

## A Novel Approach to a High Speed, Large Memory Spacecraft Data Storage Unit

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**ABSTRACT:** A high capacity Data Storage Unit is key to the store and forward mode of operation for numerous science and commercial missions and services that generate very high data volumes at high data rates. This paper introduces just such a commercial service in the form of the CASCADE service. In order for this service to succeed, one of the key spacecraft components is the Data Storage Unit, or DSU. Besides high capacity, the Data Storage Unit needs to have a relatively random access, low power consumption, and a reasonable size and mass. There are currently two storage technologies that appear to be candidates for the Data Storage Unit. These are DRAM based Solid State Recorders, and space qualified RAID's based on commercial hard disk drives. The space qualified RAID's are not as proven as the Solid State Recorders. However, the space qualified RAID's currently have a significant advantage in terms of size, mass, and power for a unit with the capacity required by Smallsat and Microsat missions.

This paper discussed a third technology now coming on the horizon which promises to have all the benefits of the RAID drives with none of the technical problems of spinning drives. This technology makes use of rugged FLASH memory modules as the storage medium.

The paper discusses the new DSU now under development at Routes AstroEngineering. This unit promises to deliver much more storage density with high reliability and speed normally associated with the Solid State Recorder at a recurring cost that is planned to be competitive with the RAID spinning drive technology. The unit is scalable, capable of storage densities of up to 10Tbits in total, with up to 8 individual memory channels sharing this memory array. Each channel is capable of 350Mbps throughput and the whole unit has a power budget of less than 65W (operations) and a total mass less than 30Kg, with built-in multiple redundant power and data paths for high reliability and availability.

### INTRODUCTION TO CASCADE

CASCADE will be a digital courier service in the sky. A constellation of Low-Earth-Orbiting (LEO) Ka-band satellites will circle the earth, picking up very large digital data packages or "GigaPackages" that can be tens to hundreds of GigaBytes in size from remote locations on land or over any ocean and deliver the data

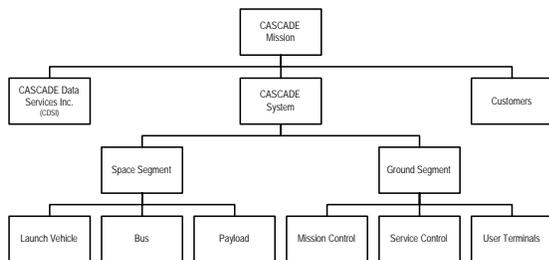
directly into a user-specified data archive or processing center.

The CASCADE digital courier service will deliver virtually error-free, secure Giga-Packages to and from anywhere on Earth. Since CASCADE is focussed on this high data volume, store-and-forward market niche, its design is optimized to meet the unique needs of the market for very large and timely data file transfers.

The CASCADE system will provide:

- daily accessibility to any point on the globe (excluding the polar areas);
- high bandwidth data links;
- large capacity storage on-board the spacecraft; and
- service on a regular and reliable basis.

The CASCADE Mission is composed of the major subsystems shown in Figure 1. The system comprises a Space Segment, Operations Segment, Ground Segment, and Business Management functions, which together will provide data delivery service to end-users. The Operations Segment and Business Management areas are responsible for the operation and business exploitation of the System after commissioning. The Space Segment is defined as all the equipment (software, hardware and documentation) in space required to support the CASCADE satellite.



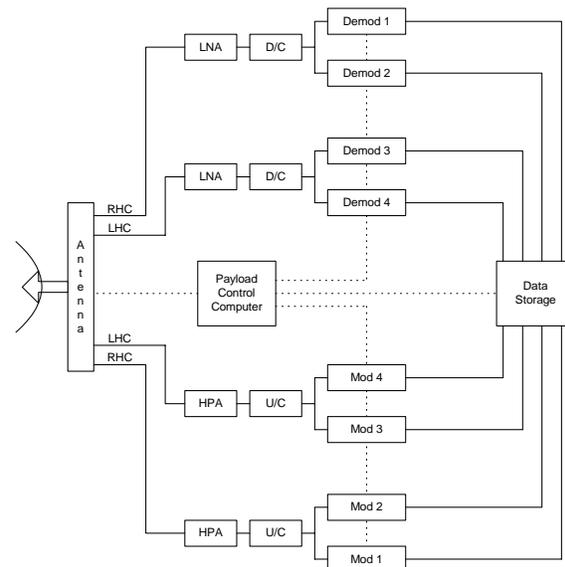
**Figure 1 - CASCADE Mission and System Decomposition**

The CASCADE mission will consist of two major phases, Phase B (CASCADE Demonstration) and Phase C (CASCADE Pre-production). Although the ultimate configurations of the complete payload and associated bus may be different for Phase B and C, the intent is to develop a data storage unit that is identical for both phases. A single development plan is envisioned. Phase B will incorporate the development of a single spacecraft, with a dedicated launch. This spacecraft will likely also contain additional non-CASCADE payloads, to maximise the use of the bus and spread the cost of the launch. Phase C will incorporate the construction of four identical spacecraft with a single dedicated launch.

