CCSDS FILE DELIVERY PROTOCOL INTEROPERABILITY TESTING FINAL REPORT

INTRODUCTION

The CCSDS has developed the "CCSDS File Delivery Protocol" (CFDP) as a disruption/delay tolerant file transfer protocol. CFDP allows an automatic, reliable file transfer between spacecraft and ground (in both directions) designed to support the operation of spacecraft by means of file transfer and remote file system management.

To support the development and fielding of the protocol in an international and cross-supporting environment, an international inter-operability test program was developed and successfully executed. First phase testing involved five independent implementations of the Core Procedures of the protocol. The second phase tests involved multi-hop transferring of files using the Extended Procedures. The third testing phase also involved multi-hop file transferring but this time using the Store and Forward Overlay Procedures. The latter two phases involved two independent protocol implementations, those of ESA and JPL. This paper is a final report on the process of testing, the test results, and the experience gained.

THE CCSDS FILE DELIVERY PROTOCOL

The CFDP enables the moving of a file from one filestore to another, where the two filestores are in general resident in separate data systems and usually with an intervening space link. In addition to the purely file delivery-related functions, the protocol also includes file management services to allow control over the storage medium. It is a delay tolerant protocol whose store and forward model of relay is much like e-mail that conveys files as attachments. The protocol as currently designed contains its own reliability mechanisms and does not assume an underlying retransmission capability.

In its simplest form, the CFDP provides a *Core* file delivery capability operating point-to-point across a single link. For more complex mission scenarios, the protocol offers *Extended Procedures*, providing an end-to-end store-and-forward functionality across an arbitrary network, containing multiple links with disparate availability, as well as subnetworks with heterogeneous protocols. As an alternative to the Extended Procedures, the *Store-and-Forward Overlay* (SFO) Procedures may be used. The SFO Procedures are implemented at the Application layer and operate as a CFDP User utilizing only the CFDP Core Procedures, and do not require the Extended Procedures.

When using its Extended Procedures or SFO, CFDP performs a type of "custodial transfer" of a file. A sender can transmit a file to an intermediate receiver over a single link and, upon receipt of the entire file, that receiver can notify the sender that it will take care of any successive forward transmission to another intermediate receiver or to the final destination. This allows the sender to release local processing and storage resources and to deploy them on new data acquisition – a very important feature for transmission of data to or from nodes with limited resources in networks with long signal propagation delays.

Another key aspect of CFDP is the *deferred transmission* mechanism, which can insulate user applications from the state of the communication system: an instrument can record an observation in a file and "transmit" it (that is, submit it to CFDP for transmission) to Earth immediately without considering whether or not physical transmission is currently possible. Knowledge of the space link availability is thus allocated to CFDP. Sequestering outbound data management and transmission-planning functions within CFDP can greatly simplify flight and ground software and thereby reduce mission costs.

The large signal propagation delays that characterize interplanetary transmission limit the usefulness and efficiency of the end to end retransmission strategies commonly used in terrestrial protocols (especially those using sliding-windows). For this reason, CFDP employs a customizable *selective retransmission model* (deferred or incremental). Data PDUs for multiple files are transmitted as rapidly as possible, one after another, without waiting for acknowledgment, and requests for retransmission of missing file segments are handled asynchronously as they are received. As a result, the amount of time required to transfer a file is reduced, as is the traffic on the return link.

CFDP is an example of a delay/disruption tolerant protocol. The current development of the Delay Tolerant Network (DTN) architecture and its Bundling protocol has leveraged lessons learned in the development of CFDP. CFDP also has the potential of operating well over the Bundling protocol (that is, utilizing Bundling as its underlying communication service), thus extending its useful life and perhaps broadening its community of interest. The experience gained with it in the development particularly of custody transfer procedures has been very valuable.

CFDP INTEROPERABILITY TESTING PROGRAM

CFDP interoperability testing is intended to be a part of a progressive set of tests, proceeding from initial internal software development testing to mission specific testing appropriate for the intended use of the implementations. An example of such a progression of tests is shown in Figure 1.

The tests in the interoperability testing are not totally comprehensive and are not Conformance Tests. However they do thoroughly exercise the procedures and options of the CFDP and provide a high level of confidence in interoperability for follow-on testing specifically oriented toward the planned application.

