A SPACE DEMONSTRATION OF THE NEXT GENERATION TT&C STANDARDS

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ABSTRACT. An initiative is underway to develop a new integrated set of space data communications protocols that will complement and expand the current Consultative Committee for Space Data Systems telemetry and telecommand standards to provide a more comprehensive set of spacecraft control and monitor data handling services. The Space Communications Protocol Standards (SCPS) initiative will provide a new set of spacecraft TT&C standards that will serve a wide range of civil and military space missions for the forseeable future. A software 'flight test' and demonstration of the capabilities of the SCPS protocols has been performed using the in-orbit Space Technology Research Vehicle (STRV) 1b spacecraft and compared to laboratory simulations. Results from this test will provide a important contribution to the continued SCPS protocol development programme.

1. INTRODUCTION

The international Consultative Committee for Space Data Systems (CCSDS) has established the standardisation of data exchange through the communications channels that interconnect remote spacecraft and their supporting ground systems. The present CCSDS Recommendations for Packet Telemetry, Telecommand and Advanced Orbiting Systems and associated agency standards are in widespread use throughout the world space community and have already had significant impact on reducing mission operations costs. With their high performance coding schemes and packetisation capabilities, the CCSDS Recommendations provide the necessary underpinning for the automated, error-free exchange of data between space and ground systems. However, their scope is mainly limited to basic data transfer; more sophisticated functions, such as the ability to aggregate both telecommand and telemetry data into recognisable files and transport them end-to-end through the space data network in a reliable and secure manner, are the subject of expensive project-unique design and labour-intensive operations.

An activity is now underway to develop a 'skinny stack' of upper layer space data communications protocols that will expand the current CCSDS telemetry and telecommand capabilities to provide a more comprehensive set of spacecraft data handling services which eliminate the need for project uniqueness. In the context of a joint project between the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) in the United States, and the Defence Research Agency (DRA) in the United Kingdom, a set of draft specifications for the next generation of Space Communications Protocol Standards (SCPS) have been produced that cover the following technical areas:

- An efficient file handling protocol (the SCPS File Protocol, or SCPS-FP), optimised towards the up-loading of spacecraft commands and software, and the downloading of files of observational telemetry data.

- A retransmission control protocol (the SCPS Transport Protocol, or SCPS-TP) with various modes of operation, optimised to provide reliable end-to-end delivery of spacecraft command and telemetry messages between computers that are communicating over a network containing one or more unreliable space data transmission paths.

- An optional data protection mechanism (the SCPS Security Protocol, or SCPS-SP) which assures the *end-to-end* security and integrity of message exchange.

- A scaleable networking protocol (the SCPS Network Protocol, or SCPS-NP) that supports both connectionless and connection oriented routing of messages through networks containing space data links.

These four SCPS specifications were accepted by CCSDS as a new work item within Panel 1f (Advanced Orbiting Systems) in November 1995 and will be progressed towards full international standards over the next two years. This paper introduces the proposed new capabilities, their impact on reducing the cost of designing and operating space missions, and provides a description and preliminary results from a recent software 'flight experiment' of three of the four SCPS protocols utilising the in-orbit DRA STRV 1b microsatellite.

2. THE SCPS DEVELOPMENT PROGRAMME

In 1992, the US National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) chartered a technical team to explore the possibility of developing a common set of space data communications standards for potential dual-use across the US national space mission support infrastructure. Thus, the Space Communications Protocol Standards Technical Working Group (SCPS-TWG) was established comprising of NASA, DoD, and US Industry experts in communications protocol development and spacecraft control systems. In 1994, the UK Defence Research Agency joined the SCPS-TWG with specific interoperability interests for the UK Skynet series of military communications satellites.

The SCPS-TWG focused on the data communication requirements associated with the control and monitor systems of civil and military spacecraft. These are usually referred to as Tracking, Telemetry and Control (TT&C) systems. Effectively, these requirements involve a ground control centre conducting a dialogue with a remote spacecraft to upload and verify onboard memory loads, transmit discrete telecommands, and verify correct system behaviour via telemetry. Mechanisms and formats for data interchange are known as communication protocols (i.e. the *packaging* of the data between systems).

