The MSX Command and Data Handling System

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The Command and Data Handling System of the Midcourse Space Experiment provides spacecraft control and data collection, formatting, and onboard storage. It has embedded encryptors and decryptors to ensure communication security during the mission. The Command and Data Handling System also maintains onboard time and performs autonomy rule checking of housekeeping data for fault protection.

INTRODUCTION

Over its 5-year lifetime, the Midcourse Space Experiment (MSX) will carry out hundreds of data collection events involving actively tracked targets, celestial backgrounds, and Earth backgrounds. Data sources include 11 optical sensors that produce images and spectra over the infrared, visible, and ultraviolet wavelengths. These events, which last from 30 min to 6 h, occur while the spacecraft is out of ground contact. Onboard computers execute the event scenario to point the spacecraft, control the measurements, and store the resultant data on the spacecraft tape recorders. After the event, the spacecraft returns to its park mode to recover power and thermal balance. Later, data from the tape recorders are dumped via the X-band telecommunication link to the APL ground station. Within this framework, the details of individual events are highly diverse.

The capability and versatility required by the spacecraft provided the design drivers for the MSX Command and Data Handling (C&DH) System. First among these drivers is the high volume of data generated during an event. System trade-offs resulted in a 25-megabit per second (Mbps) aggregate real-time science data rate and redundant tape recorders, each capable of storing 54 gigabits (Gb). Each event has its own selection of instrument operating modes. Therefore, a flexible method of allocating science data bandwidth was required to use this limited resource efficiently. The 5-year mission life and the criterion that there be "no credible single-point failure" for C&DH functions led to fully redundant C&DH hardware, which implies cross-strapping between units and design of interfaces to ensure fault isolation. For spacecraft fault protection, an uploadable, rule-based autonomy capability is required. Relatively simple rules, based on such engineering housekeeping points as tape recorder head temperature and power bus voltage, are used to detect and circumvent problems having the potential to end the mission. Autonomy rules are stored in and executed by the C&DH command processors. Data security requirements apply to the telecommunication links between the spacecraft and ground, which are all encrypted.

To meet these requirements, the MSX C&DH System was designed using a systematic approach that led to a partitioned design providing high-performance data processing and needed mission flexibility while still retaining high reliability and fault tolerance. The following sections describe the system design and its components.

OVERVIEW

The MSX C&DH System consists of command processor, data handling, key generator (KG)/tempest, power switching, and tape recorder components, as shown in Fig. 1 and listed in Table 1. Each of these units is discussed in the following sections. Together, they provide the following capabilities for the MSX spacecraft:

- Control of the spacecraft, using pulse commands, data commands, and more than 200 power switching relays. Commands transmitted from ground stations are acquired via the S-band transponders. They may be executed immediately or stored in command processor memory for later execution. Commands are also accepted from the tracking and attitude processors.

Table 1. Components of the MSX Command and Data Handling System.

Function	Hardware assemblies	Provider
Command processing	Command processors 1 and 2	APL
Data handling	Data handling systems 1 and 2	APL
Data encryption and decryption	Key generator/tempest electronics units 1 and 2	Cubic Defense Systems, Inc.
Power switching	Power switching units 1 and 2 Ordnance control unit	APL
Data storage	Tape recorder electronics units 1 and 2	Odetics, Inc.

