File Based Operations – The Way Ahead ?

C. R. Haddow[1], M. Pecchioli[2], E. Montagnon[3] and F. Flentge[4]
ESA/ESOC, Robert-Bosch-Str 5, 64293 Darmstadt, Germany.

Traditionally ESA missions have been operated using packets in accordance with the ECSS Packet Utilization Standard (ECSS E-70-41). Increasingly however there is a move towards off-line operations concepts as file transfer has become an ever more common function for ESA missions recently launched and in development (Rosetta, Mars Express, Venus Express, BepiColombo, GAIA). Operations at packet-level on the downlink are perfectly adequate for engineering type of data (housekeeping, etc.), which are processed in near real-time on the ground. Science data however are not processed in near real-time and normally not at the control centre. For this type of data, moving to a file based approach, where each file contains a self-consistent set of data, would make more sense and simplify the downlink operation as well as the distribution to the end user. Similar considerations can be made for other on-board generated products used for spacecraft 'maintenance' operations. The use of a file-based data delivery is made possible by the availability of standardized file transfer protocols, such as the CCSDS File Delivery Protocol (CFDP). However the availability of a suitable file delivery mechanism is not sufficient to realize the full benefits of file based operations. In addition it is necessary to have a suitable file management system on-board. This is expected to be provided by the CCSDS Spacecraft On board Interface Services (SOIS), which will among others provide file and packet store services. A further prerequisite for file based operations is the availability of on-board services supporting access to files to carry out the required operations. ESA is currently embarking on an activity to identify the required services. This paper identifies the areas in which adoption of file based operations would be beneficial for future ESA missions and discusses some of the scenarios in which these could be deployed. Some of these scenarios have implications on how mission ground segments should be designed and the consequences of these are outlined.

I. Introduction

AN ESOC Working Group has looked into the possible benefits and implementation of file based operations, this was previously reported at SpaceOps 2010[1]. The main objective of the Working Group was to consolidate the concept of File based Operations for ESA Missions and to analyse the impact on the future space systems, with particular reference to ground infrastructure, related standards and operational requirements for the space segment. This objective has been accomplished by means of the following activities:

1) Analysis of the main utilization scenarios (use cases) of files as a basic data storage and exchange unit in spacecraft operations;
2) Evaluation of the potential benefits that the adoption of file based operations would allow;
3) Analysis of applicability of the identified use cases to the current and planned ESA missions;
4) Definition of the main requirements that shall apply to future space systems in order to support file based operations;
5) Analysis of the main related standards regulating the data transmission and management in ESA space systems;
6) Identification of the most representative mission topologies to be considered for the definition of technical solutions;

[1] Senior Software Engineer, Data System Infrastructure Division, HSO-GI.
[2] Section Head, Operation Centre System Infrastructure Section, Data System Infrastructure Division, HSO-GIC.
[3] Bepi-Colombo Spacecraft Operations Manager, HSO-OPB.
[4] Software Engineer, Ground Station Backend Section, Data System Infrastructure Division, HSO-GIB.

7) Trade-off analysis between various possible technical solutions against the applicable requirements;
8) Selection of the recommended solutions meeting the applicable requirements and respecting the relevant constraints (e.g. compatibility with the existing ground station infrastructure);
9) Definition of recommendations for future work covering the impact on the space segment, on the related standards and on the ground infrastructure;

II. File based operations concept

The need of file based operations is a consequence of the more complex interactions between ground and space segment (both mission and payload) and is enabled by the increased size of on-board storage devices and the advent of more sophisticated on-board autonomy and file management services. The proposed concept to accommodate this need and to exploit the associated benefits is based on the definition, adoption and consistent use of two complementary sets of services supporting the ground/space interactions, namely:

1) Control services which involve, in general, small data structures and are atomic in nature from an operations point of view;
2) Data services which, in general, support the exchange and management of larger data structures which take an appreciably long time to transfer and cannot be managed by atomic transfers from an operations point of view. The data managed by these services are typically stored on both sides i.e. prior to transmission and following reception. The underlying data transfer protocol focuses on completeness rather than on timeliness.

