IMPLEMENTATION OF CCSDS TELEMETRY AND COMMAND STANDARDS FOR THE FAST AURORAL SNAPSHOT (FAST) SMALL EXPLORER MISSION

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ABSTRACT

Recommendations of the Consultative Committee for Space Data Systems (CCSDS) provide a standard approach for implementing spacecraft packet telemetry and command interfaces. The Fast Auroral Snapshot (FAST) Small Explorer mission relies heavily on the CCSDS virtual channel and packetization concepts to achieve near real-time commanding and distribution of telemetry between separate space borne science and spacecraft processors and multiple ground stations. Use of the CCSDS recommendations allows the FAST mission to realize significant re-use of ground systems developed for the first Small Explorer mission, and also simplifies system interfaces and interactions between flight software developers, spacecraft integrators, and ground system operators.

1.0 INTRODUCTION

The Small Explorer (SMEX) program at National Aeronautics and Space Administration's (NASA) Goddard Space Flight Center (GSFC), Special Payloads Division, in Greenbelt, Maryland was established in 1989 to provide rapid (3 year development) low cost ($35M) mission opportunities (about 1 per year) to the space science community. The first SMEX mission, the Solar Anomalous Magnetospheric Particle Explorer (SAMPEX) was launched in July of 1992. SMEX missions currently in development are the Fast Auroral SnapshoT (FAST) Explorer and the Sub-millimeter Wave Astronomy Satellite (SWAS), scheduled for launch in August of 1994 and June of 1995, respectively. Critical to achieving the SMEX low-cost, fast turnaround objectives is a reliance on standardization, re-usable designs, and system-wide interfaces that can be applied to a wide variety of science missions. As such, the CCSDS recommendations for Telemetry and Command (T&C)

communications have become a key and integral design standard for SMEX spacecraft and ground systems.

A previously developed GSFC mission, the Gamma Ray Observatory (GRO), implemented key aspects of CCSDS packet telemetry. Experience with GRO has been providing valuable experience in the development and operations of ground-based systems at GSFC [1]. The first SMEX mission, SAMPEX, is the first GSFC mission to implement the full range of CCSDS recommendations for both telemetry and commands across all spacecraft and ground systems. Building on this, the FAST mission has been able to take advantage of significant design carry-over from the GRO and SAMPEX efforts, albeit with a spacecraft Command and Data Handling (C&DH) system that differs from SAMPEX.

2.0 CCSDS OVERVIEW

The CCSDS approach yields benefits similar to those realized from other packet-based layered communication techniques in that it provides a powerful method for hiding application-dependent information from data transport mechanisms and protocols. The CCSDS committees have provided both an initial Version 1 set of recommendations, and a follow-on version known as Advanced Orbiting Systems (AOS). FAST implements Version 1 to maintain commonality with the previous SMEX mission. The Version 1 recommendations define up to seven layers for both telemetry and telecommand, and include numerous optional features. The Version 1 layers implemented on FAST are briefly described.

For telemetry [2], the Packet Layer encapsulates spacecraft application data within variable length packets, and includes headers that provide length, source identification, and sequencing information. Below the Packet Layer, the Transfer Layer supplies the basic structures of the digital telemetry channel through use of fixed length transfer frames. Transfer frames start with a frame synchronization marker, follow with header data (for frame and channel identification and status), the frame data field (packets from the above layer), and end in a trailer (which includes telecommand error control features). Transfer frames can be interleaved through up to 8 virtual channels, which allows the spacecraft to easily route data into streams destined for functionally and (possibly) geographically separate ground systems. Below the Transfer Layer are the Coding Layer, which protects against noise-induced errors in the space-ground link, and the Physical Layer, which is the modulated RF signal.

For commanding [3.4], a layered approach similar to telemetry is used, with the addition of command verification mechanisms at both the sending and receiving ends.

The Packet Layer encapsulates variable-length application-specific command data through use of packet headers with length, destination and sequence control information. Below the Packet Layer, the Transfer Layer consists of a transfer frame, which moves command data from the ground to the spacecraft, and the Command Link Control Word (CLCW), which flows back from the spacecraft to the ground via the telemetry transfer frame trailer. The telecommand transfer frame consists of a header, which includes length, identification, and command control information, followed by the frame data field (packets from the above layer). The CLCW contains counters and flags which communicate command verification information between the Frame Operation Procedure (FOP) implemented on the ground and the Frame Acceptance and Reporting Mechanism (FARM) implemented on the spacecraft. Together the FOP and the FARM make up the Command Operational Procedure (COP), of which three optional levels are specified by CCSDS. As with the telemetry link, below the Transfer Layer are the Coding Layer, which protects against noise-induced errors in the space-ground link, and the Physical Layer, which is the modulated RF signal.