After a survey of representative US civil and military space data communication requirements and an analysis of available standard ground communication protocols (primarily from the Internet community), the SCPS-TWG concluded in Sept 1993 that the US civil and military space communities have common needs for four new space communications protocols as identified in section 1.

Using the seven-layer Reference Model for Open Systems Interconnection (OSI) to form the basis of the protocol architecture, the SCPS-TWG proposed to focus on the network layer and above and assume an underlying data link (primarily for channel coding) and physical layer (for RF modulation). The scope of the SCPS protocols is shown in figure 1.

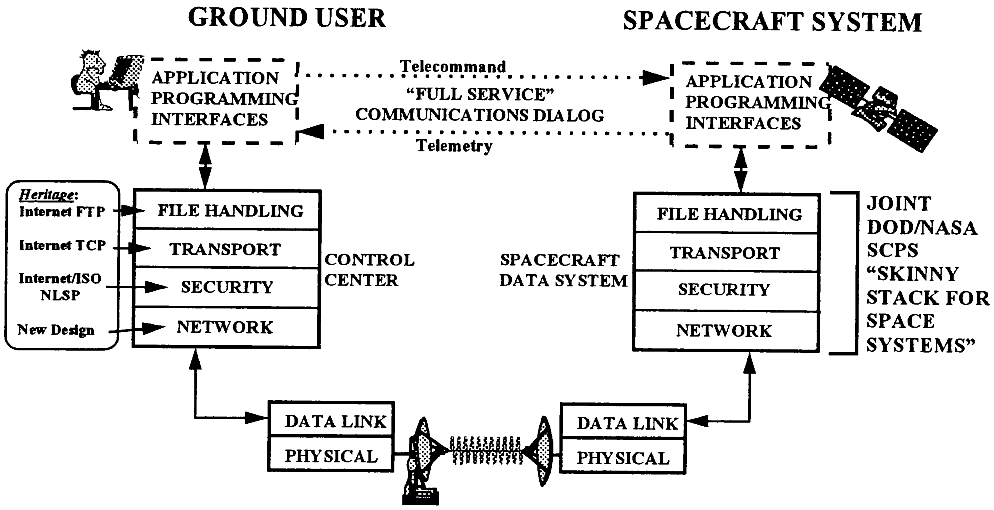

Figure 1 : Scope of the SCPS System

3. PROTOCOL HERITAGE AND CAPABILITIES

After a comprehensive assessment of currently available commercial protocols and a wide ranging future mission requirements analysis, four protocol development approaches were selected by the SCPS-TWG:

1) The Internet FTP was chosen as the basis for the SCPS File Protocol (SCPS-FP). The SCPS-TWG concluded that commercial FTP requires a number of extensions for operation in the space mission environment. These extensions include the ability to read and update individual file records, allow the user to temporarily stop a file transfer so that it may be restarted later, allow a transfer to automatically resume following an interruption in space/ground data communications, and to support file and record integrity so that an interrupted file transfer or record update does not leave files in a potentially dangerous interim state. While preserving the protocol architecture to maintain interoperability with commercial FTP, the SCPS-FP development adds the necessary capabilities and restructures the code so that it can be tailored to match various onboard processing and operating system limitations.

2) The Internet TCP/UDP was selected as the basis for the SCPS Transport Protocol (SCPS-TP). TCP is designed to operate in terrestial environments characterised by congestion loss, low bit-error rates and symmetric data rates. Application to the space mission environment requires a number of modifications for effective operation. These modifications include the delimiting of record boundaries (i.e. packets) instead of just delivering a byte-stream, provision of a 'best effort transport service' (BETS) so that a sender is not blocked indefinitely by unacknowledged data in the event of temporary outages on the space link, allow window scaling so that very large numbers of octets may be allowed to be in transit on high rate and/or long delay links, incorporation of an existing TCP option allowing timestamping to support accurate determination of round trip time or sequence number extensions for very high data rate (>100Mbps) users, permit selective acknowledgement of out-of-sequence data, and

implementation of robust end-to-end header compression which reduces the size of TCP headers (a necessary feature for bandwidth-constrained missions). This list is not exhaustive and a number of other SCPS-TP options are available depending on the mission requirements. Again, while preserving a protocol architecture that can be interoperable with commercial TCP, the SCPS-TP development adds capabilities and restructures the code so that it can be tailored to match the limitations of onboard computers.