In general, for ESA missions both families of services are implemented by means of the same data unit, namely the Space Packet (TM and TC). There is no intermediate layer enabling a higher level of abstraction when exchanging larger data structures which are stored on both ends. It should also be noted that the ESA Packet Utilization Standard[2] (PUS) specifies all operational services without a clear distinction and separation between the data required/generated by the on-board service and the way in which this data is transmitted/received to/from ground. This has to an extent also shaped the way on-board data is currently stored, where on-board data systems are ‘packet store oriented’ as opposed to a conventional and familiar file system as used on ground. With the increase of the size of data to be exchanged, this introduces an unnecessary level of complexity in the execution of the relevant operations as well as in the management of the relevant data (e.g. to trace the transmission state and to verify completeness of the data at each transmission node).

The proposed concept relies instead on two data units which are directly available to on-board services in order to support the required ground/space interactions, namely: Packets and Files. Packets are data conveyance containers, with attributes for transmitting data between systems in single messages. Files are instead to be used as data storage containers, with attributes for the storage, access and multiple uses of data by the end users/applications. This is largely analogous to the typical use made of equivalent data units in common information technology, where a file is a persistent data storage container and a ‘packet’ is a formatted unit of data carried by a computer network. It should be noted that the two main differences between packets and files are in size and attributes:

1) Firstly, the size of a packet is restricted by data rates and connectivity, whereas the size of a file is restricted by local storage. Generally the upper size of packets is much smaller than a file;
2) Packets have attributes designed for a single instance of use between sender and receivers. Files have attributes designed for multiple use and organisation of data, potentially in a file system context.

Where data is not needed for real-time interactions but rather for user handling, it should be first placed in a file and associated to the attributes required for its management. An important part of the proposed concept is that, if the file then needs to be transferred between separated entities, it may be sent as transmission packets, but the transmission packets are transparent to the user after delivery: only the files and their data payload are visible to the two ends. This is similar to the case of transferring files between file storages on ground e.g. as e-mail attachments or via FTP.

The concept also relies on suitable file management functions implemented on-board. To this end the family of CCSDS SOIS standards[4] are particularly relevant as these will define on-board interfaces involving the complete spacecraft, with the goal to improve the process of spacecraft development and integration as well as the quality of the finished product. It also aims at facilitating the adoption of new hardware and software technologies supporting international on-board interface interoperability. Particularly relevant to File based Operations is the SOIS Standard defining the File and Packet Store Services[3].

III. Proposed solution for the various operational scenarios

This section defines the various monitoring and control scenarios which are considered as relevant to future ESA missions and proposes the approach/protocols to be used in order to accommodate the files exchange needs identified above. The proposed solutions have been identified on the basis of the following main drivers/objectives:

1) Compatibility with existing ground infrastructure, especially in the area of ground stations;
2) Commonality of solutions across different mission topologies/scenarios;
3) Clear separation between the monitoring and control and the data delivery roles. This latter one is to be considered as a service provider with well defined interfaces;
4) Identification of a minimal set of cross-support needs at the lowest possible level (in order to maximise inter-operability across organisations that may adopt different solutions for the service provision).

The following scenarios are considered relevant to current and future ESA missions (and indeed a study is being initiated to examine these in more detail):

1) Spacecraft Control with direct access to uplink/downlink
2) Direct mission data distribution to end-users
3) Spacecraft Asset Control via Relay

The proposed solution for the scenarios above is described in the following sections. It is however important to emphasize that, independently from the protocol which supports the exchange of files between space and ground, the full benefits of adopting a file based approach, including a simplification of the overall operations concept, can only be realised if an end-to-end concept of managing files is introduced, both on-board and on-ground, whereby each file contains a given product as needed by the end consumer (e.g. a S/W patch, an OBCP, an image, an observation, a set of Mission Timeline commands, a TM replay file, etc.) and is generated, managed, transferred and distributed in a way which enables its end-to-end traceability.

A. Spacecraft Control with direct access to uplink/downlink

This scenario is illustrated in the following figure.