3.0 FAST MISSION AND SPACECRAFT

The FAST mission will investigate the physical processes of auroral phenomena at extremely high time and spatial resolutions. From a highly eccentric, near-polar, 133 minute period orbit, FAST will repeatedly sample the high altitude charged particle environment over earth's auroral zones. In order to capture the auroral phenomena over small time and spatial scales, FAST will utilize high speed data sampling and on-board software that triggers on various key phenomena, for selecting data for downlink or for storage in a large burst memory.

The SMEX missions do not utilize the NASA Tracking and Data Relay System (TDRS) and instead rely on a network of ground stations. For FAST, these are located at Poker Flat (Alaska), Wallops Island (Virginia), Kiruna (Sweden), and Santiago (Chile). As backup, FAST will also use the Deep Space Network (DSN) station at Canberra (Australia). All of these stations will receive FAST telemetry; all but Kiruna will be used for commanding. A multi-mission Payload Operations Control Center (POCC) at GSFC will support all SMEX missions (currently in use by SAMPEX). The FAST mission Principal Investigator (PI) is Dr. Charles Carlson at the University of California (Berkeley), which is where the FAST Science Operations Center (SOC) will be located. FAST auroral science investigation requirements dictate a 'campaign' style of mission operations during the winter. For two months, up to 30 minutes of telemetry will be scheduled every orbit (10-11 per day), with commands being sent at least once per day (and be possible every orbit). For the rest of the 1 year mission, non-campaign telemetry contacts will reduce to 120-150 minutes per day. Downlinks will be done at the highest rate possible. This mission scenario will yield an average data volume ranging from 4-5 Gbytes per day (campaign) to 1-3 Gbytes per day (non-campaign).

The FAST spacecraft is a small, lightweight, orbit-normal spinner with multiple on-orbit deployables (two rigid axial booms supporting electric field sensors, two rigid radial booms supporting magnetometers, and four wire radial booms supporting electric field sensors). The spacecraft provides structure, power, thermal control, telemetry and communication links, attitude control, and health monitoring support for the scientific instruments. Details of the spacecraft data system design important to telemetry and command aspects are shown in Figure 1 and summarized in the following paragraphs.