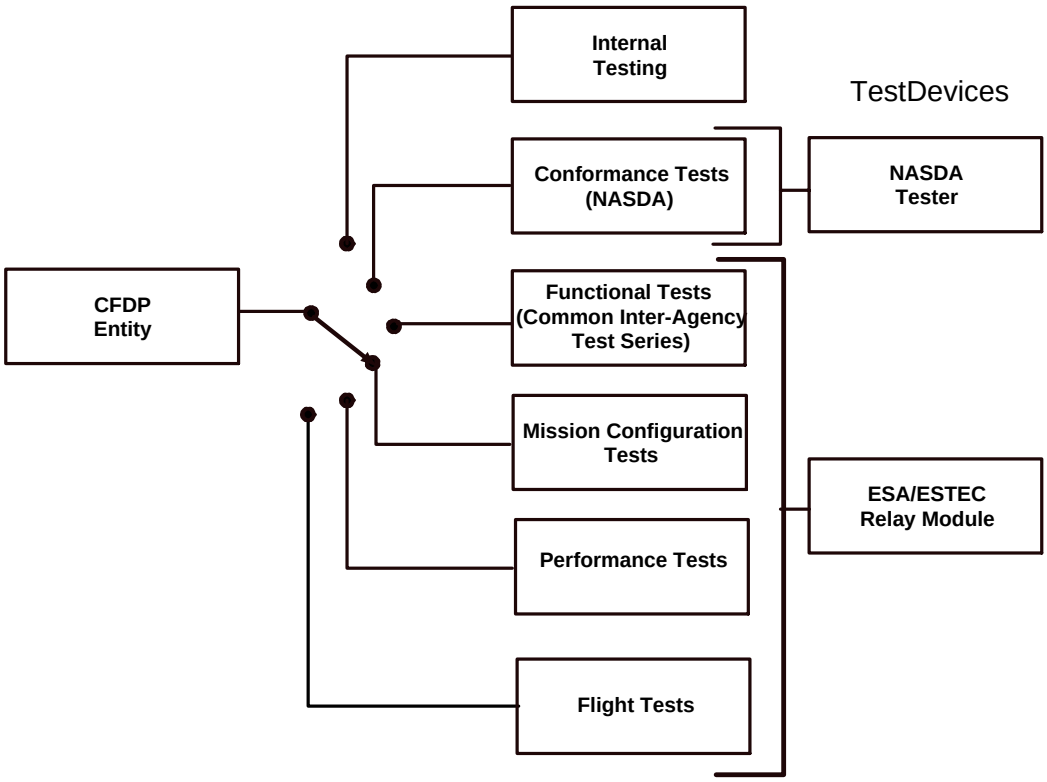

Figure 1: Testing Progression

Test documentation available to implementers include the document CCSDS File Delivery Protocol (CFDP) - Notebook Of Common Inter-Agency Tests for Core Procedures, the document CCSDS File Delivery Protocol (CFDP) - Notebook Of Common Inter-Agency Tests For Extended Procedures, and the document CCSDS File Delivery Protocol (CFDP) - Notebook Of Common Inter-Agency Tests For Store And Forward Overlay (SFO). In addition, support items were developed and contributed by participants to assist in the testing and to place the tests on a common basis so that valid test comparisons could be made and progress assessed. The NASDA NEC developed and contributed a Conformance Tester which provides both the software system and the attendant (software) scripts to allow an implementer to perform true CFDP Conformance tests on his/her implementation of the Core Procedures. ESA/ESTEC developed and contributed a Relay Module tester which provides for the insertion of known errors in the protocol stream (either inbound or outbound), including dropping of specific PDU types, insertion of duplicate PDUs, insertion of random noise type errors, insertion of link delays for simulation of deep space environment, etc. It is especially useful in executing the tests through its ability to create many different types of specific error conditions on the intermediate links. All these items are available on the Internet to interested parties, as are CFDP reference implementations by ESA and JPL.

The CFDP Inter-Agency interoperability testing program had four distinct purposes. These were:

- to verify the correctness of the protocol specification by creating multiple implementations according to that specification and thoroughly testing those implementations;

- to provide measurements of the resources required by the protocol from its hosting system, including the size of the software implementations;
- to demonstrate the interoperability of independent implementations by inter-implementation testing, and
- to make available the tested implementations as reference implementations for the use of projects and programs which wish to adopt the CFDP.