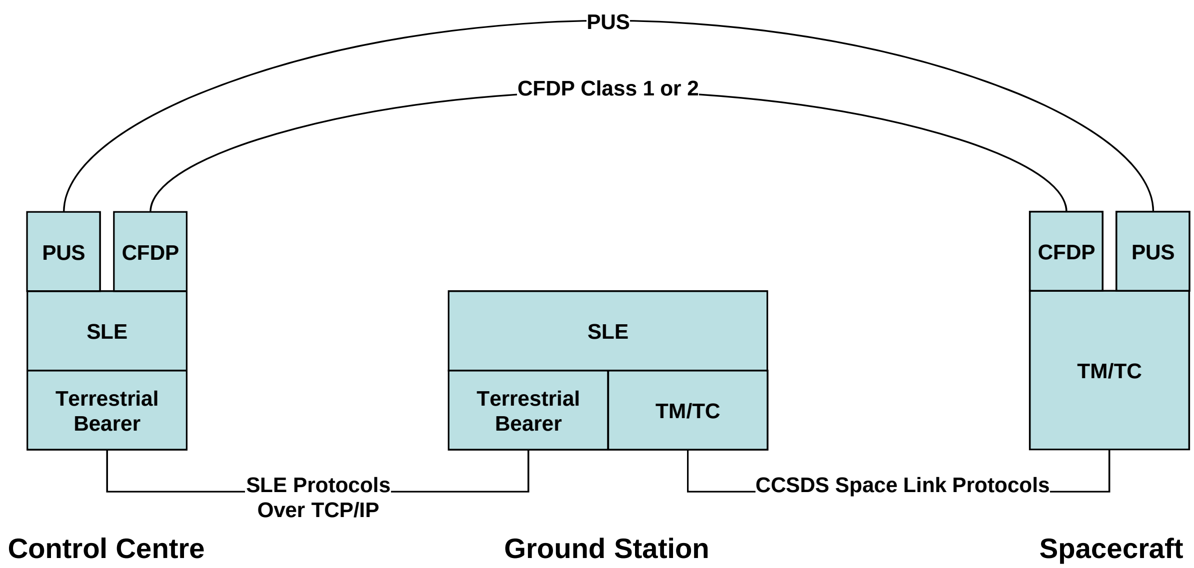

Figure 1. Proposed solution for file based Spacecraft Control operations

Figure 1 above shows the proposed solution to accommodate file based operations in the standard scenario of spacecraft monitoring and control based on a ground station network ensuring direct uplink and downlink visibility. The proposed solution is based on the following data exchange protocols:

1) SLE (over TCP/IP) between Control Centre and Ground Station. This ensures complete compatibility with the existing ground infrastructure and also cross-support capabilities. It should be noted that in this solution the SLE Protocols dealing with TM Frames and TC CLTUs can still be used i.e. the adoption of packet level protocols is not imposed;
2) CCSDS Space Packets between Ground Station and Spacecraft. Again, this ensures complete compatibility with the existing ground infrastructure and also cross-support capabilities;

3) Packet based Services (PUS) between the Control Centre and spacecraft;
4) CCSDS File Delivery Protocol[5] operated in closed-loop and/or open-loop between Control Centre and Spacecraft. This enables a peer-to-peer relationship between Control Centre and Spacecraft for the exchange of files in both directions. The natural choice for this protocol is CFDP but restricted to its basic operations i.e. without multi-hop capability.

The solution proposed above is based on a clear separation of the protocols between the Control Centre and the Spacecraft (namely, PUS and CFDP) and the protocols between the service provider and the mission assets (namely, SLE and TM/TC Packets over the Space Link).

B. Direct mission data distribution to end-users.

This scenario is similar to the previous one except that downlink of the mission data files may be terminated at the ground station. This implies that there needs to be a CFDP entity at the ground station, however due to operational concerns direct uplink of CFDP PDUs from the ground station is not permitted. Instead these PDUs would be forwarded to the OCC for uplink via the control system commanding chain. This scenario may be useful in cases where an unreliable downlink is used (need for retransmission), the bandwidth of the link between the ground station and the OCC is not sufficient to send all data immediately after it is received at the station and there are requirements to minimize the latency between the generation of mission data and their delivery to the processing centres.

Such a scenario is similar to that which exists for some current ESA Earth Observation where payload data (and stored housekeeping data) is downlinked via X-band to the ground station, where it is received and stored by the payload data system. The payload data is then transmitted to the data processing centre without passing through the OCC. (The stored housekeeping data is stored in files of telemetry frames that are retrieved by the control system at the OCC and “played back” into the system after the pass). However, currently there are no ‘automatic’ re-transmission requests for missing data via dedicated protocols. It should also be noted that some passes may be downlink only, i.e. there is no uplink during the pass.

This is illustrated in the following figure.