The Payload Module (shown in Figure 2) provides two-way data communications capability to selected user ground stations. The payload consists of two major parts, the RF/Digital Subsystem, and the Data Storage Unit. The payload will be operated in a half-duplex mode, that is, it will be either transmitting or it will be

receiving, but not both simultaneously. Generally during a single contact with a ground station the payload will transmit or it will receive, however, nothing should preclude the payload from switching between transmit and receive during a contact.

The RF/Digital Subsystem consists of a spacecraft-pointed transmit/receive antenna, and a set of high-speed modems. To increase the amount of data that can be transferred during a contact with a ground station both right-hand and left-hand circular polarizations are used. Each polarization requires a separate modem, and, to reduce technical risk, each polarization is split into two channels, each with its own modem.



Key:

- LNA – Low Noise Amplifier
- HPA – High Power Amplifier
- D/C – Down Converter
- U/C – Up Converter
- Demod – Demodulator
- Mod – Modulator
- RHC – Right Hand Circular (Polarization)
- LHC – Left Hand Circular (Polarization)

**Figure 2 - Payload Block Diagram**

At Ka band, rain fade of the RF signal can be significant. To minimize the chances of sending data during high fade conditions the receiving end of the satellite/ground station link transmits a beacon signal. The transmitting end of the link monitors the strength of the beacon signal, and transmits dummy fill data when the beacon signal strength is below the operational threshold. To provide error-free transmission of data the CASCADE system uses a combination of methods. The primary method is the use of an interleaved Reed Solomon forward error

correction method to correct the majority of transmission bit errors. The Reed Solomon code used is the CCSDS recommended (255,223) code. The second method is the use of a low speed backhaul link (a dial-up telephone link at 9600 bps or better) between the receiving and transmitting ground terminals to retrieve random data blocks with uncorrectable errors. The third method is to retransmit bad segments of data from the originating ground terminal.

A high capacity Data Storage Unit (DSU) is key to the store and forward mode of operation for CASCADE. Besides high capacity the Data Storage Unit needs to have a relatively random access, low power consumption, and a reasonable size and mass. Ideally the Data Storage Unit would have a single Data Storage Unit for all four data channels, however, up to one Data Storage Unit per data channel would be acceptable.

There are two storage technologies that appear to be candidates for the Data Storage Unit. These are Dynamic Random Access Memory (DRAM) based Solid State Recorders, and space qualified Redundant Arrays of Inexpensive Drive (RAID) based on commercial hard disk drives. The space qualified RAIDs are not as proven as the Solid State Recorders. However, the space qualified RAIDs currently have a significant advantage in terms of size, mass, and power for a unit with the capacity required by CASCADE. Routes AstroEngineering has proposed a third technology now coming on the horizon which promises to have all the benefits of the RAID drives with none of the technical problems of spinning drives. This technology makes use of rugged FLASH memory modules as the storage medium.

### DSU PERFORMANCE HIGHLIGHTS

- Dual-redundant internal power supply strings
- Dual-redundant CPU capability
- Dual-redundant spacecraft Command and Data Handling (C&DH) interface
- Up to 20Tbits of data storage at Beginning Of Life (BOL) in maximum configuration
- Up to 6 independent data channels plus a 7<sup>th</sup> test channel. Each channel consists of an input and an output interface.
- Any data channel (input and output) can be routed to one of two internal DSU storage channels, for maximum redundancy and flexibility
- Data interfaces are LVDS I, Q and Clock for each channel, for input and output
- Maximum volume is 65,000 cubic centimetre.

- Box size is approximately 45cm x 45cm x 33cm
- Box mass is targeted to be less than 30kg
- Power consumption is 112W nominal, 125W maximum
- Reliability is better than 0.93 for 5 year mission
- Command/Telemetry Test port allows full internal status and diagnostics using Ethernet 10/100 interface during spacecraft Integration and Test (I&T) cycle.