CORE PROCEDURES TESTING

The Core Procedures interoperability testing program began with face-to-face workshops and over time developed into a worldwide distributed configuration utilizing the Internet. The first Workshop was held in May, 2000, at the Applied Physics Laboratory (APL) of the Johns Hopkins University, and was so productive that it resulted in two more face-to-face workshops, held at DERA, Farnborough, UK, in November 2000, and then at JPL, Pasadena, USA, in May, 2001. Although the face-to-face workshops were very beneficial, they were expensive because of the travel involved and the host resources required. These were strong motives for developing an arrangement in which the various implementers could test with one another while remaining at their home sites. The Internet was the obvious technology to use to create such a distributed testing capability. It is free, available 24 hours per day, 365 days per year, provides almost unlimited connectivity (i.e., no limit on number of parties involved in tests), and all of the implementers were already connected.

Following the Pasadena Workshop the testing configuration for the Core Procedures migrated to what has become a worldwide Distributed Inter-Agency Testbed, operating over the Internet. The resulting configuration is shown in Figure 2. It is especially interesting that the implementers are distributed in a truly worldwide manner, from the Netherlands to the United Kingdom to the east coast of the U.S. to the west coast of the U.S. to Japan, and back to the Netherlands.

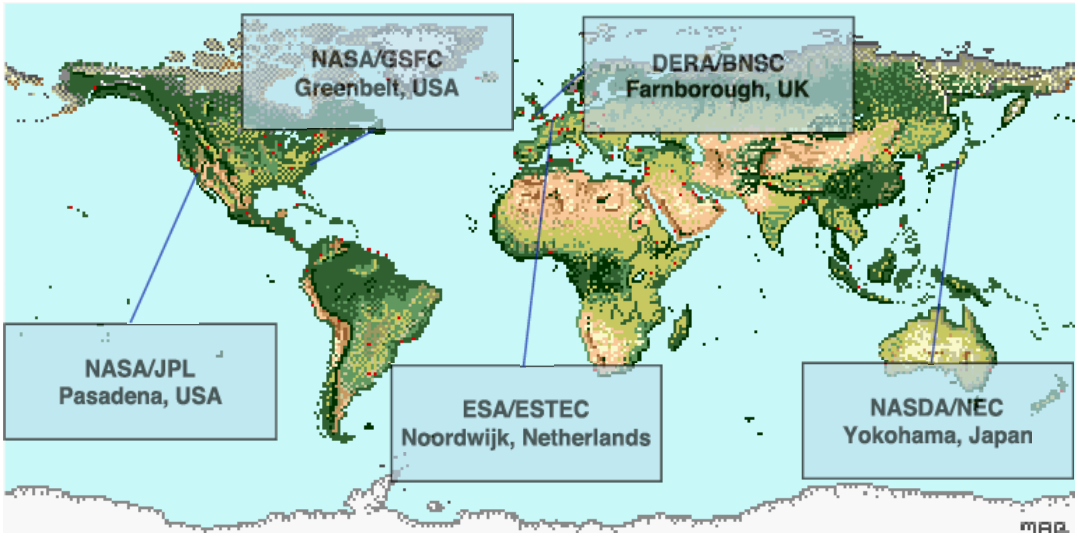

Figure 2: Core Procedures Distributed Testbed

As the culmination of the testing of the CFDP Core Procedures, a series of proctored tests were held as a "Final Exam Week" before requesting that the CFDP go from Red (draft) to Blue (final) status. In most (but not all) cases the proctor was not one of the implementers, and was located separately from the implementers. Fifteen Test Sessions of approximately four hours each were held with implementers and a proctor. Four hundred ninety tests were conducted, of which four hundred sixty two were successful. Of the unsuccessful tests, areas of the specification which were subject to different interpretations were found (and corrected), but no true errors in the protocol. While all of the tests were functional, four successful tests simulated an inter-entity range of 2.7 million miles (mission configuration tests).

The tests which constitute the Core Procedures test series are shown in Table 1 below. It should be noted that the full test series consists of a multiple of those shown in the matrix, due to the fact that many tests must be executed repeatedly as implementations are moved from one location to another in the end to end string. The full Test Series for the Core Procedures are documented in the CFDP Notebook of Common Inter-Agency Tests for Core Procedures as Test Series F1 through F5.