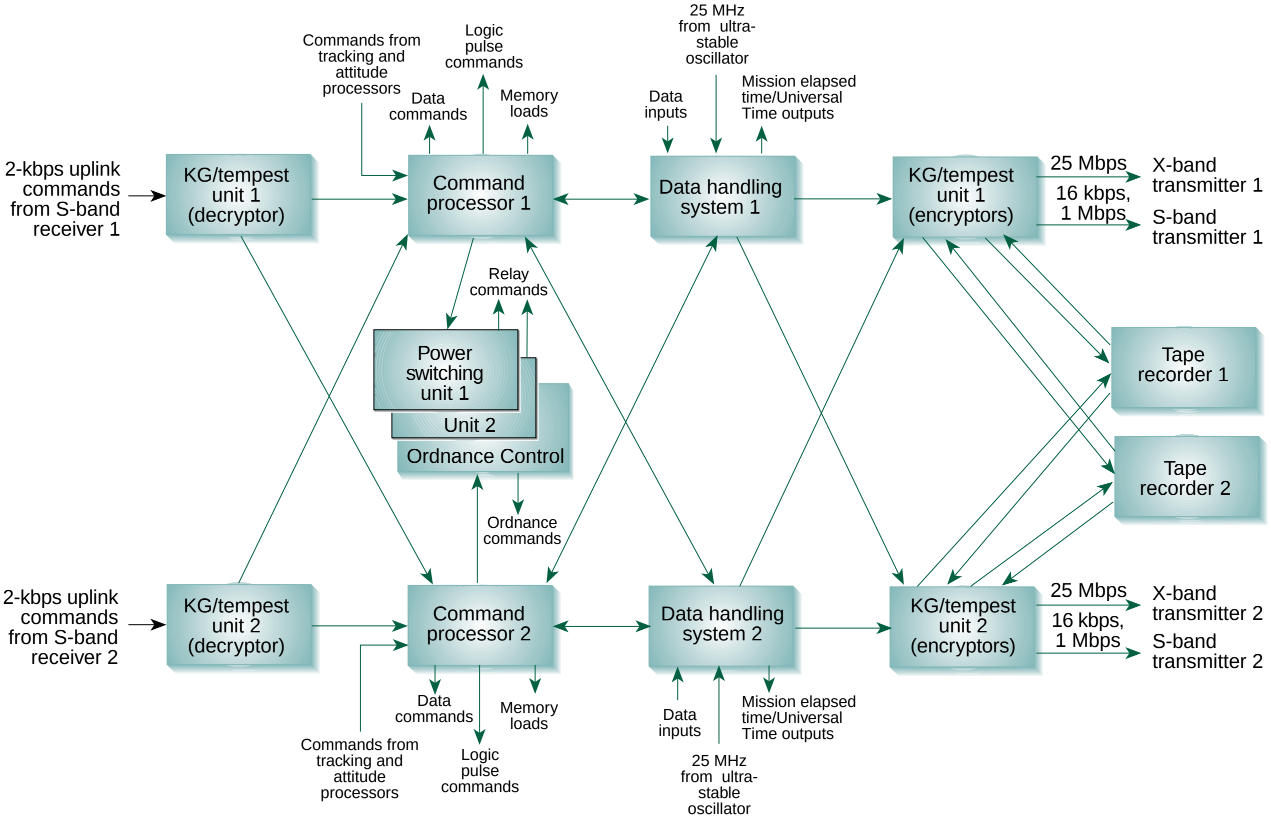

Figure 1. Functional block diagram of the MSX Command and Data Handling (C&DH) System, showing cross-strapped interconnection between redundant units (KG = key generator).

- Collection, formatting, and serial output of the 16-kilobits per second (kbps), 1-Mbps, and 25-Mbps data streams. When enabled, these data streams are generated simultaneously and in synchronism with each other.
- Maintenance and distribution of mission elapsed time and Universal Time on the spacecraft.
- Provision of spacecraft autonomy functions.
- Encryption of downlink data, decryption of uplink (command) data, and command authentication.
- Recording of the prime science data stream at 5 Mbps or 25 Mbps. Data storage capacity is 54 Gb per recorder. Data playback is at the single rate of 25 Mbps to the APL ground station via X-band radio frequency (RF) link. As an option, the prime science data path can be switched to place the real-time 25-Mbps data stream on the X-band downlink.