The configuration of the DSU as required by the CASCADE program limits the performance and configuration to the following:

- 4 independent active storage channels, with a 5<sup>th</sup> channel as backup.
- Minimum of 6.2 Tbits of storage space at End Of Life (EOL)
- Maximum of 350Mbps data rate on individual channels (175MHz clock rate)
- Power consumption is 55 W maximum, 36.6W nominal, less than 20W orbit average

### DSU SYSTEM DESIGN

To help in the system design we have partitioned the system into a hierarchy, which is shown in Figure 3.



Figure 3 – DSU System Hierarchy Diagram

The details of this hierarchy are as follows:

The Data Storage Unit contains 5 Modules as follows:

- a) Power Supply Module - PSM
- b) Control Electronics Module – CEM
- c) Storage Transfer Module – STM
- d) Mass Memory Module – MMM
- e) Enclosure Module - EM

The Power Supply Module contains two Assemblies, as follows:

- a) Thermal Wall Assembly, (TWA) for the converters and hot components

- b) Power Control Assembly (PCA) which handles the over current limit, H&S acquisition and control of the power for the DSU

The Control Electronics Module contains two assemblies, as follows:

- a) Control Interface Assembly (CIA), which interfaces to the spacecraft for C&DH. The CANBus standard is the CASCADE interface.
- b) Control Processor Assembly (CPA) which is the overall DSU controller, currently baselined as an Intel Pentium-class processor

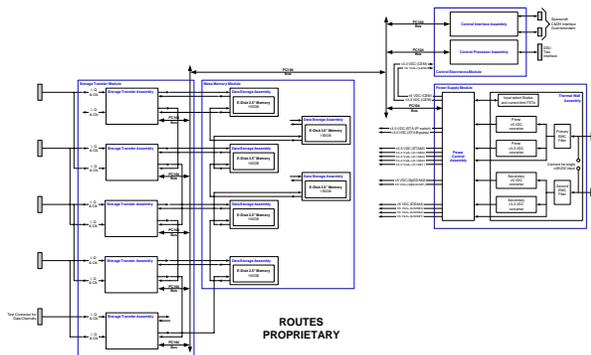
The Storage Transfer Module contains six identical assemblies, as follows:

- a) Storage Transfer Assemblies (STA), one assigned to each data channel and one to the test channel

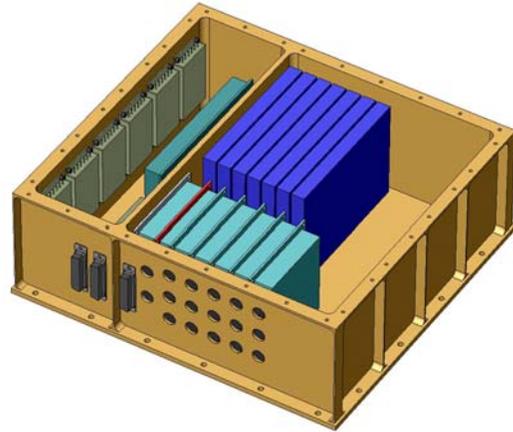
The Mass Memory Module contains six identical assemblies, as follows:

- a) The Data Storage Assembly (DSA), which form the data storage array. This is the flash memory component of the DSU.

All the assemblies in the CEM, STM and PSM are linked together using the PC104 bus for the command/control functions. We baseline this form factor for the electronics because of the size constraints of the mission. It also allows a lot of flexibility for the mechanical design and has high reliability and ruggedness. The CASCADE Data Storage Unit block diagram is given in Figure.4, and the physical box is shown in Figure 5.



**Figure 4 – CASCADE DSU Block Diagram**



**Figure 5 – CASCADE DSU Box**

*DSU Power Consumption*

The total peak maximum power consumed by the design is around 55W. This is the total Peak Maximum power consumption for the whole unit, with all drives and channels operational and running at maximum data rate capacity, and with the spacecraft C&DH communicating constantly with the DSU via the CANBus interfaces (both prime and redundant ports exercised alternately). The Orbit average power is calculated to be less than 20W, given the duty cycles in the mission and the fact that the DSU C&DH interface will not be active all the time during DSU operation.