Table 1: Core Procedures Test Matrix

CFDP Core Procedures Interoperability Tests	Test Series Segment Number	One Way (Unreliable)	Two Way (Reliable)	Recovery from lost PDU	Deferred NAK mode	Immediate NAK mode	Prompted NAK mode	Asynchronous NAK mode
	TEST SERIES F1							
Single File Data PDU	**1**	X						
Multiple File Data PDUs	**2, 3**	X	X		X			
File data PDU loss	**4**		X	X	X			
Duplicate data	**5**		X		X			
Out of order data	**6**		X		X			
User messages	**7**		X		X			
Cancel sender initiated	**8**		X		X			
Cancel receiver initiated	**9**		X		X			
Cancel sender initiated	**10**	X						
	TEST SERIES F2							
Metadata PDU	**1**		X	X	X			
EOF PDU	**2**		X	X	X			
Finished PDU	**3**		X	X	X			
ACK (EOF) PDU	**4**		X	X	X			
ACK (Finished) PDU	**5**		X	X	X			
Extremely noisy environment	**6**		X	X	X			
Ack Limit Reached	**7**		X	X	X			
NAK Limit Reached	**8**		X	X	X			

CFDP Core Procedures Interoperability Tests	Test Series Segment Number	One Way (Unreliable)	Two Way (Reliable)	Recovery from lost PDU	Deferred NAK mode	Immediate NAK mode	Prompted NAK mode	Asynchronous NAK mode
Inactivity Timer at sender	**9**		X	X	X			
Inactivity Timer at receiver	**10**		X	X	X			
	TEST SERIES F3							
Two party Remote Put	**1**		X		X			
Create File directive	**2**		X		X			
Delete File directive	**3**		X		X			
Rename File directive	**4**		X		X			
Append File directive	**5**		X		X			
Replace File directive	**6**		X		X			
Create Directory directive	**7**		X		X			
Remove Directory directive	**8**		X		X			
Deny File Directive	**9**		X		X			
Directory Listing Request	**10**		X		X			
	TEST SERIES F4							
Deferred NAK mode	**1**		X	X	X			
Immediate NAK mode	**2**		X	X		X		
Prompted NAK mode	**3**		X	X			X	
Asynchronous NAK mode	**4**		X	X				X
Segmentation Control (record boundaries observed)	**5**		X		X			
No Segmentation Control (record boundaries not observed).	**6**		X		X			
Sender initiated Suspend and Resume	**7**		X		X			
Receiver initiated Suspend and Resume	**8**		X		X			
Unbounded file type	**9**		X		X			
File Data PDU CRC mode	**10**		X	X	X			
Keep Alive function	**11**		X		X			

CFDP Core Procedures Interoperability Tests	Test Series Segment Number	One Way (Unreliable)	Two Way (Reliable)	Recovery from lost PDU	Deferred NAK mode	Immediate NAK mode	Prompted NAK mode	Asynchronous NAK mode
Prompt (Keep Alive)	**12**		X		X			
Multiple Open Transactions (clean)	**13**		X		X			
Multiple Open Transactions (w/ data loss)	**14**		X	X	X			
	TEST SERIES F5							
Remote Put Order (2 Party)	**1**		**X**		**X**			
Remote Put Cancel	**2**		**X**		**X**			
Remote Fault Handler Override, Remote Transmission Mode, Remote Flow Label, and Remote Segmentation Control	**3**		**X**		**X**			
Remote Message to User	**4**		**X**		**X**			
Remote File Store Request	**5**		**X**		**X**			
Remote Status Report Request	**6**		**X**		**X**			
Remote Suspend/Resume	**7**		**X**		**X**			
Exercise three party Remote Put (Proxy) operation	**8**		X		X			

EXTENDED PROCEDURES TESTING

The interoperability testing approach was so successful with the CFDP Core Procedures that it was determined to extend such testing to the Extended Procedures and to the Store and Forward Overlay Procedures. SFO testing was begun in May of 2004, at a workshop held during the Spring CCSDS meeting in Montreal, Canada. At this meeting, because of continuing very stringent limitations on the available time of the protocol implementers, it was decided to complete both the SFO and Extended Procedures testing within the Protocol Testing Laboratory (PTL) of NASA/JPL's Telecommunications Section, Advanced Communications Concept Group, mainly using PTL staff.

