- The remote onboard filesystem is only visible to the ground during spacecraft passes. Therefore the ground software needs to model the expected content of the onboard filesystem based on the operations initiated by the ground software (such as uploading a file to the spacecraft), and the feedback from the spacecraft, such as telemetry report of the filesystem’s status. The modelling complexity comes from the latency between a file operation being initiated and the feedback that it has been performed (or not, in case some error has occurred in the process).
- The functions to support file-based operations should be as generic as possible, maximising re-use across different missions, and minimising the modifications and tailoring needed for each specific mission.

The functions for supporting file upload and file download are significantly different, and although there are common elements where software re-use is possible, such as CFDP protocol handling, from an operations point of view they require different capabilities. In the following, the implementation of the functions for file upload and file download is explained.

6.1 File Upload Functions

Addressing the need to provide independence between the operation of the spacecraft filesystems and the underlying protocol for file upload operations, the ground software has a clear separation between operator interface and the different possible protocols and mechanisms for performing the file transfer. The figure below shows how this separation is implemented by a set of adaptors, each supporting a different mechanism (CFDP, ECSS PUS, etc).

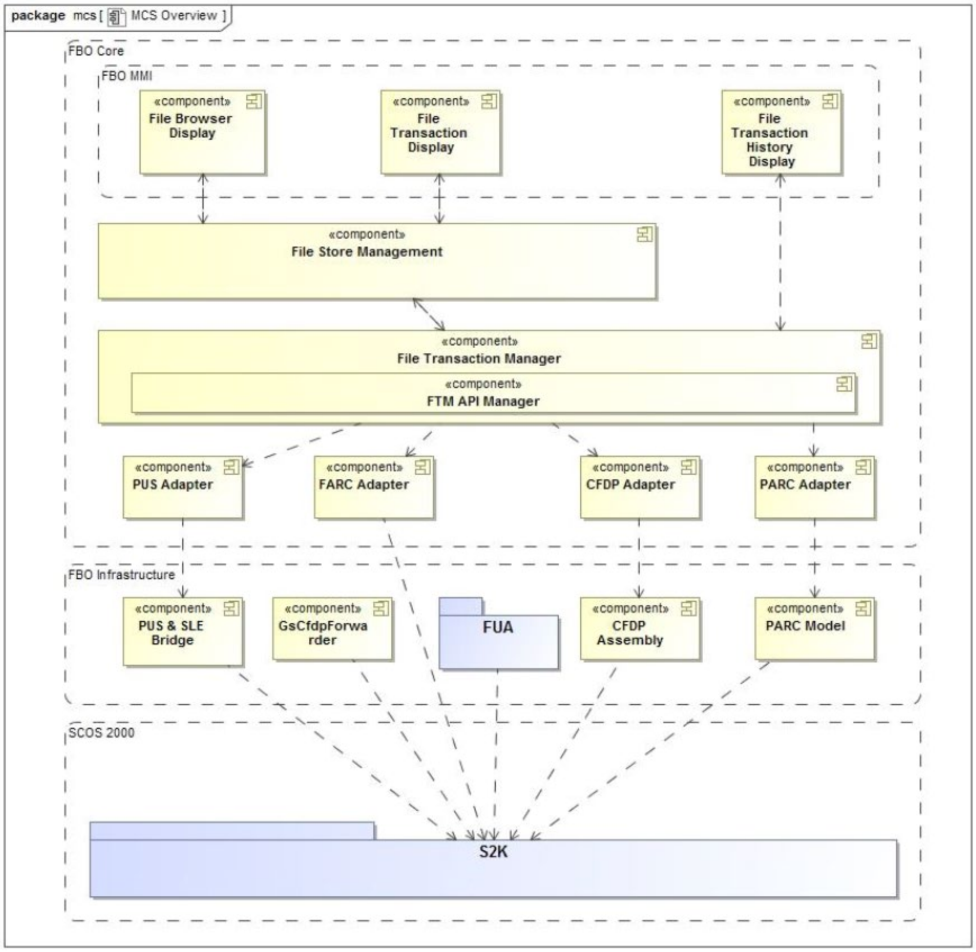


Figure 10: FbO File Upload Functions Architecture

The figure above shows the FbO application built on top of ESA's generic Mission Control System SCOS-2000 (S2K) application, which itself is part of ESA's re-usable package of software applications for mission monitoring and control.