3) A custom design was selected as the basis for the SCPS Security Protocol (SCPS-SP), the primary driver for defining a new protocol being bit efficiency. SCPS-SP is a very low overhead hybrid of the ISO Network Layer Security Protocol (NLSP), the Internet NLSP, the Internet Protocol version 6 (IPv6) security proposal and the DOD's Security Protocol 3 (SP3). It supports various authentication, integrity, confidentiality and access control options for space data exchange without assuming the use of any particular cryptography, algorithms or key management scheme.

4) A custom design with a wide range of capabilities was selected as the basis for the SCPS Network Protocol (SCPS-NP), with the primary driver in rejecting commercial network protocols being the difficulty of providing the required space mission services with reasonable bit efficiency. The original goal of the NP was to provide an upgrade to the current connection-oriented CCSDS Path service to support connectionless routing through satellite constellations having dynamic topologies and the need for different routing treatments for different messages. However, to provide scaleability for various mission types, the resulting protocol supports selectable address sizing, selectable priority, various selectable addressing options that include point-to-point, multicast and broadcast, and separate signalling of corruption and congestion. It can provide a minimum point-to-point capability with half the overhead of the current CCSDS packet, a CCSDS 'Path-like' configuration with equivalent overhead, and various modular expansions of capability and overhead all the way up to 'IP next generation' addressing.

The protocols may be deployed in several end-to-end space data communications configurations, but will often support dialog between a ground operations center and the onboard spacecraft data system (i.e. the TT&C application, see Figure 1). They may be deployed in various ways depending on the mission requirements. The File and Security protocols are both optional and may be omitted. The Transport protocol may be carried within the new SCPS-NP, or encapsulated within current CCSDS Path service. In all cases, the existing underlying CCSDS capabilities are all preserved (though it should be noted that CCSDS Panel 1a is also separately studying the feasibility of a 'next generation' underlying standard space data link protocol). The effect of SCPS on top of current CCSDS is to support an Internet-like 'full service' end-to-end communications dialog for space mission users, thus fostering widespread automation of space communications systems through interoperable networks and the consequent reduction in long-term mission operations costs.

4. THE SCPS PROTOCOL TEST PROGRAMME

An integral part of the SCPS initiative is the protocol test, validation and demonstration programme. This is being achieved through the development of software to implement the protocols, extensive test and simulation in the laboratory, and 'protoflight' of the protocols on suitable target spacecraft.

The SCPS STRV Flight Experiment (SSFE) is the first protocol flight test within the SCPS programme. It has utilised the in-orbit DRA Space Technology Research Vehicle (STRV) 1b spacecraft, which is at the end of mission life, to test the functionality of the SCPS protocols over a real space link. The STRV spacecraft are the first in Europe to fully implement the

CCSDS compatible ESA Packet Telemetry[1] and Telecommand[2] standards in an operational mission. The flexibility provided through use of the ESA standards and the availability of reprogrammable on-board computers facilitated the SSFE to be performed.

The SSFE had primary and secondary objectives as follows :

1) To test and validate the correct performance of elements of the SCPS protocol stack (see Figure 1) when exercised in an actual space mission environment, and to feed-back this experience into the development of the protocols prior to their finalisation as international standards.

2) To demonstrate the remote operation of the protocols over an international boundary.