Therefore, the available ESA-ESTEC CFDP implementation was installed and integrated in the PTL facility in order to allow in-situ protocol testing. This solution required the PTL staff to be trained on the use of ESA-ESTEC software. Thus, it was agreed to have one week of training/face-to-face testing in JPL, with the presence of the ESA-ESTEC CFDP implementer, on how to operate the provided software. This training/testing week was held in September 2005.

The Extended Procedures testing was begun in September 2005 during the training/testing session at JPL and completed in December 2005.

Initially, testing was fairly successful and few problems were encountered. These problems were mainly due to software issues and not to protocol issues. Subsequently, the implementation issues have been fixed and the same tests were successfully rerun. Overall, Extended procedures proved to be definitely easier to trace and verify than SFO procedures.

The tests which constitute the Extended Procedures test series are shown in

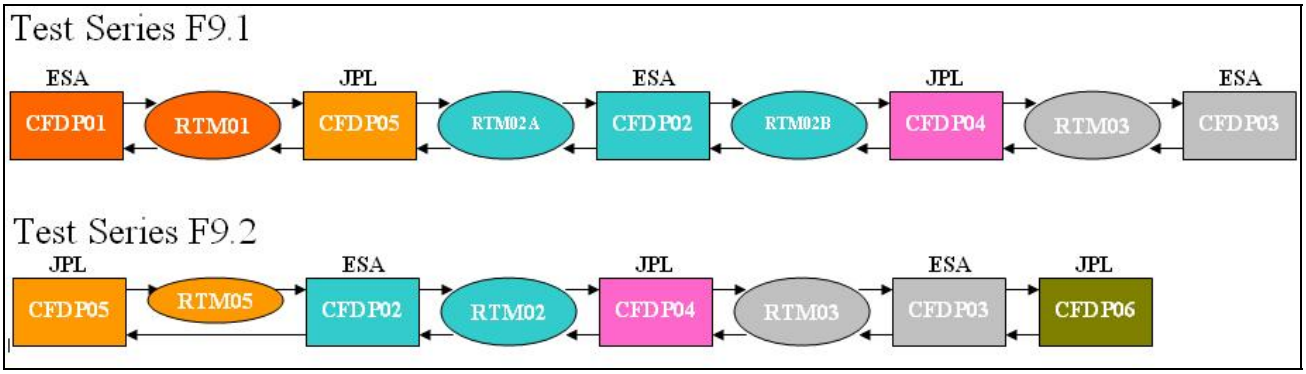

Figure 4 Example of Extended/SFO Test Configuration

Four Test Series (F6 to F9) were conducted twice (once for each test configuration), for a total of 78 test. The interoperability testing involved two independent implementations of the Extended Procedures, those by ESA/ESTEC and NASA/JPL. The testing of the Extended Procedures took place at, and was performed primarily by personnel of, the NASA/JPL Protocol Testing Laboratory.

Table 2 below. It should be noted that the full test series consists of a multiple of those shown in the matrix, as many tests must be executed repeatedly as implementations are moved from one location to another in the end to end string. The full Test Series for the Extended Procedures are documented in the CFDP Notebook of Common Inter-Agency Tests for Extended Procedures as Test Series F6 through F9, which is a continuation of the numbering of the tests for the Core Procedures described in CCSDS File Delivery Protocol (CFDP) Notebook of Common Inter-Agency Tests for Core Procedures. (It is necessary that the Core Procedure tests be performed on the entities before attempting the Extended Procedure tests)

The Figure 3 and Figure 4 below are an example of the test configuration used for ESA and JPL CFDP entities during Extended/SFO testing. Note that RTM is the ESA-ESTEC Relay module.