In order to maximise flexibility and reduce the cost and complexity of adapting the software for each mission such as CO2M, the adaptors used for each specific function are configurable at runtime, thus avoiding the need to modify the software for each mission.

The user interface for managing file uploads to the spacecraft provides the views of the file store within the Mission Control System, and the file store onboard the spacecraft. An example is shown in the figure below.

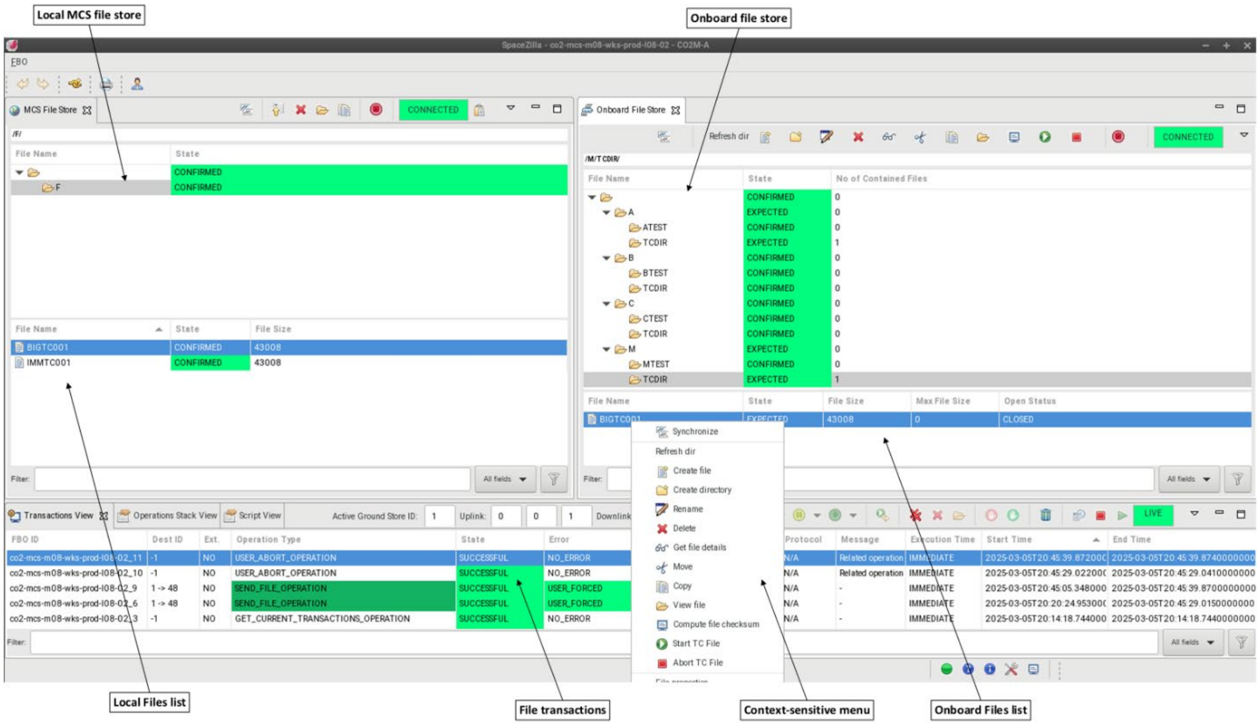


Figure 11: File-based Operations – File Upload - Graphical User Interface

Through the use of context-sensitive menus the user can select a file in one of the file stores and then select the operation to be performed. Examples of the context-sensitive menus are shown in the figure below.