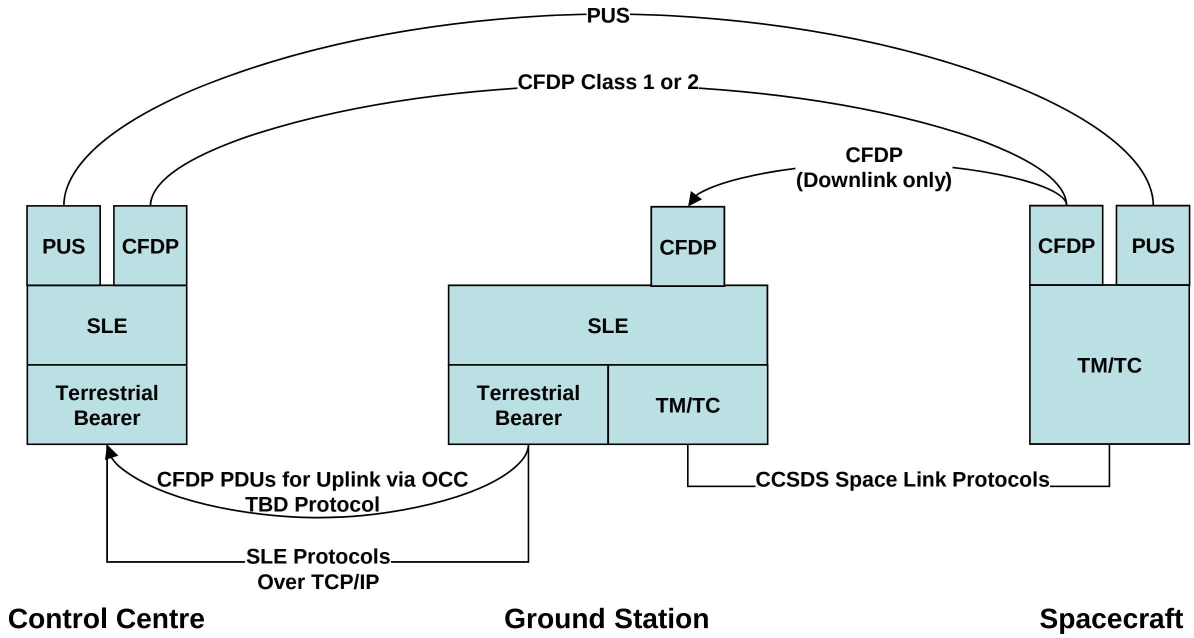

Figure 2. Proposed solution for file based Spacecraft Control operations. File Delivery to ground station.

Figure 2 above shows the proposed solution to accommodate file based operations in the scenario of spacecraft monitoring and control based on a ground station network ensuring direct uplink and downlink visibility, but that also may terminate downlink of files at the ground station.

The proposed solution is based on the following data exchange protocols:

1) SLE between Control Centre and Ground Station. This ensures complete compatibility with the existing ground infrastructure and also cross-support capabilities. It should be noted that in this solution the SLE Protocols dealing with TM Frames and TC CLTUs can still be used i.e. the adoption of packet level protocols is not imposed;
2) CCSDS Space Packets between Ground Station and Spacecraft. Again, this ensures complete compatibility with the existing ground infrastructure and also cross-support capabilities;
3) Packet based Services (PUS) between the Control Centre and spacecraft;
4) CCSDS File Delivery Protocol operated in closed-loop and/or open-loop between Control Centre and Spacecraft. This enables a peer-to-peer relationship between Control Centre and Spacecraft for the exchange of files in both directions. The natural choice for this protocol is CFDP but restricted to its basic operations i.e. without multi-hop capability.
5) Additionally the use of CFDP restricted to its basic operations i.e. without multi-hop capability between the Spacecraft and the Ground Station. However, there will be no direct generation of CFDP PDUs in the ground station as received CFDP PDUs are forwarded to the OCC for processing and generation of uplink CFDP PDUs to be sent via the telecommand chain of the Control System.
6) The use of a proprietary protocol to forward generated File Delivery Protocol PDUs from the ground station to the OCC.