5. THE SPACE TECHNOLOGY RESEARCH VEHICLES

The STRV 1a and 1b missions were conceived with the principal aim of providing the space technology community with affordable access to earth orbit to allow in-orbit evaluation of new technologies. The spacecraft were designed, built and tested at DRA Farnborough and are operated from the DRA Lasham ground station in Southern England. The short duration time scale of the project (from the design phase to operations in 3 years) has guaranteed the return of experimental data in a meaningful time frame.

Despite a maximum mass of only 55 kg each, a total of fourteen different experiments are incorporated in the design of the two vehicles. The majority of the technologies flown are associated with ongoing internal research programmes within the Space Department of the DRA and in conjunction with UK industries and universities. In addition, there is a major international collaborative aspect to the project. The Ballistic Missile Defence Organisation (BMDO) Materials and Structures Programme has sponsored four experiments that were built at the Jet Propulsion Laboratory (JPL) and are flown aboard STRV 1b. The BMDO also negotiated access to the NASA Deep Space Network (DSN) antennas to supplement the DRA ground station (connection to the DSN is achieved through the NASCOM system). The European Space Agency (ESA) also submitted experiments and solar panels and have provided the programme with design effort and radiation facility time. The Phillips Laboratory, Albuquerque, has provided solar panels and experimental solar cells as part of an experiment. The Geostationary Transfer Orbit (GTO) is used for the mission for radiation environment research and to achieve accelerated component testing. Figure 2 is a schematic of the orbit which also indicates phenomena that are of particular interest to the mission.

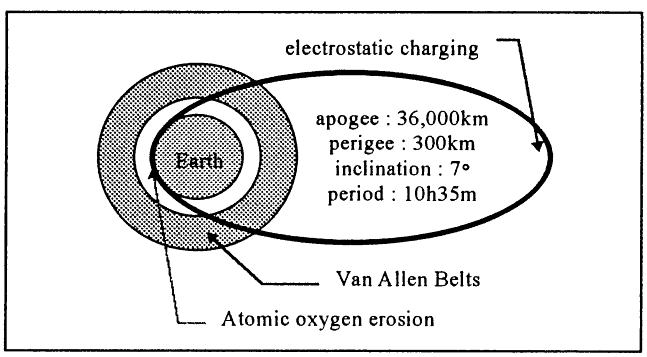

Figure 2 : Schematic of the STRV-1 GTO

[1] ESA PSS-04-106 Issue 1 January 1988
[2] ESA PSS-04-107 Issue 2 April 1992

The STRV 1a/b mission objectives are :

1. To provide the technology community with cost effective access to a harsh earth orbit environment.
2. To implement the mission with a short development timescale and return data quickly to the experimenters.
3. To enhance DRA capabilities in all aspects of spacecraft design, evaluation and operations.

Both spacecraft were launched on 17th June 1994 by Ariane 4 from Kourou, French Guiana. The one year primary mission was highly successful and a large amount of scientific data has been collected from all the on-board experiments. Due to the desire to continue operations for a number of experiments, the mission was extended and both spacecraft remain operational (June 1996). This mission extension provided the opportunity for utilisation of one of the STRV spacecraft within the SCPS protoflight test and demonstration programme.

6. THE SCPS STRV FLIGHT EXPERIMENT

The SSFE was conducted between 2 January and 30 April 1996. The testing involved using an on-board computer on the STRV 1b spacecraft as a space-based endpoint to test the SCPS-FP, SCPS-TP and SCPS-SP services in an operational environment. The primary objective of the experiment was to gain experience in hosting the protocols on an actual spacecraft and to examine the performance of the protocols when running over a real space to ground data link. The SCPS-NP protocol was not included in the tests as representative networking scenarios could not be established using the STRV control system in the time available. Figure 3 provides an overview of the SSFE.