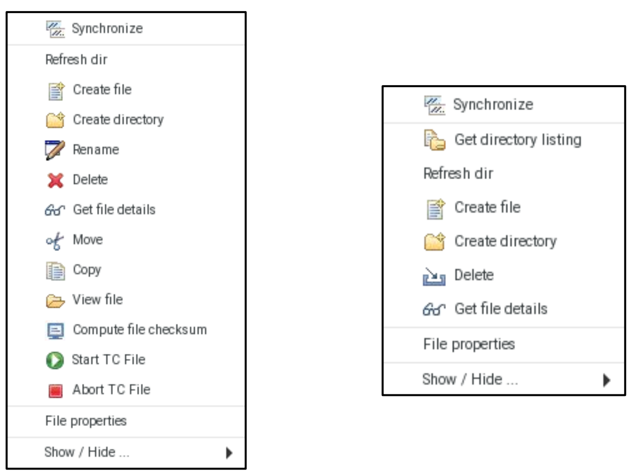


Figure 12: File-based Operations Context Menus for File and Directory User Actions

The generic functions represented in the menus, such as "Create file" are mapped to the specific spacecraft services and telecommands by the CO2M mission specific configuration. The table below shows the mapping configured between the user actions from the context-sensitive menus and the corresponding CO2M Service 23 "File Management" service.

User action	TC	Telecommand description
Create directory	[23,9]	Create a directory
Create file	[23,1]	Create a file
Delete (on directory)	[23,10]	Delete a directory
Delete (on file)	[23,2]	Delete a file

User action	TC	Telecommand description
Copy (on file)	[23,14]	Copy a file
Move (on file)	[23,15]	Move a file
Rename (on file) [Note 1]	[23,15]	Move a file
Get directory listing	[23,12]	Summary-report the content of a repository
Get file details	[23,3]	Report the attributes of a file
Refresh directory	[23,212]	Detail-report the content of a repository
Compute file checksum	[23,140]	Compute and report file checksum

Note 1: The CO2M on-board software does not support an explicit file rename telecommand. Therefore, the FbO *Rename* user action is mapped to the *Move* telecommand to the spacecraft.

With the current state of the CO2M ground segment preparations, the functions supporting file-based upload operations have been verified at subsystem level within the spacecraft Mission Control System using test tools. Full verification will be completed when the development of the CO2M Operational Simulator (and, in particular, the embedded onboard software that supports the file-based operations) has advanced sufficiently such that it can perform the file management operations on the spacecraft. Operational validation will be assured through compatibility tests with the CO2M spacecraft flight and engineering models.

6.2 File Download

Download of files from the spacecraft may be initiated by commanding from the ground, or by onboard control procedures. This implies that the ground must be ready to receive or resume file downloads any time the spacecraft is in communication with the ground.

The Distributed CFDP (DCFDP) software presented in section 3 adds some extra complexity in terms of the software deployment and its operation, particularly in relation to the split of responsibility between the CFDP data reception at the Ground Station (GS-DCFDP application), and the CFDP protocol handling at the Control Centre (CC-DCFDP application). The DCFDP software has been designed to be loosely coupled from the other systems that make use of it. However, since it is positioned in the flow of data from the spacecraft to the ground systems, in order to ensure secure and reliable operation, the protocol handling aspects are in fact tightly coupled to the handling TM and TC data flows during the spacecraft passes.

In order to automate the handling of data flows during spacecraft passes, the ground schedule executed by the Mission Control System incorporates ground system commands in a similar way to spacecraft commands to be uplinked at scheduled times. Such ground commands follow the concept of Throw Events defined within the CCSDS SLE standard by triggering an action on the receiving system. These Throw Events are used to trigger the establishment of the network connection between the core MCS applications and the DCFDP at the Control Centre. This in turn is used to establish the session between the CC-DCFDP at the Control Centre and GS-DCFDP application at the Ground Station.