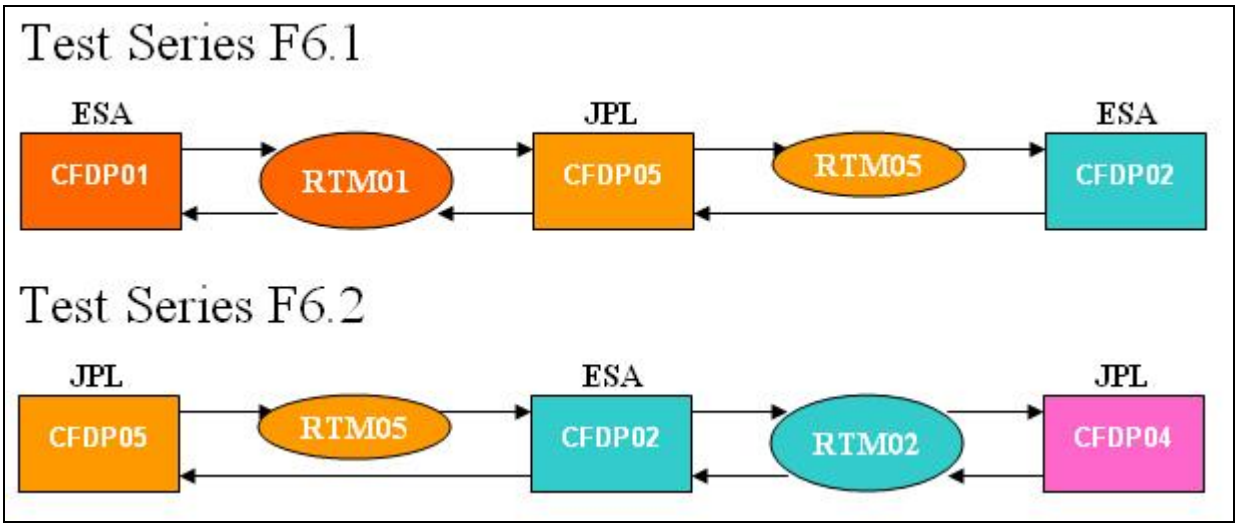

Figure 3 Example of Extended/SFO Test Configuration

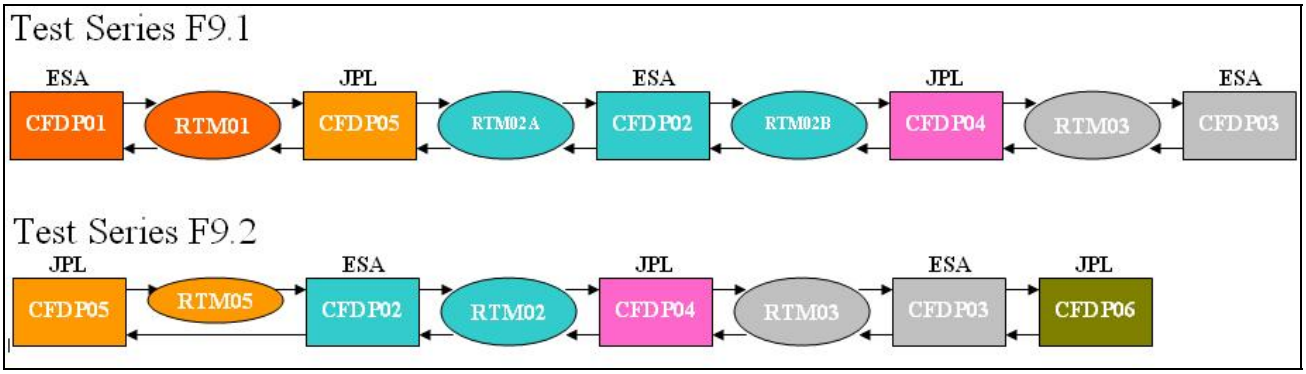

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Table 2: Extended Procedures Test Matrix

CFDP Extended Procedures Interoperability Tests	Test Series Segment Number	One-way (Unreliable)	Two-way (Reliable)	Recovery from Lost PDU(s)	Number of Waypoints (incl. Agent)	Simultaneous End-to-End Connectivity	Time Disjoint End-to-End Connectivity	Fwd Mode - Incr. and Immed.	Fwd Mode - In Total Upon Custody Acquisition
	TEST SERIES F6								
Single File Data PDU	1	X			1	X		X	
Multiple File Data PDUs	2, 3	X	X		1	X		X	
File Data PDU Loss	4, 7		X	X	1	X		X	
Duplicate Data	5, 8		X	X	1	X		X	
Out of Order Data	6, 9		X	X	1	X		X	

