Deployment of File Based Spacecraft Communication Protocols

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The prospect of augmenting traditional message based spacecraft communication is now offered by protocols and procedures for transferring data as files. For information such as science data products formatting the data into packets for message based communication is an unnecessary aspect of the transfer mechanism since the packets are not usually processed in real-time but are instead disassembled and used to reconstitute the required product on the ground. In addition to science products higher level file based structures have obvious application to a variety of operational data such as plans, procedures, onboard software, configuration data and databases. The presence of such potentially large data structures moving around the system over time requires an evolution of the associated mission operations concepts to ensure the data in transit can be tracked and retains consistency and relevance to the overall mission. Important work has been performed to define the protocols such as CFDP and DTN which support a file based transfer capability to/from spacecraft with potentially sporadic connectivity. The next step is to define how these new capabilities map onto existing technologies and practices and how operational concepts need to be evolved to make best use of them. This paper examines from an operations perspective how file handling functionality provided by an automated communication architecture based on CFDP/DTN/LTP might be deployed for different mission types. In doing this we examine extensions and simplifications to the operations concept to support file based operations. This evolution encompasses new aspects of data management that considers what file types are used and how the files themselves are created, stored, transmitted/received and managed to enhance mission operations.

I. Introduction

This paper investigates how previous work developing ground and onboard implementations of protocols and technologies that can be used to support file based spacecraft operations. In doing this it is necessary to do more than simply define a way of using a remotely accessible file system or specifying appropriate extensions to the Packet Utilisation Standard (PUS) to support file based transfers. Instead our analysis is based on the following steps:

- A summary of the underlying protocols and technologies that make file based operations a possibility.
- Precursor work relating to deployment of these protocols and technologies.
- The need for file based operations and the advantages that are implied.
- Evolution of operational concepts to support file based operations.

II. Underlying Protocols and Technologies

Before considering operations concepts it is important to outline work that has been performed on the range of protocols and technologies that address the underlying challenges of the space communication environment and are enablers for a more automated file based communications architecture.

To date the majority of file-based communication with spacecraft has made use of bespoke protocols and operational procedures resulting in limited flexibility and high levels of operations effort. More recent developments

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in space communication protocols promise a move towards a more capable, standardised and re-usable basis for operations.

A. CCSDS File Delivery Protocol (CFDP)

CFDP supports the transfer of data between two (normally remote) file stores, taking into consideration issues commonly experienced in space communication environments such as latency, interruptions in the communication links, use of intermediate relay nodes and a range of lower level protocols. Use of CFDP is not limited to the space segment and it could be used to replace bespoke / mission specific ground segment applications or services that have been developed, particularly with respect to the movement of large data structures.

CFDP offers the following capabilities

1) A reliable data transfer engine supporting operation in the space communication environment
2) File transfer and remote filestore manipulation primitives
3) Extended procedures (EP) : a store and forward mechanism where parts of a file are forwarded by relay immediately upon receipt so initial parts of a file are delivered rapidly to the final destination
4) Store and Forward Overlay (SFO): a store and forward mechanism where each file is assembled at each relay. This allows detailed status reporting and allows queues of files at relays to be manipulated.

What CFDP cannot do is to dynamically take advantage of multiple parallel data paths to optimize data transfer, for example by transparently handing over data transmission from one ground station to another prior to loss of signal (LOS) or by using multiple orbiting relays in parallel to deliver a file.

With regard to defining operations concepts it is important to note that CFDP connections between nodes are based the transfer of complete files. This means that if a given file is too large to transfer during the next contact then data will be held up in the network waiting for contact to be re-established between source and destination even when there alternative paths may become available. The implication here is that the files should be appropriately fragmented at source to match the available pattern of contacts.

B. Disruption/Delay Tolerant Networking (DTN)

Disruption/Delay Tolerant Networking (DTN) focuses on store-and-forward capabilities aiming to provide a network layer that is tuned for communication links where there is high latency and the prospect of disruption. DTN relies on a Bundling Protocol (BP) and an underlying transmission protocol such as the Licklider Transport Protocol (LTP) described below to collect application data blocks into bundles that can be sent with a guaranteed level of service.