Because of the deployment complexity, an important aspect is the integration testing and validation of the deployed applications. In the case of the EUMETSAT Control Centre, this is particularly significant since the TTC Ground Station will be provided as a service by ESA, and therefore EUMETSAT does not have direct access to the Ground Station for preparation and test purposes. Instead, EUMETSAT uses a combination of representative test tools provided together with the DCFDP software, and the CO2M Operational Simulator integrated with the GS-DCFDP software, representing a model of the Ground Station together with the spacecraft model.

6.3 S-band File Reconstruction

Reconstruction of the original spacecraft files from the CFDP Protocol Data Units (PDU) is performed independently from the CFDP protocol handling. The CFDP PDUs are received from the Ground Station by file transfer following each spacecraft pass and automatically processed by the CFDP File Reconstruction application. Once all PDUs for a specific file have been received and processed, the completed file is made available for use by other Control Centre applications.

In the case of a file containing telemetry packets, the file is transferred automatically to the Mission Control System for ingestion and processing as deferred telemetry.

Verification of file reconstruction is achieved using a test tool provided as part of the DCFDP software.

6.4 File Utilisation

Once files have been transferred and reconstructed, their use has an impact on operations compared to non-file-based operations. For the CO2M mission, file-based operations are used for:

- Downloaded telemetry files
- Telecommand schedule files (mission timeline and orbit position schedules)
- Uploaded and downloaded raw memory images handling
- Uploaded On-board Control Procedure (OBCP) files

TM files from the spacecraft contain the TM packets stored by the onboard software. Downloaded telemetry files are handled in a similar way to deferred telemetry downlinked using packet services on other missions. In order to minimise changes for CO2M to the re-used generic Mission Control System Software, the approach taken for ingesting the telemetry data is to encode the telemetry packets from the file into pseudo telemetry frames and send the frames into the telemetry receiver using a TM frame replay application. In this way, the telemetry is subjected to exactly the same processing as it would have been if received as TM frames containing deferred (recorded) telemetry directly from the Ground Station.

Telecommand files containing command schedules may be uplinked to the spacecraft for either immediate or delayed execution. Telecommand files for delayed execution are activated using specific Service 21 commands. An application, the TC File Manager, keeps track of the state of uplinked TC files. Once a file is activated, the contained commands are modelled on the ground and verification performed in the same way as command schedules uplinked using packet services. The main addition to the Mission Control Software is the TC File Manager to handle the notification of activation of TC files.

For handling of uploaded and downloaded raw memory image files, the processing on the ground is somewhat simpler than the case with earlier missions where the data is received via telemetry packets. Since memory images are managed in the Control Centre application as files, the fact that the data from the spacecraft are also received as files avoids the need to reconstruct the image data from telemetry packets or encode the memory load command as telecommand packets.

On-board Control Procedures are encoded as bytecode files. Once uploaded to the spacecraft, they are stored ready to be activated using Service 18 “On-board control procedure” commands.

The functions for supporting file utilisation operations are currently being verified using software test tools. Full verification of the Control Centre ground software will be achieved using the CO2M Operational Simulator once the related on-board software includes the functionality for handling the related TM and TC services.

6.5 Ka-Band Files reconstruction

It is worth noting that CFEP is not including a “CFDP Entity” to handle the CFDP protocol. CFEP is working on CFS and reconstructs on-board files encoded into CADUs according to CFDP and CCSDS protocols.

CFEP Prototyping Activities have been completed yielding very positive results especially in two areas:

- onboard files reconstruction performances,
- handling of missed / corrupted data and recovery capabilities.

The CFEP Prototype has been tested with a set of CADUs containing around 2 million ISPs performing all CRC checks at Transfer Frame, CFDP TM Packet and ISP levels. Performed tests demonstrated a performance of around 9300 packets per second running on an Intel® Xeon® Gold 5218 CPU @ 2.30GHz, 16 cores (with hyperthreading).

In the following *Figure 13* the CPU consumption and the dynamic memory (heap) allocation are presented for the PDU extraction (diagrams on the top) and the ISP Raw Files Reconstructor (diagrams on the bottom) components. The diagrams were produced during CFEP Prototype’s test.