User Message	**10**		X		1	X		X	
Cancel Function (Source init.)	**11, 14**	X	X		1	X		X	
Cancel Function (Dest. Init.)	**12, 15**	X	X		1	X		X	
Cancel Function (Waypoint init.)	**13, 16**	X	X		1	X		X	
	TEST SERIES F7								
Metadata PDU lost	**1**		X	X	1	X		X	
EOF PDU lost	**2**		X	X	1	X		X	
ACK (Finished) PDU lost	**3**		X	X	1	X		X	
ACK (EOF) PDU lost	**4**		X	X	1	X		X	
Finished PDU lost	**5**		X	X	1	X		X	
Gross data loss	**6**		X	X	1	X		X	
Ack Limit Reached error	**7**		X	X	1	X		X	
NAK Limit Reached error	**8**		X	X	1	X		X	
Inactivity Timer limit reached	**9**		X	X	1	X		X	
Multiple Open Transactions	**10**		X		1	X		X	
Multiple Open Transactions	**11**		X	X	1	X		X	

CFDP Extended Procedures Interoperability Tests	Test Series Segment Number	One-way (Unreliable)	Two-way (Reliable)	Recovery from Lost PDU(s)	Number of Waypoints (incl. Agent)	Simultaneous End-to-End Connectivity	Time Disjoint End-to-End Connectivity	Fwd Mode - Incr. and Immed.	Fwd Mode - In Total Upon Custody Acquisition
	TEST SERIES F8								
Incremental and Immediate	**1, 3**		X		1	X	X	X	
In Total Upon Custody Acquisition	**2, 4**		X		1	X	X		X
	TEST SERIES F9								
Unacknowledged	**1**	X			3	X		X	
Acknowledged	**2**		X		3	X		X	
Metadata PDU lost	**3**		X	X	3	X		X	
EOF PDU lost	**4**		X	X	3	X		X	
ACK (Finished) PDU lost	**5**		X	X	3	X		X	
ACK (EOF) PDU lost	**6**		X	X	3	X		X	
Finished PDU lost	**7**		X	X	3	X		X	
Gross data loss	**8**		X	X	3	X		X	

STORE AND FORWARD OVERLAY TESTING

As with the Extended Procedures, interoperability testing involved two independent implementations of the SFO, those by ESA/ESTEC and NASA/JPL. As previously noted, SFO testing was begun in May of 2004, at a workshop held during the Spring CCSDS meeting in Montreal, Canada, and at this meeting it was decided to complete both the SFO and Extended Procedures testing within the Protocol Testing Laboratory (PTL) at NASA/JPL, using PTL staff. Therefore, the testing of the SFO took place at, and was performed primarily by personnel of, the Protocol Testing Laboratory, with the on-call support of ESA personnel.

The tests which constitute the test series are shown in Table 3 below. It should be noted that the full test series consists of a multiple of those shown in the matrix, as many tests must be executed repeatedly as implementations are moved from one location to another in the end to end string. The full test plan for the SFO is contained in CCSDS File Delivery Protocol (CFDP) - Notebook of Common Inter-Agency Tests for Store and Forward Overlay (SFO). (It is necessary that the Core Procedure tests be performed on the entities before attempting the SFO tests.)

Table 3: SFO Test Matrix

SFO Interoperability Tests		***Start-up***		***Msg Types***					***Error Conditions***		***Trace***				***Trace***			
Items Under Test		*One-way (Unreliable)*	*Two-way (Reliable)*	*Msg to user*	*Flow Label*	*Fault Handler Override*	*Filestore request and response*	*Segmentation control*	*Max Number of Waypoints exceeded*	*Delivery from Agent to Final Destination fails*	*Trace to original source*	*Trace to final destination*	*Trace to both*	*No trace, report failure*	*Trace to original source*	*Trace to final destination*	*Trace to both*	*No trace, report failure*
		Test Series F6, Seg.s 1, 2	Seg. 3, 4	Test Series F7, Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Test Series F8, Seg. 1	Seg. 2	Test Series F9, Seg 3	Seg. 4	Seg. 5	Seg. 6	Test Series F10, Seg 3	Seg. 4	Seg. 5	Seg. 6
Number of Entities	**Field value**	3	3	3	3	3	3	3	3	3	4	4	4	4	5	5	5	5
SFO Msg Types																		
SFO Request	40	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
SFO Message to User	41			x														
SFO Flow Label	42				x													
SFO Fault Handler Override	43					x												
SFO Filestore Request	44						x											
SFO Report	45			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
SFO Filestore Response	46						x											
Options																		
Trace control flag																		
No trace	0	x	x											x				x
Trace toward source only	1										x				x			
Trace toward destination only	2											x				x		
Trace in both directions	3			x	x	x	x	x	x	x			x				x	