C. Spacecraft Asset Control via Relay

This scenario deals with a space asset (e.g. a lander) that is controlled via a relay (e.g. an orbiter), with the Space Asset Control Centre (CC) distinct from the Relay Control Centre. In principle CFDP could be used end to end from the space asset control centre to the space asset. There may however be organisational and operational restrictions to adopt this approach, which is the reason why an activity is starting in CCSDS to define a terrestrial file transfer mechanism. In view of this it has been assumed that this terrestrial protocol will be used between the Space Asset Control Centre and the Relay Control Centre.

It is assumed that the CCSDS terrestrial file transfer mechanism will permit the delivery of metadata associated with a file. Thus some processing of the file will be required at the Relay Control Centre,

1) on reception of a file from the Space Asset Control Centre extracting the metadata from the delivered file and injecting the data file into CFDP.

   NOTE: The file received from the Space Asset Control Centre could contain two sets of metadata:

   a. The first being data for the ground segment related to the processing of the file on the ground (e.g. timing constraints on when the file should be uplinked etc.)
   b. The second being data for the spacecraft related to the processing of the file on-board. Delivery of the metadata to the spacecraft could be either via the metadata capability of CFDP or by utilising a PUS service.
2) on delivery of a file for the Space Asset Control Centre extracting the appropriate metadata either from CFDP or delivered via a PUS service, inserting this into the CCSDS terrestrial file delivery mechanism along with the data file and transmitting this to the Space Asset Control Centre.

There are also additional considerations that apply to the relay. It is not sufficient to assume that use of files to the Space Asset will provide all the commanding/telemetry capabilities required. For instance in the event that the space asset is in a safe mode it may not have the capability to process files. In this situation the Relay will need to be able to send direct commands to the space asset. This could be achieved by transmitting a file containing the required command to the relay which then extracts them and transmits them to the space asset as Direct TCs when the relay has visibility of the space asset. Similarly it is necessary to consider the case of the relay receiving TM from the space asset which it then constructs into a file to be downlinked to the Relay Control Centre via CFDP, from where it can be delivered to the Space Asset Control Centre using a terrestrial file transfer protocol.

There may also be the case where TC and TM packets are routed via the relay, i.e. TC packets sent from the relay control centre are routed to the space asset via the relay and TM packets from the space asset are routed to the relay control centre, again via the relay.

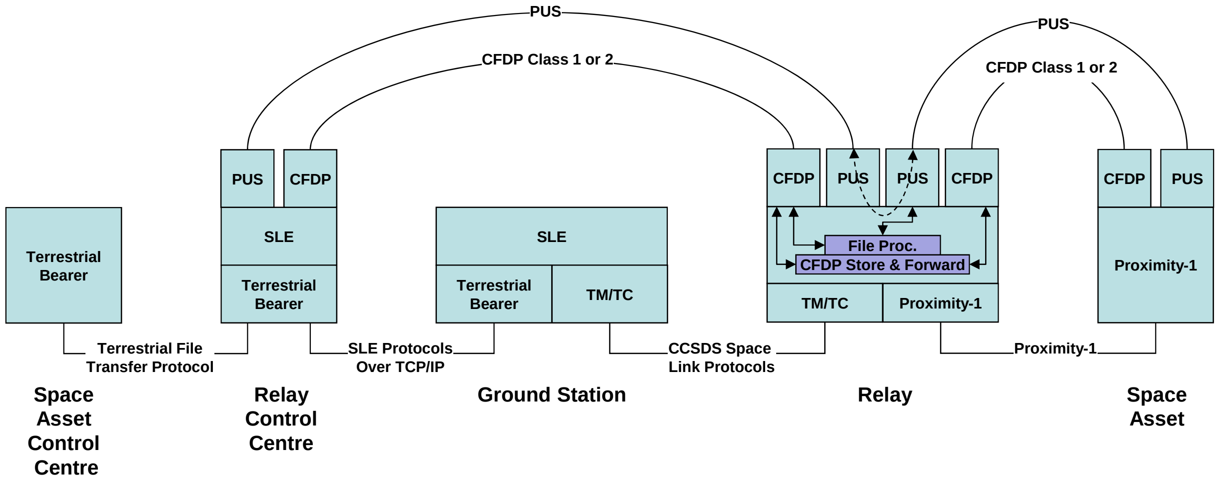

Figure 3. Proposed solution for file based Space Asset Control operations via a Relay in space.