CPU and Memory usage for both components, is limited in terms of resources: CPU around 10% with 15% peaks (only for the PDU Extraction), allocated RAM around 5 GB, less than 3GB actually used (even less for the RAW Files Reconstructor).

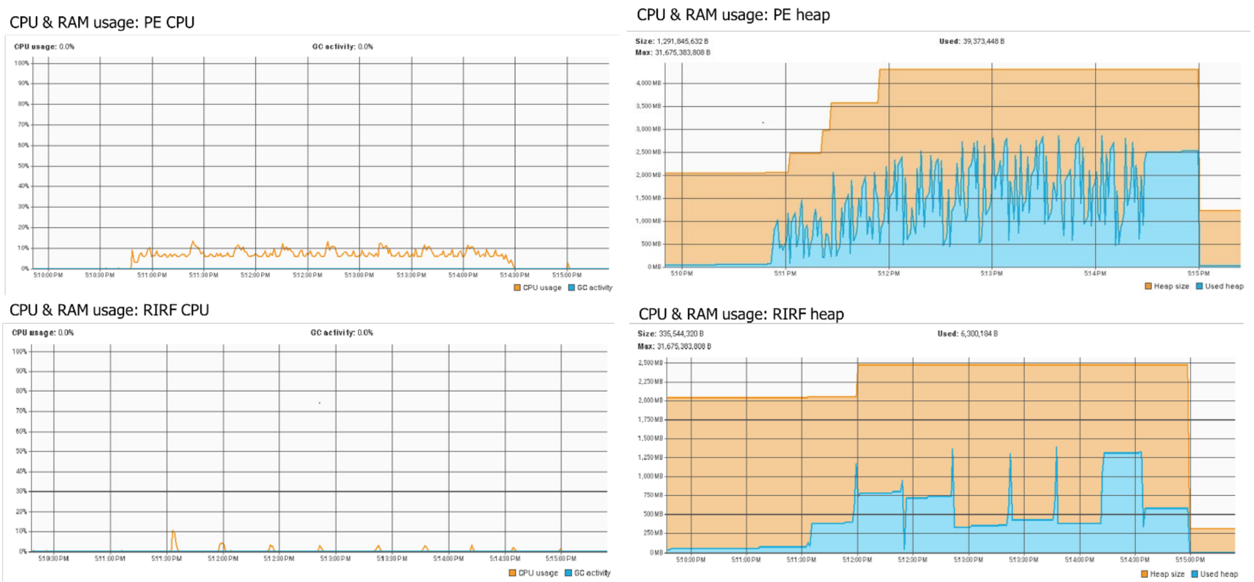


Figure 13: CFEP Prototype CPU usage and Dynamic Memory (Heap) Allocation

To estimate the time required to reconstruct all the files contained in an entire orbit of data, we must consider that PDU Extraction and ISP Raw Files Reconstruction activities are executed in parallel for multiple instruments / bands and Satellites. This means that the time required to process an entire orbit is the time needed to process the instrument / band having the highest number of packets sensed; all other instruments / bands will be processed in parallel and in less time (having less packets). Considering CO2M specific case, the most demanding instrument, in term of number of packets to reconstruct, is the Multi-Angle Polarimeter (MAP) instrument with around 24.1 million packets per orbit (considering MAP typical figures of 50 minutes of earth observation data sensed during daylight condition, and 10 minutes of calibration data sensed in nightlight condition). Extrapolating from the CFEP Prototype performances (9300 packets/sec), considering the number of MAP packets in one orbit (24.1 million), will give us an approximate time to reconstruct one orbit of data in around 43 minutes.

The CFEP prototyping activity also confirmed the capability of handling corrupted input data affected by space to ground transmission issues (CADUs loss), retaining those not corrupted ISPs from damaged PDUs.

Capability of handling corrupted / missed data is one of the critical areas identified since the beginning of the activities especially because, using CFDP Class 1 protocol for Ka-Band mission data transmission, implies that it is not possible to recover corrupted data retransmitting it.