Key capabilities of the Bundling Protocol include:

1) Use of scheduled and opportunistic connectivity
2) End-to-end security based on a range of mechanisms providing to encryption and the ability to check that a received bundle was transmitted by a known, trusted source and that it has not been modified.
3) Flexible addressing using Uniform Resource Identifiers (URIs) which allow data to be addressed to destinations that meet some criteria in addition to traditional addressing based on explicit identification of specific destinations.
4) Support for fragmentation which allows bundles to be broken up and then reassembled inside the network as required.
5) Automatic removal of data from the network that has exceeded a *Time-to-live* attribute assigned by the source.
6) Reliable data transfer (optional) using a custody transfer feature to checkpoint the progress of a bundle.
7) Status reports relating to a bundle’s progress through the network which may be sent to the source or some other destination for retrieval as required.

C. Other protocols

In the context of file based operations CFDP and DTN are the primary focus for this paper. The following protocols are also of relevance:

1) IP/UDP/TCP : for those parts of a mission network which are not subject to long delays standard terrestrial protocols may provide the required network capability. Indeed, provision has been made within CCSDS to carry IP packets in CCSDS space links.

2) CCSDS TM/TC : packet based delivery of telemetry, science data and telecommands

3) Proximity-1 : a link layer protocol design for operations that involve limited power and contact periods, such as between a lander and an orbiting relay

4) Licklider Transport Protocol (LTP) : reliable data transport capability over links with a high degree of latency and disruption.

5) Spacecraft Onboard Interface Services (SOIS) : standard application services including file access/management within a single spacecraft

6) Space Link Extension (SLE) : supports remote manipulation of the space link service interfaces via a proxy installed at the ground stations allowing the transfer of data structures associated with CCSDS TM/TC

7) Packet Utilisation Standard (PUS) : ESA standard defining command and monitoring services. This includes the large data transfer service (service 13) providing segmentation and acknowledgement of large data transfers, though this is not as optimised for long delay and disrupted links as CFDP/DTN. There are plans to update PUS to include explicit support for file based operations.

III. Precursor Work

Work has been performed on behalf of ESOC to implement a CFDP Entity Library[1] for managing a set of distributed filestores. The resulting library fully implements the CFDP protocol[4] and its peripheral services and has the potential for integration within ESA Ground Segment software systems.

Building on the CFDP Entity Library a Space Communications Simulator based on ESA's SIMSAT infrastructure, components from ESOC's Ground Systems Test and Validation infrastructure (GSTVi) and incorporating a DTN implementation provided by Trinity College Dublin has been developed[2,3]. This simulator has been used to exercise various different mission scenarios ranging from conventional near earth EO spacecraft to planetary landers with multiple relays and ground stations. Having defined a given mission scenario the demonstrator can be used to analyse communication architectures, protocol configurations and file-based operational concepts.

Under contract to ESTEC the Space Internetworking and DTN Prototyping project has enhanced the Space Communication Simulator and refined the reference space communications architecture from the earlier CFDP studies. The result is a set of CFDP/LTP/DTN based references architectures supporting packet and file-based operations including prioritorised commanding, network management and emergency commanding for LEO, Lunar, L2 and Mars mission scenarios.

In addition a prototype of the reference communications architecture has been deployed on the RASTA Avionics Test bed in ESTEC's Avionics Lab to support measurement of spacecraft resource utilisation and integration with wider space communications simulations.

IV. Evolution to File Based Operations

Historically files have always been used to pass data around the ground segment while packet-based protocols have been used to move data between space and ground. The incidence of increasing numbers of high resolution data producers on board spacecraft means that payloads are acquiring increasingly large volumes data. In addition, advances on onboard storage, processing and compression technologies means that this large volume of data is potentially available in a wider range of data product types while the presence of on-board post-processing of the data also permits intelligent selection of the sets of data products to be transmitted to the ground. The need to transfer semantically large data structures which has existed on the ground and in the ground to space direction for some time is now required throughout the space segment. Extending the ground file-based paradigm into the space segment is consistent with the reality that multiple applications across ground and space require access to the same data products

Using traditional packetisation mechanisms imposes an undesirable overhead on data that has already been assembled into structures designed to support subsequent processing and analysis since reassembly is required at the remote end of the communications system. If these structures can instead be transferred as files then interfaces in the wider space/ground system can be rationalised. At the same time transmission and dissemination is simplified as each file contains a self-consistent set of data with end-to-end traceability. In the following sections we look areas where evolution of the overall operations concept is required in a move towards end-to-end file based data management.

A. File Usage in the Space Segment

Files have long been used with in the ground segment for the movement of operational configuration data and products. In looking at potential usage of files in the space segment we consider the forward and return links separately. Table 1. describes a set of generic file data types supporting operations between ground and space.