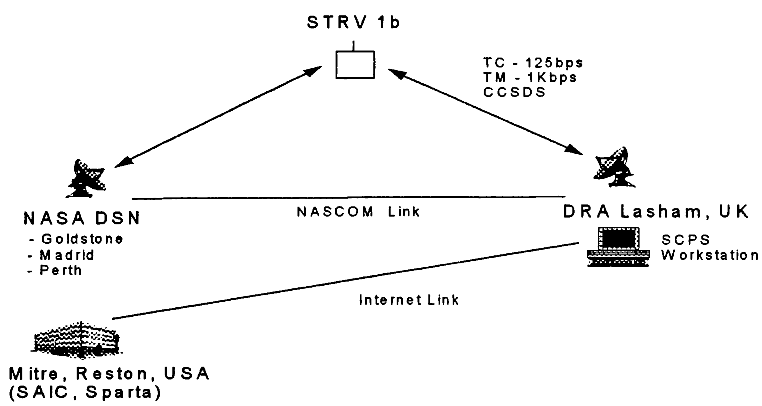

Figure 3 : Overview of the SSFE

In order to perform the experiment, a number of modifications to the current STRV control segment at DRA Lasham were made. The Lasham modifications included the installation of two new PCs, one for secondary CCSDS telemetry processing and one to host the ground based SCPS protocol software (known as the SCPS workstation). The SCPS workstation, shown on the left-hand side of the Figure 4 is a 486-based PC running the 'FreeBSD' UNIX operating system. The PC has a 14.4 kbps internal modem, through which the PC is connected to the Internet via a commercial Internet provider to allow remote test supervision from US facilities. The SCPS software runs as an application on this workstation and sends CCSDS telecommands over an RS-232 line to the telecommand workstation. The telecommand workstation forwards the packets to the spacecraft and provides performance feedback to the SCPS workstation over the same RS-232 line. The SCPS workstation receives CCSDS telemetry packets and frame status information from the CCSDS telemetry processor over another RS-232 line. The STRV ground segment communicates the CCSDS packetised data by using a 12 meter antenna that is co-located with the Lasham ground station, or via the NASA DSN, or via both.

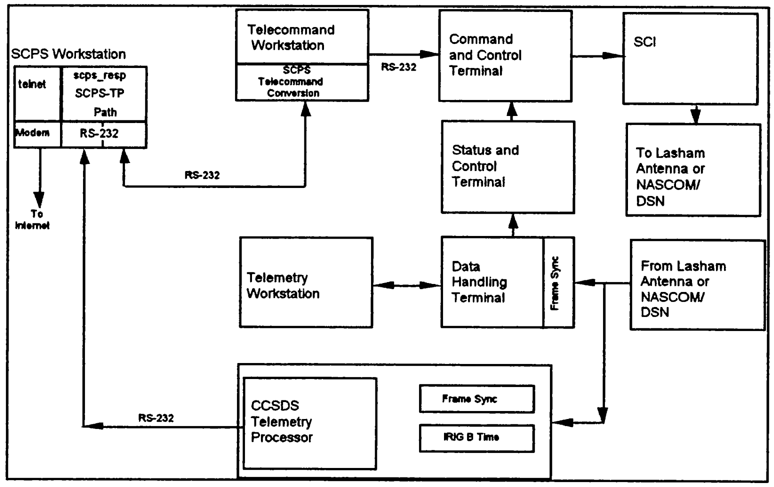

Figure 4 : SSFE DRA Lasham Ground Segment Architecture

The SSFE on-board system was hosted on one of the dual-redundant Mil-Std-1750A CPU based On-Board Computers known as OBC2. This computer has 64K 16-bit words of Random Access Memory (RAM) and 32K 16-bit words of read only memory to support the primary mission. The SCPS software development team produced 'lightweight' versions of the SCPS-TP, SCPS-FP and SCPS-SP code. After compilation into 1750 assembler code and extensive debugging using a 1750 development environment and an STRV engineering model on-board data handling subsystem located at DRA Lasham, the software was uploaded to the OBC2. A Kernal developed by Mitre provided the SCPS interface to OBC2. The full complement of uploaded SCPS software occupied approximately 120 Kbytes of RAM.