*DSU Reliability*

The overall reliability of the DSU is calculated to be around 0.93 for a 5-year mission. This is done without RAID drives. The reason we could get away with no RAID configuration is that the Mean Time Between Failure (MTBF) and error rate performance of the flash memory component is above that of spinning disks. The MTBF of the flash memory components is rated at over 630,000 hours operations, while a spinning disk is around 150,000 power-on hours. The error rate for the flash memory component is  $10^{-20}$  Bit Error Rate (BER) while a spinning disk would be lucky to get  $10^{-12}$  BER. Because of this, we should not need a RAID configuration to provide data integrity. However we provide backup capability with the addition of a 5<sup>th</sup> channel.

**DSU MODULE DESIGN**

*Power Supply Module*

The PSM implementation consists of dual redundant strings of DC/DC converters fed from a redundant spacecraft bus power interface and redundant EMI

input filters. The redundant converter outputs are combined and the resulting single-string voltages are then separated into multiple power feeds for the DSU.

The circuits in the Power Control Assembly include an over-current limiter and a control switch for each independent power feed, allowing full control over the activation of separate areas of the DSU. The activation of the individual switches are done under the control of the CPA during the DSU start-up, and can be controlled in any combination during the normal operation of the DSU. If a particular feed is current-limited during normal operation, its associated switch will trip to isolate the fault. The switch must then be commanded back on via a DSU command.

The individual feeds are monitored for voltage level and current draw and this data is reported back to the Control Processor Assembly, for possible inclusion as part of the Health and Status (H&S) data for the DSU. The input voltage and current from both the prime and secondary power input feeds are also monitored and reported back to the CPA.

The design of the PSM includes a provision to run the dual redundant converter strings from a single spacecraft input power feed if necessary.

The over current monitors and output switches are custom circuits designed and implemented by Routes AstroEngineering. They have a flight heritage in that the same circuits are used on the Canadian Space Agency (CSA) SciSAT 1 spacecraft bus Power Control Unit (PCU), which Routes designed and built. In fact the whole of the PDA is a smaller scale version of the SciSAT 1 PCU, with identical power components (FETs, diodes, etc.) used whenever possible, to maximize the use of flight-qualified circuits and components. All components which have a requirement for thermal heat dissipation (FET switches and diodes, along with the converters and the EMI filters) will be mounted on a Thermal Wall Assembly which will be directly connected to the DSU enclosure for maximum heat conduction to the spacecraft base plate. The DSU is designed to operate in an environment from -25C to +30C.

### *Electronics Module*

#### *Control Interface Assembly*

The Control Interface Assembly is a custom designed PC104 card that implements the CANBus low-level control and data protocols. This protocol and interface has flight history with satellites built by SSTL in the

UK. The electrical bus interface is likely to be RS422/RS485

#### *Control Processor Assembly*

The Control Processor Assembly is a Commercial Off The Shelf (COTS) board procured from SECO. The board is identified as the ELAN520. This board is built around the AMD Elan CPU chip. The board is in a PC/104 compliant form factor and implements a full function PC/AT with up to 256MBytes onboard DRAM protected with Error Checking and Correction (ECC) hardware.

The board software includes a ruggedized Basic Input/Output System (BIOS) software suite and a bootable Solid State Disk-On-Chip memory area, where the DSU operating system and application software will reside. There is an onboard Flash memory to 1MB where the boot upload/download code will reside. The assembly is specified for extended operating temperature range of -40C to +85C

#### *Boot BIOS and Custom Download Code*

The DSU boot BIOS is based around the Award BIOS code, modified by Routes AstroEngineering to include a component, which allows code uploads if a critical boot failure of the application or operating system code occurs. This mitigates the failure by allowing a work-around in case of a total unit software hang-up.

#### *Operating System*

The target operating system for the DSU is Linux, kernel release 2.6.x. The distribution code is trimmed to fit within the memory and disk space of the CPA, and the kernel is re-compiled to take advantage of the internal hardware features (watchdog timer for example) of the CPA. This operating system offers security benefits for separating the data partitions for multiple users.

The operating system offers drivers for the CANBus hardware, the CPA hardware and the external test port Ethernet hardware. The kernel will be embeddable in a flash disk or DoC (Disc-On-Chip).

#### *Application Code*

The application code for the DSU will reside on the Flash memory area, and will be written in C. This application will be divided into software modules, which can be loaded and run independently, for maximum reliability. If a module is deemed to be corrupted, then the main code module (small and

running in protected memory areas) can re-load the affected module with minimal effect on the DSU operation. Code and data scrubbing will be used to protect against Single Event Upset (SEU) bit flips in the memory areas.