Activities performed at prototype level went in the direction of demonstrating that, in case of corrupted or missed data affecting PDUs, CFEP can:

- in any case reconstruct the on-board file, even if with some data gap inside due to removal of corrupted or incomplete packets.
- limit the impacts of corrupted data removal to the bare minimum; removing only corrupted or incomplete packets, while other valid packets are retained and delivered to the production chain for being processed.

The prototype has been tested with input CADU files where sets of CADUs were removed to simulate data gaps and corruption and activated to reconstruct the onboard files including only fully valid packets. The algorithm adopted to identify corruptions and next valid packet is described in section 4.2.

Concerning CFEP development status, it is now in its final stage and due to be completed in the second half of 2025. Some of the CFEP SW modules have already been completed, like the CADU Collection system (CCS), the Data Distribution and Local Monitoring and Control. The PDU Extraction (PE), the File Reconstruction (RIRF), the File Distribution (DD) and the User Interface are still in final development, and they are approaching (mid-April 2025) their internal integration and verification.

The CADU Collection system has already been successfully pre-integrated with a test instance of the CADU Interface delivery Point and confirmed the capability to retrieve CFS from ESA's CSC GS under nominal and non-nominal conditions.

Additional in-factory verification activities will focus on extensive test of functionality, performances, configurability with particular attention on non-nominal situation during the reconstruction of onboard files.

7. Conclusions

CO2M will be the first mission to be operated by EUMETSAT implementing fully File-based Operations and demonstrating the use of CFDP. This represents a major evolution of the EUMETSAT Ground Segment and a shift of paradigm, moving from the traditional operations concept based on transfer from and to on-board memories. Some of the expected benefits of using CFDP at EUMETSAT include:

- Reliable data transfer in uplink and downlink when operating in class 2. This allows start/stop of transfer at lower ground station antenna inclinations (e.g. at 5 degrees inclination), which implies longer transfer windows for LEO missions.
- Simplified operations concept for managing data uplinks and downlinks, with automatic retransmission of missing or corrupted PDUs, across multiple passes and ground stations, when operating in class 2.
- Simplified operations concept also for managing data storage using files onboard the spacecraft through the use of a standardised concept (when compared to spacecraft-specific data storage management).
- Common reusable implementation of the ground segment elements needed to support CFDP in both class 1 and class 2.
- Interoperability with other space agencies providing ground station services and implementing CFDP Cross Support Transfer Service (RCFDP-CSTS) to support operations in class 2.
- Take-up of CFDP across the space industry (particularly by space-segment primes) is expected to result in overall programme cost reductions for future missions.

In preparation for the routine operations of the CO2M spacecraft, EUMETSAT's Operational Ground Segment has been evolved to fully support FbO and CFDP. Furthermore, the development of the CFEP has equipped EUMETSAT with the necessary capabilities to support other future missions under preparation interfacing ESA's CSC Operational Framework for the retrieval of CADU file segments encapsulating CFDP-based payload data.

With the development of the CO2M space and ground segments well advanced, the focus is now shifting to the integration, verification and validation of the full end-to-end CO2M System including the CFDP distributed architecture and the file-based operations concept and procedures.

Acknowledgements
The tasks in this paper were carried out with funding by the European Union under the Copernicus component of the EU space programme.

References

[1] CCSDS 727.0-B-5, CCSDS File Delivery Protocol (CFDP), Recommended Standard, Blue Book, July 2020.
[2] F. Flentge, H. Dreihahn, P. Choukroun, J.P. Pont, D. Calado Alas, M. Kiermeier: Distributed CFDP Ground Infrastructure Implementation for High Data Rate Downlink, SpaceOps 2023, United Arab Emirates.
[3] C. R. Haddow, H. Dreihahn, F. Flentge, F. Keck, and M. Schmidt: File based Operations, CFDP Assembly and Euclid, SpaceOps 2018, Marseille.