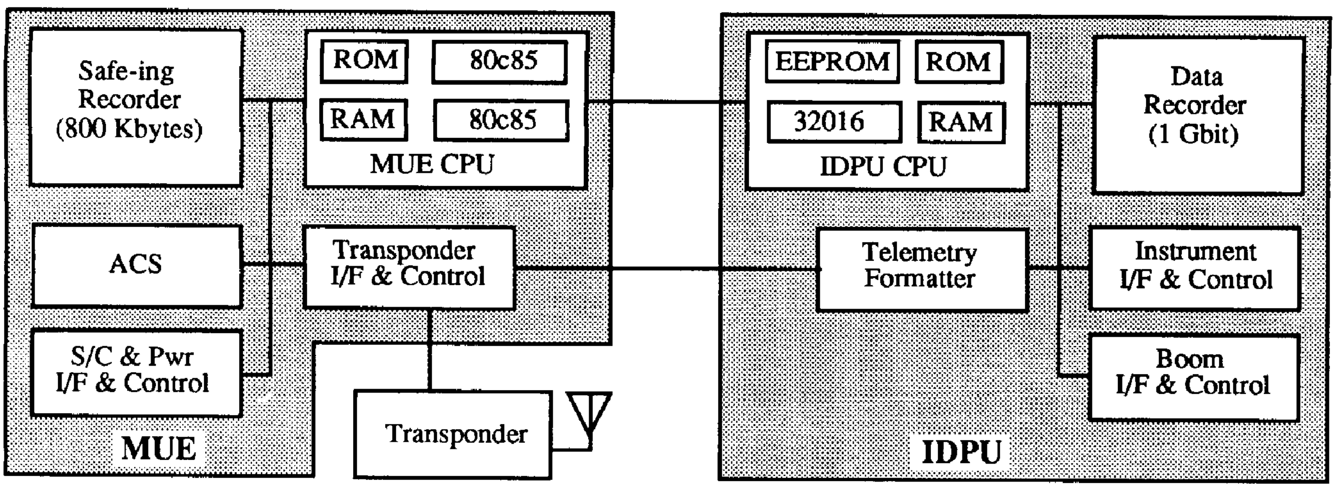

Figure 1: FAST Data System

The spacecraft command and data handling (C&DH) system is embedded within the spacecraft electronics module. This module is known as the Mission Unique Electronics (MUE), and uses a pair of 2 MHz 80c85 microprocessors, with 72Kbyte ROM and 320Kbyte RAM. The MUE performs telecommand reception, stored command processing, telemetry data collection and generation, attitude control, power management and battery charge control, and spacecraft health and safety functions. Also within the MUE is an 800Kbyte RAM recorder for capturing spacecraft safe-ing events. Power, weight and orbit radiation constraints dictated the use of the 80c85s for the C&DH (in lieu of the 80386/80387 processor flown on SAMPEX). Science objectives required a processing system more capable than the 80c85, and since the critical spacecraft functions were being performed by the MUE, the processing system for the instrument could be less radiation-tolerant. The Instrument Data Processing Unit (IDPU) uses a 10 MHz 32c016 derivative, with 16Kbyte ROM, 64Kbyte EEPROM, and 256Kbyte RAM. The IDPU manages and controls multiple instrument components, including boom deployment. Within the IDPU is a high density 1 Gbit solid state recorder, which includes a selectable (1-2 Mbyte) partition for spacecraft health and safety data.

FAST uses a standard 5-watt NASA transponder that receives commands at a data rate of 2Kbps that are transmitted as Non-Return to Zero (NRZ) bi-phase modulation on a 16 KHz subcarrier at 2.03964 Ghz. Telemetry data is transmitted at 4 digital data rates (4 Kbps, 900 Kbps, 1.5 Mbps, and 2.25 Mbps) using NRZ phase modulation directly on the carrier.

4.0 CCSDS IMPLEMENTATION

These mission, operations, and system design requirements, together with a strong desire to maintain commonality with SAMPEX ground systems, directly influenced the CCSDS options and features implemented for FAST. They also drove the need for considerable data flow between the MUE and the IDPU, shown in Figure 2, which has been implemented at both the packet and transfer frame level.