Table 1. File Based data on the Forward Link. *Transmission of single telecommands remains packet based.*

Data Type	Description
Telecommand Files	Grouping of commands in the form of time/position based schedules or simple command stacks constructed on the ground for onboard execution. This data type offers several use cases including: • Update of onboard time/position based schedule • Reuseable schedules e.g. position based schedule for entire repeat cycle • Reuseable command stacks, effectively a macro command capability Note that with a file based approach to operations the monitoring of a command schedule or stack could be via an appropriate *parameter set* as defined in Table 2.
On board Control Procedure	Reuseable user defined on board automation procedures.
Onboard Software	On board software patch or complete image. Held in persistent on board storage to allow re-applicable in the event of corruption or a hard reset of the on board hardware

Table 2. describes a set of generic file data types supporting operations between space and ground. Note that the on board software and configuration table data types are needed in this direction also to support ground based anomaly investigation and analysis.

Table 2. File Based data on the Return Link. *Routine parameter reporting remains packet based.*

Data Type	Description
Product	Data products generated by payload instruments or platform subsystems (e.g. GPS data) for a specific activity in the format required to ground based dissemination and analysis.
Parameter Set	Sets of telemetry parameters serving a specific purpose, for example: • Command acknowledgements and parameters associated with execution of an OBCP or a *telecommand file* as defined in Table.1. • Diagnostic telemetry, potentially at high sampling rates to support anomaly investigation. • Parameter sets constructed onboard on the basis of filter and/or time range to support monitoring of specific operations.
On board Software	On board software patch, complete image or other memory dump for ground analysis.
Configuration Table	Configuration data from platform/payload hardware and applications for ground analysis.

The correlation between the *Telecommand File* on the forward link with the *Parameter Set* on the return is worth noting. This provides an example of the use of file based containers to simplify the monitoring and control of schedules, stacks (and OBCPs) by lifting all of the communications to a suitable, equivalent level of abstraction i.e. execution status is represented at the level of the original schedule, stack or OBCP rather than at the level of the lower level commands or procedure steps.

B. Management of Data In-Transit

Having visibility of the data structures directly during transmission from source to destination allows monitoring, and management of the data as it passes through store and forward networking nodes, in accordance with the requirements of the data sets themselves. The essential point is that application semantics are maintained throughout the transfer so that the original file based data structures can be identified at all points on the transmission path

Visibility of the progress of data transfer is required by the operations system for monitoring purposes and for analysis of autonomous routing and delivery, this monitoring data will include notifications when a node begins transmission/reception of a file as well as regular estimates of the time to complete each transfer. Access to this status data also supports intervention in the communications process to optimise performance or in the event of contingency situations. Specifically the system may wish to

- Browse a file store by requesting the catalogue of all files/directories.
- Change delivery sequence or priority of files
- Manually pause, restart, initiate or cancel onward transmission of a file
- Modify/replace or append file content
- Modify routing information tables or other autonomous transfer management mechanisms.
- Monitor automatic data aging via a ‘time to live’ field based on file content and destination.
- Control bandwidths and permitted traffic over a given link.
- Perform data driven routing based on the content of a file.
- Perform traffic prediction

- Creation of emergency bandwidth by delaying or deleting other traffic.

In the hostile communications environment of the space segment it is also necessary to track what has been delivered in the even of link disruption and deal with deletion of redundant data in file stores when the link is restored.

C. Data Transfer Services

The deployment of file based communication services will complement rather than replace lower level packet based mechanisms. As indicated in the preceding section *message services* based on small data structures remain the most appropriate choice for real-time monitoring and control while file services are a better fit for larger structures such as science data products. The following top level data transfer services are envisaged:

- Message Service : for small data structures that can be transferred in an immediate manner. Transfer is atomic in that the message is received in its entirety, or not at all.
- File Service : for large data structures that take time to transfer. Transfer is not atomic and may even require more than one contact.

From an operational point of view the fact that the transfer of a file may take considerable time, perhaps even requiring multiple contacts to complete, is highly significant. The status of the mission may evolve while a file is in transit making the data it contains more of less important or requiring update/extension of the file contents. It is also possible that partial data files become available but will remain incomplete for many hours due to fragmentation in the space segment. The potential for fragmentation in an interplanetary mission involving one or more relays is obvious but may also occur for simpler LEO spacecraft downlinking file fragments as a series of different ground stations are overflown. In cases where extensive fragmentation is unavoidable the operation concept should ensure that partial files contain useful ‘quick look’ data which is accessible before the file is complete.