Transmission mode																			
Acknowledged	0		x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x
Unacknowledged	1	x																	
Segmentation control																			
Record boundaries respected	0							x											
Record boundaries not respected	1	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x
Reports to Original Source																			
Relay transaction success				x	x		x	x		x	x	x		x			x		
Relay transaction failure						x									x				x
Reports to Final Destination																			
Relay transaction success				x	x		x	x		x	x		x	x			x	x	
Relay transaction failure						x									x				x
Error Conditions																			
Max number of Waypoints exceeded										x									
Delivery from Agent to Final Destination fails											x								
Transaction to succeed/fail		succeed	succeed	succeed	succeed	fail	succeed	succeed		fail	fail	succeed	succeed	succeed	fail	succeed	succeed	succeed	fail

Most of the interoperability (ESA-JPL) tests of CFDP SFO and Extended procedures have been performed in the protocol-testing laboratory at JPL in “absentee owner” mode.
For this purpose, a special tool was developed by the ESA implementer, which allows receiving, via email, hex dumps of PDUs causing problems and re-inserting those PDUs into a local debugging system at ESA ESTEC in Noordwijk, Holland, thus exactly recreating the problem encountered in the CFDP transaction tested in the Lab at JPL in Pasadena.
Such a tool enables a kind of “batch remote debugging” operation during the test phase.

The SFO procedures testing was begun in May 2004, continued off-line in “absentee owner mode” and also during the training/testing session at JPL. Eventually, the SFO testing completed in December 2005.

Four Test Series (F6 to F9) were conducted twice (once for each test configuration), for a total of 34 test. The SFO interoperability testing involved two independent implementations of the SFO Procedures, those by ESA/ESTEC and NASA/JPL.

Initially, testing was fairly successful and few problems were encountered. These problems were mainly due to software issues but also to some ambiguities and inconsistencies in the specs. Subsequently, the implementation issues have been fixed and the related tests were successfully rerun. The issues found in the specs have been thoroughly discussed and solution agreed. Appropriate changes will be proposed in following Pink Sheets.

Overall, SFO procedures proved to be more difficult to trace and verify than Extended procedures. This because of the higher number of reporting and success/fault tracing traffic generated by SFO with respect to Extended procedures.

LESSONS LEARNED

It became evident at the very beginning of the test program that cross-testing independent implementations made from the same specification had great value as a verification of the documents defining the protocol. Many occurrences of wording which was technically correct but subject to differing interpretations were found and corrected. This is always an issue in technical definition documents, but is especially important in documents intended for international use, and where independent implementations of the protocol are to be expected.

Second, many instances of errors in implementation were found which had not been detected by "self testing"; that is, testing an implementation against another instance of itself. These errors were usually due to systematic errors which were self-canceling.

Within the test program itself, it was an early and major lesson that detailed, agreed upon test plans were a necessity. Without them testing, especially in the early phases, tended to wander about rather erratically as implementers did individual software debugging. The testing Notebooks provided a common structure and direction, and allowed re-synchronizing the participants to be achieved reasonably easily. It was also clear that face-to-face testing is very desirable for the first two or perhaps three testing workshops. These tend to be centered around software debugging of the individual implementations, and the co-location of the participants encourages mutual assistance in that process and also provides very beneficial mutual confidence building. Finally, it was clear that once past these initial two or three workshops, distributed testing via the Internet is perfectly feasible and effective, and offers many advantages among which are greatly lowered resource requirements and very flexible scheduling.

The benefits of inter-implementation interoperability testing were so evident in the CFDP development that the concept is being expanded in CCSDS with the Proximity-1 protocol being the next target for such testing, and for the approach to be used in the development of the new Bundling protocol.