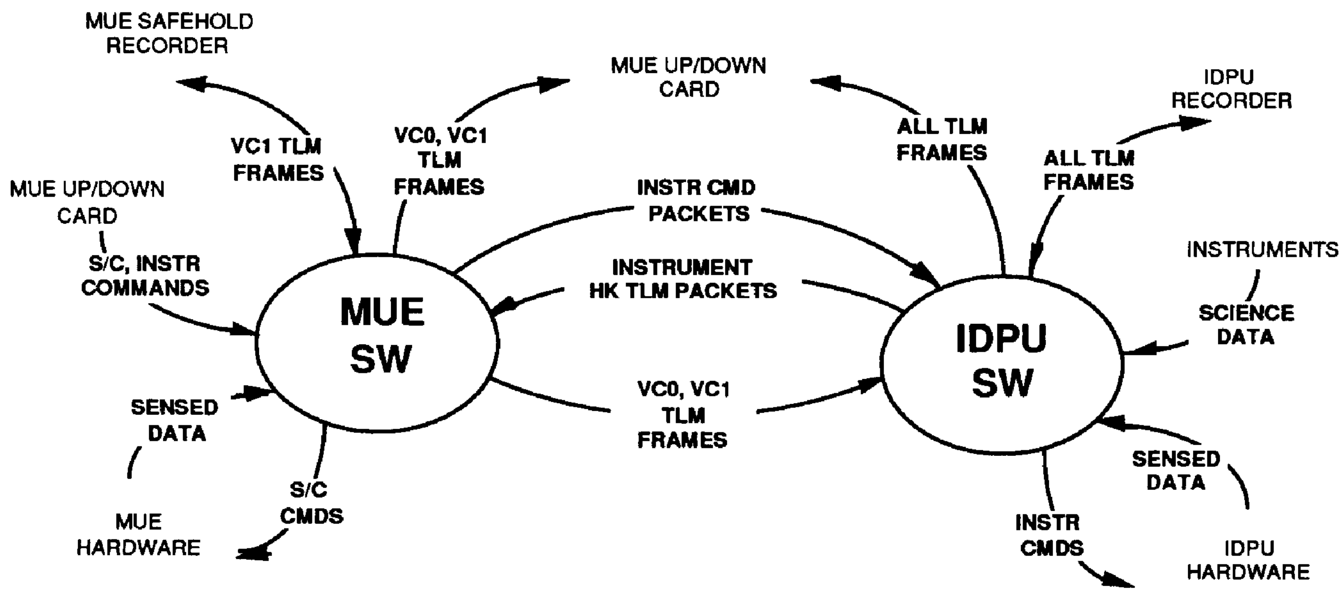

Figure 2: FAST Spacecraft Data Flow

4.1 COMMANDS

For simplicity, spacecraft and instrument commands are received by the MUE on a single COP-1 protocol telecommand channel. COP-1 uses sequential ("go-back-n") re-transmission techniques to correct any frames rejected by the spacecraft due to an error. CCSDS recommendations provide a chained control specifier mechanism at the transfer frame layer for specifying FARM parameters to the spacecraft. Use of COP-1, a single telecommand channel, and a simplified control scheme reduces the potential complexity of this mechanism to a single (unchained) control specifier using only two control commands. For operational commands, spacecraft and instrument command packets are held to a single fixed length (16 bytes) containing a single command in order to reduce the processing burden on the MUE. Software memory load and table load command packets are variable in length, but with no more than 200 bytes of load data per packet.

The FAST MUE and IDPU make extensive use of CCSDS packet header information to keep application-specific information hidden, which speeds command management processing and greatly simplifies software-to-software interfaces. Commands received by the MUE can be either executed immediately (real-time commands) or stored in buffers for later activation, according to the value of a timecode in the command packet header. When executed, all commands are routed to the appropriate MUE software module based on the application identifier (APID) in the command packet header. Command packets labeled with an instrument-related APID are sent over to the IDPU for execution.

4.2 TELEMETRY

At the packet level the MUE samples spacecraft engineering, health, and safety data (currents, voltages, temperatures, attitude measurements) and creates time-tagged housekeeping (H/K) packets. Data is allocated on the basis of functionality and sample rate (e.g., low-rate ACS data, high-rate ACS data, power data) into packets of various lengths (of order 10 to 100 bytes). Functional allocation optimizes data transfer from spacecraft subsystems to respective engineering groups, while sample rate allocation simplifies telemetry processing overhead. The IDPU creates similar instrument H/K packets and passes them over to the MUE, which merges them with spacecraft H/K packets into transfer frames.

Data from the spacecraft recorder in the IDPU is read out in 1024 byte increments. To reduce IDPU processor overhead, all science packets have a fixed length of 1054 bytes and only one packet is inserted in each frame(see Figure 3); total transfer frame length (not counting sync) is 1072 bytes.

At the transfer frame level, FAST telemetry is separated into 6 separate Virtual Channels (VCs). VC0 contains H/K packets collected while in contact with a ground station (real-time data). H/K packets collected while out of range of any ground station and stored in an on-board recorder are played back in VC1. The primary science channels are VC2 (continuous survey data), VC3 and VC4 (burst event data), and VC5 (instrument diagnostic data), all of which can contain either real-time or playback data.