Figure 3 above shows the proposed solution to support monitoring and control operations of space assets which are not directly visible from their Control Centre (i.e. they rely on a data relay in space). The proposed solution is based on the following assumptions and data exchange protocols:

1) All communication with the space asset is via the relay
2) Communication links are disjoint so that all data sent to and from the apace asset must first be stored on the relay
3) The Space Asset Control Centre prepares files containing PUS based commands, Direct TCs and files.
4) The Space Asset Control Centre receives files containing PUS based TM, Direct TM and files
5) The communication associated with the operation of the relay is based on real-time Packet TM/TC and CFDP file transfer
6) The underlying transfer service for CFDP is the Space Packet protocol
7) The use of terrestrial file delivery mechanism between the Space Asset Control Centre and the Relay Control Centre.
8) The Relay CC receives files from the Space Asset CC, these are transmitted to the relay, along with meta data, using CFDP.
9) At the relay the received files are processed by an on-board application and, depending on content and meta data, sent to the space asset using CFDP or the packet service of the Prox-1 protocol
10) The return direction is similar: The relay receives files and space packets from the space asset. These are transmitted to the Relay CC using CFDP. The Relay CC forwards the files using a terrestrial file transfer protocol
11) A number of trade-offs need to be considered with respect to this scenario:
    a. The use of CFDP class 1 (open-loop) or 2 (closed-loop)
    b. The store and forwarding function within the relay. Note that CFDP class 3 and 4 are not proposed for use and the Store and Forward Overlay (SFO) is probably best replaced by a dedicated application able to deal with files as well as Direct TM/TC
    c. The format and contents of the meta data associated with the file transfer
    d. The use of meta data transfer capability of CFDP (message to user)

IV. Ground Segment

Figure 4 below shows a high-level view of the various components involved in the file based operations support in the future mission control system infrastructure. This architecture is based on the standard ESOC SCOS-2000 Mission Control System software. A brief description of the various components and how they are expected to interact with each other is given below.

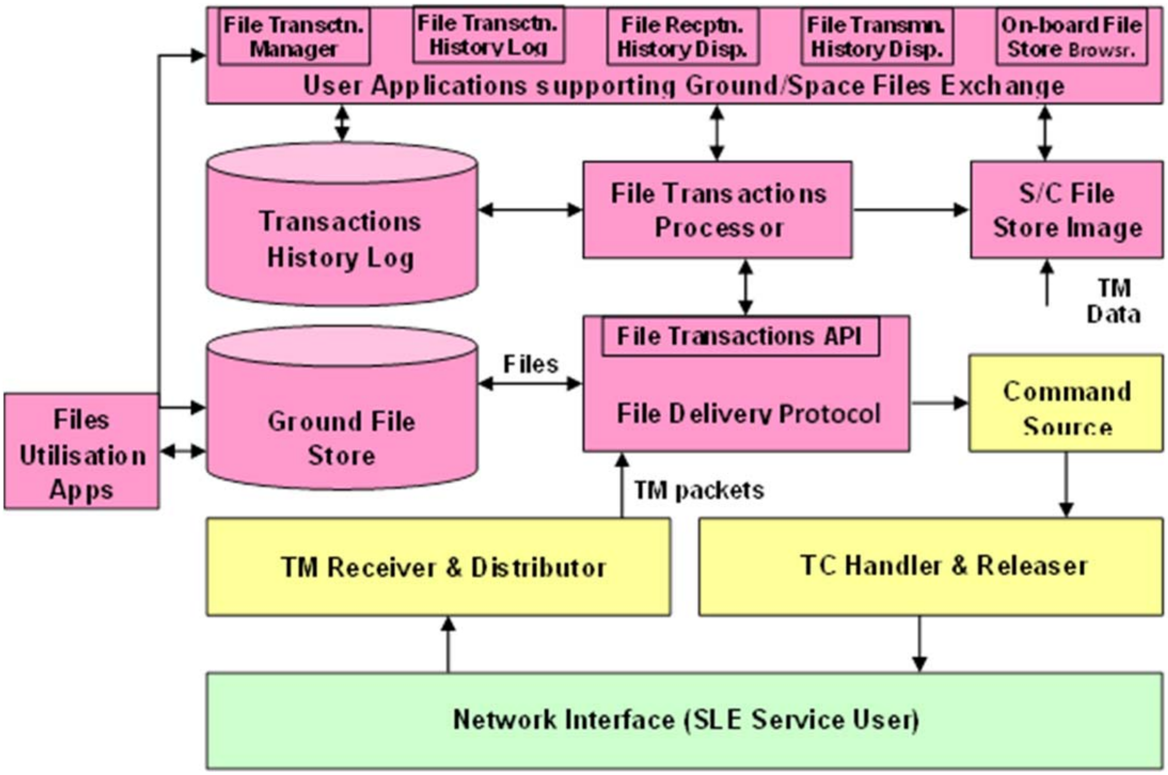

Figure 4. High-level architecture of the Control System components supporting File based Operations