#### *Storage Transfer Assembly*

The core functions of the STA are implemented in a single Field Programmable Gate Array (FPGA), from Xilinx, the VertexII-Pro family. This FPGA family is capable of handling clock rates of over 350MHz internally.

The FPGA contains internal logic to implement the following functions, in Triple Mode Redundant (TRM) fashion:

- a) Channel selection mux/demux, to handle the 2:1 redundancy for the data channel side
- b) I&Q data mux/demux – to combine or split the I and Q channels in a single serial stream.
- c) Data formatter/de-formatter – to block off the serial stream in efficient blocks of data for storage and retrieval.
- d) Fill pattern generator – To generate the CCITT pattern for fill data.
- e) Internal STA Finite State Machine (FSM) – to control and synchronize the operation of the STA
- f) PC104 bus controller
- g) Fibre Channel controller A – this is the Point-to-Point controller, which is dedicated to the channel's disk
- h) Fibre Channel controller B – this is the Alternate Loop controller, which shares the data array with all the other STAs

#### *Mass Memory Module*

##### *Data Storage Assembly*

The Data Storage Assembly consists of only one component. This component is the mass storage device which is key to the implementation of the DSU. The mass storage device we have identified is a rugged flash memory component with Fibre Channel interface. This device utilizes proven Solid-State Flash based proprietary technology, a non-volatile storage solution in the industry standard 3.5-inch form factor.

The baseline storage size selected for the CASCADE mission is 155Gbyte per DSA. The fibre channel interface can support sustained read/write access at a rate of 68 Mbytes/sec.

During the Proof of Concept phase of the program, we will procure a flash drive and subject it to radiation and life testing. This will be done to retire early in the program the risk factors associated with radiation and EOL performance. The current plan is to procure a smaller size drive (40Gbyte) instead of the full 155Gbyte drive, in order to save the program some money. We have the assurances of the manufacturer that the smaller drive uses the identical drive control electronics and the identical memory chips as the larger drive, just less of the memory chips. The package is the same for both drives. Therefore we feel the radiation test results and the life test results will scale correctly to the final DSU drive configuration. At the time of writing the radiation testing is underway at the TRIUMF test facility in British Columbia, and at the Defense Research and Development Canada (DRDC) facility in Ottawa.

#### *DSA Environmental Specifications*

The DSA model selected for the DSU can operate between -25C and +75C, and be stored at temperatures between -60C to +125C. The component has been tested for shock up to 1500G according to MIL-STD-810C and for vibration according to MIL-STD-810E. The component has been tested to 120,000 feet altitude and requires no airflow for cooling. These components are extended temperature grade units, and satisfy all the environment requirements of the CASCADE mission.

#### *Reliability and Error Tolerance*

The flash memory component reliability has been stated to be >630,000 hours MTBF, with a read BER of better than  $10^{-20}$

The Erase/Write endurance limit of Flash memory can be an issue for long duration missions such as the CASCADE mission. This is overcome in the DSA by firstly using the highest quality state-of-the-art Flash Memory Chips with: (i) the highest rated Physical Block Address (PBA) erase/write endurance; (ii) a minimum of 10 years data longevity without re-write; and (iii) unlimited number of reads. In addition the flash memory component uses in the background: (i) a wear-leveling technique, wherein the PBA of a Logical Block Address (LBA) with the most written PBA is swapped with another LBA with least written PBA; (ii) a re-mapping technique, wherein bad blocks in LBAs are automatically replaced with reserved good blocks; (iii) fully associative caching which minimizes unnecessary flash memory block erase/write cycles; and (iv) sophisticated interleaving, EDC and Reed-Solomon ECC which are optimized for use with flash memory and ensure increased data integrity, optimum system

performance, and extreme device longevity. This yields a typical erase/write cycle endurance of 123 years at 100Gbyte/day. The read cycle endurance is unlimited.

For extended data reliability, the solid-state component uses a customized and robust Reed-Solomon Error Correction Code (RS ECC), which is optimized for use with Flash memory. This code's undetected data errors is less than  $10^{-30}$ . It corrects up to six random byte errors per 528-byte blocks and detects burst errors up to nine bytes long. This RS ECC, with the proper decoding algorithm, will mis-correct less than one time in 1024, for errors greater than 9 bytes out of 528 bytes.

### *Conclusions*

In this paper we presented an alternative concept for the implementation of a high-speed, very large memory array Data Storage Unit, for use on small satellites. The use of FLASH and COTS technology, combined with redundant modular architecture leads to a high performance cost effective DSU for future missions.

### *Acknowledgements*

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