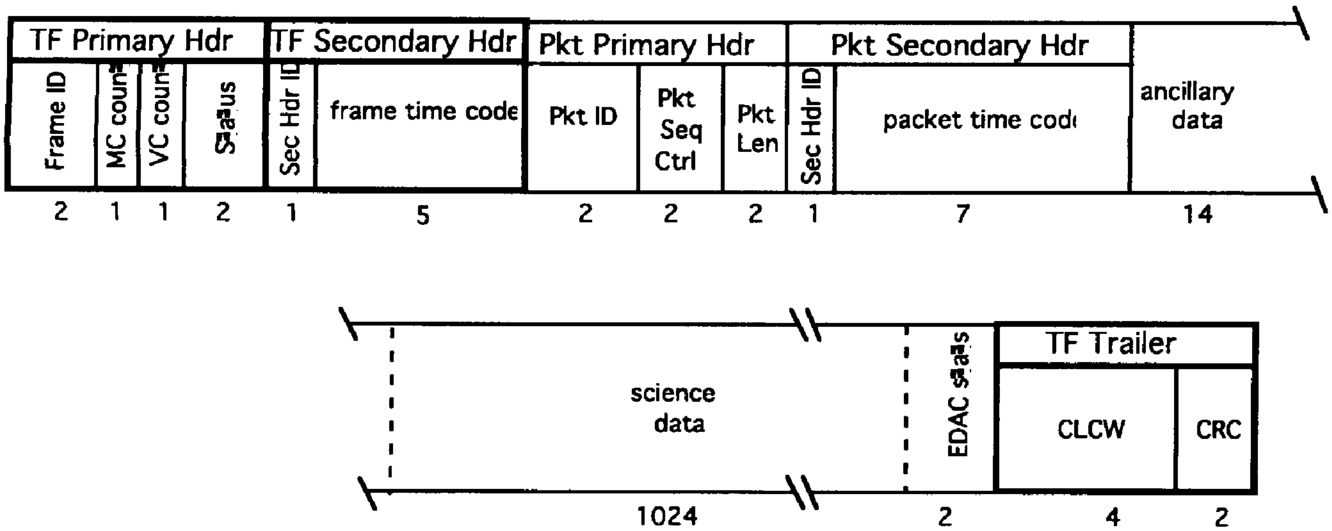

Figure 3: FAST Transfer Frame with Science Packet

The MUE processor can only generate telemetry frames at the slowest downlink rate (4 Kbps). This restriction necessitates that the IDPU controls the telemetry generation process at the three higher downlink rates. To simplify MUE/IDPU interfaces, at the higher rates the H/K packets are first formatted into VC0 or VC1 transfer frames, and the interface back to the IDPU is handled at the frame level. During downlink, the allocation of virtual channels to the physical link is ground controllable and based on numerous factors. For example, to meet the constraints of the multi-user DSN, which can only allocate 50 Kbps to FAST at any one time, VC3 functions as a metered channel for sending VC4 data at this slower rate. In other words, when in contact with a DSN station VC3 is activated (which carries a sub-sample of burst event data), but when in contact with other more capable ground stations VC4 is activated (which carries the full set of burst event data).

4.3 GROUND SYSTEMS

The mission-specific systems developed for FAST (MUE and IDPU on the spacecraft, subsystem Ground Support Equipment (GSE), post-launch software maintenance, and the SOC on the ground) must interface and operate with numerous ground systems already developed and in place at GSFC. As shown in Figure 4 these are: the Payload Operations and Control Center (POCC) for spacecraft command and H/K telemetry monitoring; the Level Zero Processor (LZP) for telemetry packet processing (time-order sorting and error flagging); the Flight Dynamic Facility (FDF) for orbit calculations and precession command generation; and the Command Management System (CMS) for command load generation. An integration and Test (I&T) GSE sends commands and receives telemetry from the spacecraft during spacecraft development and I&T activities. Each of these systems represent a fairly large investment in their own right, typically consisting of one or more mid-class workstations and requisite software for data display and management. In addition, the 5 geographically dispersed ground stations and the NASA Communications (NASCOM) network provide transparent connections between the spacecraft and the POCC/LZP, regardless of orbit position.