New user applications will be needed supporting the management of 'file transactions' i.e. of ground/space files exchange operations. These new user applications are:

1) a Files Transaction Manager, enabling a privileged user to initiate the files transactions (e.g. to uplink a file) and to control the status of on-going transactions, including the ones related to reception of files. This application shall support operations at transaction level such as start/stop/suspend/resume/abort as well as the inspection of the lower levels (e.g. the reception/transmission of PDUs);
2) a Files Reception History Display (equivalent to the TM Packets History Display), showing the history of all files received from the Space Segment along with their attributes/status;
3) a Files Transmission History Display (equivalent to the Command History Display), showing the history of all transmitted files along with their attributes and transmission status;
4) a File Browser of the On-board File store (equivalent to the File Browser of the control system file store), supporting the user interactions in the area of on-board files browsing and management (e.g. delete, create directory, downlink, etc.). This application will be fed by the underlying image of the on-board file store and will generate appropriate commands for managing the real on-board file store.

The Files Transaction Processors will support all processing required to manage file transactions. It will receive requests from the user applications and interact with the file delivery protocol engine to request the uplink of files and to be notified of the reception of files. It will also maintain the status of each transaction and feed the relevant information to the history log and the ground image of the on-board file store.

The Files Transaction History Log is the equivalent of the TM/TC Packet History Archive. It will contain one record per file transaction (in both directions) containing all relevant details, including a link to the ground file store (see below) where the file is archived (which can be activated by the relevant user application in order to open the corresponding file). It is planned to implement this history log using the Packet ARChive (PARC), similarly to all other operational logs in the ESOC Mission Control System infrastructure.

The S/C File store Image is responsible for maintaining a mirror image of the on-board file store. This image is updated on the basis of ground requests (considering their confirmation status) and on the basis of relevant reports received from the spacecraft. The image is meant to serve the needs of visualising the content of the on-board file store and to generate file management operations requests to be submitted to the spacecraft. It is the responsibility of this application also to maintain an image of the TC Files which have been uploaded to the spacecraft for delayed (on-request) execution.

The Ground File store provides the file storage and retrieval services to control centre applications. It will receive reconstructed files from the File Delivery Protocol engine it will support the retrieval of ground files for upload purposes as well as for utilisation purposes. The intention is to base the implementation of this file store on the existing File ARChive (FARC), which enables a centralised management and distributed access to files.

The Files Utilisation Applications represent all the ground applications that need the received files to perform their job and/or generate files for upload to the spacecraft. An example of this application is the On-board S/W Manager, which will need to dump files in order to update the ground image of the on-board memory and generate patch files in order to update the real on-board memory. Other files utilisation applications will generate TC files which are destined to the On-board Scheduler for time-tagged execution or uploaded to the spacecraft for delayed execution (on-request).

The other components in Fig. 4 above (e.g. TM Receiver & Distributor, TC Handler & Releaser, Network Interface) already exist but may require modifications in order to serve the needs of file based operations. For example, the support of Delayed TC Files (i.e. the TC Files uploaded to the spacecraft whose execution can be requested multiple times by ground) will likely require modifications in the processes that support command execution verification. Finally, in case the ground/space interface is moved from TM/TC Space packets to Encapsulation Service, both the TM Receiver and TC Releaser will be affected (this is however a change which may be needed independently from the support of file based operations).