A wide range of tests were then conducted during planned link sessions direct from Lasham or via the DSN to test selected elements of the SCPS protocol functionality over the STRV space-ground link. Low data rates (125 bps uplink and 1K bps downlink) and high error rates provided a suitably stressing environment for the tests. Accurate calculation of the STRV downlink bit error rates has proved difficult. This is necessary for some aspects of the data analysis. Preliminary data analysis has utilised a bit-error rate calculation based on the ratio of received good and corrupted CCSDS telemetry packets.

The transport protocol testing concentrated on the performance of three of the SCPS-TP enhancements to TCP for space applications. These were the header compression, TCP timestamps, and the Selective Negative Acknowledge (SNACK) options. Various combinations of these SCPS-TP options were tested (8 in all). Data analysis is continuing at present, and a number of additional tests are planned during July to complete the data set. *Preliminary results* comparing the SSFE SCPS-TP data (Xs) to laboratory simulations (line) when all the above three options are 'on' in a high error rate environment are shown in Figure 5 below. The vertical scale is data rate (bps).

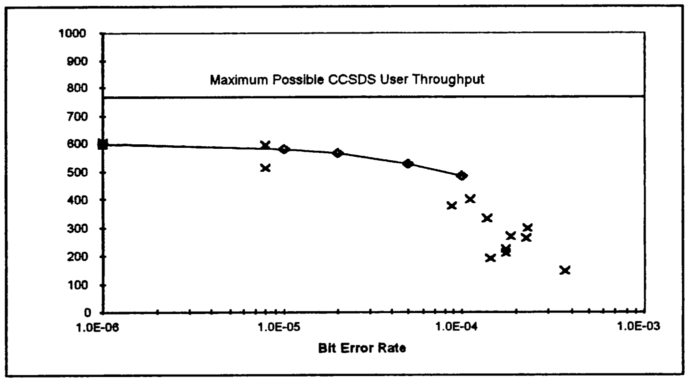

Figure 5 : Preliminary SSFE SCPS-TP Laboratory to Real Data Link Comparison

Laboratory comparisions of SCPS-TP to TCP throughput have indicated that SCPS-TP is 8 to 30 times better than TCP over high error rate data links (the performance is dependent on data packet sizes). Also, when bit error rate exceeds 10^{-4}, TCP throughput approaches zero. The SSFE TP data analysis is continuing with the primary aim of validating the laboratory simulations with flight data.

The basic capabilities of the SCPS-FP and SCPS-SP were tested with SCPS-TP providing the communicating link. All tested functions worked reliably and the tests are considered a success. Commands to open a SCPS-FP connection, transfer a file from space to ground (40 times), read a file record and edit a file worked every time.

7. CONCLUSIONS AND FUTURE DEVELOPMENTS

The SSFE has provided an important representative flight environment for test and checkout of the SCPS protocol functionality while they are still in the development stage, and generated very beneficial data in terms of feed-back on their operation over real space data links. The ultimate objective of verification of laboratory simulation will be met once full data analysis is complete towards the end of 1996. The experiment has also demonstrated the operationally beneficial capability of in-orbit computer reprogramming to change mission characteristics at short notice and at low cost. Many lessons have been learnt during the experiment that will lead to a better end product for future military and civil space missions.

Use of the end of mission STRV spacecraft has proved very successful. As part of the continuing research into TT&C standards development, control of the STRV spacecraft is planned to be 'handed-over' to the University of Colorado in Sept 1998. Further SCPS tests are planned after the handover to fully satisfy the secondary SSFE objective of remote operation of the protocols over an international boundary. Further STRV spacecraft are planned for launch in 1998.

The SCPS protocol suite may be applied to other space communication applications (non-TT&C) such as the efficient routing of messages in internet-type satellite communications networks. Demonstrations for these other applications are planned in the near future.

ACKNOWLEDGMENTS

Many personnel were involved in the SSFE from a number of organisations including the US DoD Space Command, NASA, MITRE, SAIC, Sparta, DRA and ESYS Ltd without whose hard work and dedication the SSFE would not have been possible.