It is noted that DTN incorporates autonomous pro-active/reactive fragmentation when there is a mismatch between the size of the files being transferred and the bandwidth/duration of the available contacts but the operations concept should still consider the issue of correlating file size with the capacity of the available contact periods to minimise fragmentation.

D. Space Segment Autonomy

Comprehensive centralised manangement of data in-transit over a complex space/ground store-and-forward network is unlikely to be practical, except for nodes that are not subject to significant latency with respect to the management node. Given this constraint remote management is best limited to occasional adjustment of static configuration data perhaps with a level of autonomous local management based on data types/priorities and selection of pre-configured backup routes as an immediate response to network failures. As the underlying protocols develop it may be the case that more intelligent routing algorithms will be feasible, perhaps driven by file attributes such as ‘time-to-live’.

File management autonomy is also applicable in filtering and selecting files for transfer. Algorithms that conduct periodic scans of prioritorised file store directories holding different categories of platform and payload data may be appropriate with the potential for enhancements to handle dynamic priorities as data ages

Autonomy may also be employed to support automatic or mixed initiative data handling, For example scientific data products can be analysed automatically onboard it to detect specific events. The resulting event summaries can then be downlinked as a priority to allow a ground based human operator to select which products to downlink in full.

E. End-to-End Traceability

A large proportion of mission operations depend on the ability to trace the lifecycle of file based data structures through the space/ground systems and the need to split a file into packets for transmission will complicate the traceability and verification with respect to the original file. For example, in uplinking an onboard schedule update that emerges from the Mission Planning System as a series of telecommand packets it is relatively easy to trace and verify uplink, acceptance and execution at command level but not with respect to the schedule update as a whole.

Similar situations arise in the space-ground direction where self contained data sets which are generated on-board need to be transmitted to the ground, verified, correlated with the original requests and disseminated to the correct destinations.

F. Reduced Load on Operations Teams

Use of common data structures throughout the wider space/ground network means that operations staff are dealing with data structures they are familiar and can easily see what data is being held in the space based assets. More importantly use of a file based protocol designed to overcomes that challenges of the latency and disruption allows human operations support to focus on the higher level tasks of analysis and planning rather than the details of file management. At the same time safeguards are needed to ensure that that traffic is not accidentally sent over a space link in such a unified network but the potential benefits are many.

G. Ensuring Completeness

It is essential that data is delivered in sequence and without any loss. This is especially true for data products such as OBSW patches, telecommand schedules and configuration tables. It is inherently easier to ensure the completeness of data transmitted as file based products through the use of files at each stage of a transfer combined with a transfer protocol that performs closed-loop data recovery.

H. Confidentiality and Integrity

Security requirements may apply to all or only part of the data carried over the space/ground network. In a file based environment where confidentially is required encryption algorithms can be implemented at the start and end of the affected communications paths and applied to the files as required. Similarly integrity can be ensured through the use of file level checksums.

I. Optimised use of Bandwidth

A file based approach to operations will include specific mechanisms to make best use of the available communications bandwidth:

- Use of data compression algorithms which can be optimised for different file types.
- Intelligent filtering and selection of data sets to prioritorise transmission.
- Onboard processing of science data to support selection and filtering.

V. Conclusion

Increasing complex missions are placing new requirements on space communications which are already characterised by high latency and signal attenuation, link disruption (both predictable and unpredictable), asymmetric links, and limited power, processing and storage resources. Operational concepts based on robust file based communications may offer solutions.

The emergence of technologies to move data as files around the space segment requires evolution of the operations processes for:

- Planning, scheduling and executing space and ground segment operations.
- Evaluating the success of executed operations and monitoring the performance of the space segment.
- Timely production and dissemination of mission products.

To support these processes the operations concept also needs to define the required characteristics of the space segment in terms of autonomous functions and mechanisms for on-board generation, storage and transmission of file based mission data.

Appendix A
Acronym List

BP	Bundling Protocol
CCSDS	Consultative Committee for Space Data Systems
CFDP	CCSDS File Delivery Protocol
DTN	Disruption/Delay Tolerant Networking
EP	Extended Procedures
GSTVi	Ground Systems Test and Validation infrastructure
LEO	Low Earth Orbit
LOS	Loss of Signal
LTP	Licklider Transmission Protocol
OBCP	Onboard Control Procedure
PUS	Packet Utilisation Standard
SFO	Store and Forward Overlay
SLE	Space Link Extension
SOIS	Spacecraft Onboard Interface Services
TC	Telecommand
TM	Telemetry
URI	Uniform Resource Identifiers

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