V. Recommendations

The main recommendations raised by the Working Group are:

1) File based Operations shall be promoted and deployed consistently in future ESA missions, covering both the forward (uplink) and the return (downlink) directions;
2) It is important that a coherent approach towards file based operations is identified/agreed within the relevant bodies (e.g. ECSS standardisation), such to avoid the adoption of different solutions across ESA missions;
3) The ECSS Packet Utilisation Standard (PUS) and the Operability Standard (E-70-11) need to be refurbished/extended in order to cover the utilisation layer of files for spacecraft operations. The definition of on-board operational services which rely on utilisation of files is an essential step in the direction of file based operations;
4) The CCSDS SOIS family of standards needs to be finalised taking into account the operational needs and eventually adopted by future ESA missions. This applies in particular to the SOIS standard covering the on-board file store and related services. The currently existing overlap between this family of standards and the PUS shall be addressed/resolved in the future evolution of these standards;
5) The adoption of CFDP as the file delivery protocol shall be promoted for all future ESA missions supporting file management and utilisation capabilities. The use of CFDP is however recommended to be restricted to the point-to-point interactions (open-loop and closed-loop);
6) It is recommended to enable cross-support in the ground-to-ground files exchange by means of a CCSDS file exchange standardised protocol, supporting the capability to deliver files in a secure and complete way across ground segment nodes;
7) It is essential that future space assets provide file management capabilities and expose the related services to the File Delivery Protocol as well as to the ground via well defined PUS services. The support of files in the on-board data services is an essential pre-requisite for the adoption of effective file based operations;
8) A reference architecture of the space segment supporting files management and utilisation shall be produced. This shall cover the main interactions between the relevant standards and associated components (e.g. file delivery, file management and file utilisation);
9) In order to minimise complexity and maximise interoperability, for missions requiring cross-support, it is strongly recommended to adopt solutions that do not necessarily rely on a consistent deployment of the same data transfer protocols in all involved nodes. A clear distinction between service user (requesting the data to be transferred to its counterpart) and the service provider (ensuring that the data transfer takes place according to the required quality of service) shall be introduced;
10) The Control Centre infrastructure shall be augmented in order to support file based spacecraft control applications..

VI. Next Steps

From what has been previously discussed in this paper it will be obvious that there are a number of issues that need further analysis before the approach to file based operations can be finalised. With this in mind a study is being initiated by ESOC that will investigate

1) The functionality required on-board to properly utilise files. This should lead to the identification of a set of File Utilisation Services (FUS)
2) Analyse the use or not of the CFDP meta data to control the transfer
3) The underlying use of (raw) CCSDS packet or PUS packet (there are some significant differences in overhead and potential implications for the ESOC ground infrastructure)
4) If the SOIS file and packet store services are complete for operational purposes
5) Examine in detail the user scenarios outlined previously and demonstrate the expected operational benefits.

This study will involve the development of a prototype of both the space and ground segment elements required for file based operations. The space segment prototype will be based on the RASTA on-board test bed developed at ESTEC, while the ground segment prototype will be based on the ESOC Mission Control System (MCS) Software SCOS-2000.

Further into the future it is possible that an in-orbit demonstration will be carried out on a micro-sat, OPS-SAT which is intended as an In-Orbit Demonstrator to test innovative mission control and operations concept. In the first two months of 2012 a multi disciplinary design team was charged with making a detailed design for OPS-SAT in the ESA concurrent design facility (CDF). The ESOC experimenters (including those responsible for File Based Operations) were tightly integrated in this design process. This was the first time that ESOC had been the customer of a CDF spacecraft design project and the new experience was appreciated by all involved. An important goal for the team was to provide a design that was robust and inherently safe. At the end of the concurrent design sessions, the team declared the project feasible and submitted a detailed design based on a 3U Cubesat. It was estimated that the project could be achieved in just 19 months and had the same or better chance of success as a standard ESA mission. OPS-SAT is now looking for funding and launch opportunities.

Figure 5. 1:1 model of OPS-SAT

Appendix A
Acronym List

CFDP	CCSDS File Delivery Protocol
DTN	Delay/Disruption Tolerant Networking
ESTRACK	ESA Tracking Stations Network
FARC	File Archive
IP	Internet Protocol
MCS	Mission Control System
OCC	Operations Control Centre
PARC	Packet Archive
PDU	Protocol Data Unit
PUS	Packet Utilisation Standard
SFO	Store and Forward Overlay
SLE	Space Link Extension
SOIS	Spacecraft On-Board Interface Services
TC	(Spacecraft) TeleCommand
TCP	Transmission Control Protocol
TM	(Spacecraft) TeleMetry

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