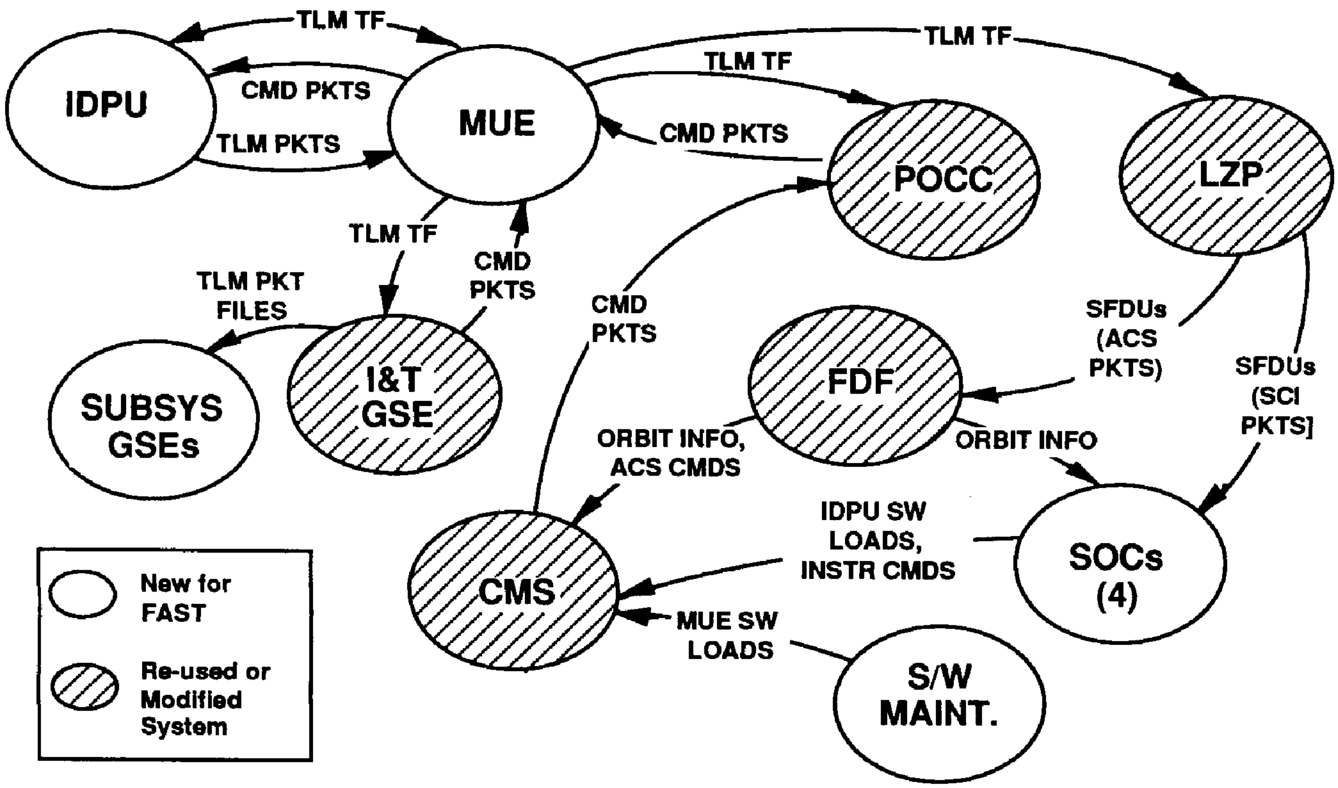

Figure 4: FAST System-wide CCSDS Data Flow

All telemetry and command data interfaces between these systems are implemented using packets, transfer frames, or Standard Format Data Units (SFDUs) – the latter being another CCSDS convention for ground system interfaces [5] – which are further encapsulated in standard ground system protocols (TCP/IP, NASCOM) as appropriate. The result has been that, although these systems are complex, geographically dispersed, and are being developed by many different organizations, interface definition and system development has proceeded smoothly and with significant software re-use.

Commonality among ground systems resulting from CCSDS implementation extends to hardware as well. The LZP system design is derived from an advanced technology prototype system developed to demonstrate CCSDS ground system usage [6]. This system uses a multi-processor VME back plane with a pipeline approach for managing the flow and level-zero-processing of CCSDS packets. The core hardware and software system was duplicated (with slight modifications) to form the basis of the

SAMPEX I&T GSE, which is also being used for FAST. Additionally, derivatives of the same core system are also being used in development of front-end systems for the Kiruna and Poker Flat ground stations.

Definition of application-specific parametric information for PCM-based satellite systems has historically been complex, tedious, and subject to difficulties in tracking changes [1]. For FAST, use of CCSDS-based telemetry and commands has significantly improved the development of ground systems in these aspects as well. A common database is being used to define commands and telemetry parameters in terms of mnemonic representation, packet structure information, standard data types, and data conversions. This database is created during spacecraft development and exchanged among all ground systems that need to interpret FAST data at the application level.

5.0 CONCLUSIONS

The genesis of the CCSDS recommendations was the recent trend to large, multi-instrument, multi-user space platforms which have increasingly greater data rate requirements. However, as has been shown on FAST, the packet-based communication approach is also applicable to small satellites. Through judicious selection of CCSDS-allowed options and features, even modest 8-bit processors such as the 80c85 can support the CCSDS standards. Packets and transfer frames provide a natural means of encapsulating data for routing between on-board processors as well as between software tasks within a processor. Virtual channels provide an effective means to, at the source, segregate science from engineering data and to meter out selected data to correspond with the ground station limitations. Hiding of application data standardizes interfaces and speeds development of both space-based and ground-based systems while at the same time facilitating software and hardware re-use among missions.

6.0 ACKNOWLEDGMENTS

Spacecraft and ground systems on FAST are being designed and developed by a highly qualified team from numerous NASA organizations and their support contractors at the GSFC. Specific to the points put forth in this paper, Jonathon Wilmot (Hughes STX) developed the telemetry and command components of the MUE flight software. Peter Harvey (UC Berkeley) led the software development for the IDPU. As SMEX Chief Systems Engineer, Jim Watzin (NASA) was responsible for the overall FAST systems architecture. Credit for successful implementation of the CCSDS recommendations must go to each team developing FAST spacecraft and ground hardware and software, and to the SAMPEX team whose systems found significant re-use on FAST.

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