Table 2 summarizes the RF telecommunication data links between the spacecraft and the ground. There are three downlinks and one uplink. S-band communication is used for commanding and the lower-rate downlinks. The S-band transponders are an industry standard compatible with omnidirectional spacecraft antennas and many ground stations. In contrast, the X-band equipment required at 25 Mbps is unique to the MSX program. A high-gain X-band antenna on the spacecraft is gimbal mounted and pointed at the ground station during the 25-Mbps downlink operations. The only ground station with receiving equipment for this signal is at APL.

Figure 1 also shows the redundancy and cross-strapping between elements of the MSX C&DH System. The uplink receivers, decryptors, and command processors are actively redundant; that is, they are powered continuously for the life of the mission. Other units are selectively powered and utilize commanded cross-strap data paths to route data appropriately. Downlink data streams are routed by selection of multiplex switches in the KG/tempest units.

All of the elements of the C&DH System (13 hardware assemblies) received thorough stand-alone testing before they were integrated with the spacecraft. Special test sets were developed for this purpose in parallel with the flight hardware and software design. The importance of these computer-controlled test sets cannot be overstated. Their availability was a key milestone in all of the C&DH deliveries. Because interfaces between C&DH components are simple and well defined, very limited tests between flight hardware items were needed. Each unit was required to pass component-level environmental tests (vibration and thermal-vacuum cycles) prior to integration with the spacecraft. Any repair or rework of a flight unit was followed by specified requalification vibration and temperature testing.

As the details in the following sections show, the spacecraft C&DH System is interface intensive. It touches nearly every other box on the spacecraft with at least one electrical interface. Careful design and comprehensive, exhaustive testing were main ingredients in the successful implementation of the MSX C&DH System.

COMMAND PROCESSOR

The MSX command processor receives uplink command messages, interprets them, and then sends

Table 2. Summary of MSX telecommunication data links.

Name	Bit rate	RF carrier	Source/ destination	Comment
Prime science data	25 Mbps	X-band	Spacecraft to ground	Three modes: 1. Playback of data previously recorded at 25 Mbps 2. Playback of data previously recorded at 5 Mbps 3. Real-time 25-Mbps prime science data
Wideband science data	1 Mbps	2282 MHz	Spacecraft to ground	Real time only
Narrowband data	16 kbps	2282 MHz	Spacecraft to ground	Real time only
Commands	2 kbps	1827 MHz	Ground to spacecraft	Commands for immediate execution Commands for delayed execution Memory load data

appropriate control signals to the spacecraft subsystems and instruments. Commands may be executed in real time (immediately after reception) or stored in memory for later processing. The command processor can also receive commands from the tracking and attitude processors, and it has the ability to check the telemetry data and generate commands autonomously based on a set of uploadable rules.

Figure 2 shows one of the two redundant command processor units in the C&DH System. The 5.9-kg processor measures 25 × 18 × 31 cm and consumes 1 W from a single 5-V supply. Processing is performed by a 0.5 million-instruction-per-second MIL-STD-1750A processor with a real-time multitasking operating system kernel. The 24 K-word application code is written in Ada and assembly language (1 K-word is 1024 16-bit processor words in the 1750A architecture). Up to 15,000 delayed commands can be stored in the 512-K-word, error-detecting and correcting random access memory. Program storage based on programmable read-only memory ensures that the processor will fully recover if a single-event upset or other anomaly should cause a reset. For fault protection, the command processor has its own independent oscillator. Universal Time is derived from the telemetry data but is maintained from the internal oscillator should the telemetry not be available.

Commands are transmitted over a variety of dedicated interfaces. Special interfaces with the power switching units can support 192 relay commands in three power-switching units. The standard interfaces are 32-bit serial data, 2048-bit serial data, and logic pulses. The 32-bit serial data commands are error checked in the command processor. If they are error free, they are sent to the subsystem via a dedicated 3-wire interface. The subsystem defines the meaning of the 32 bits. Typically, the bits are used to control modes or set parameters within the subsystem electronics. Long serial commands, on the other hand, are passed through to the subsystem without error checking by the command processor. The purpose of long commands is to load memories in the other onboard processors. The subsystem is responsible for error checking the long load message.

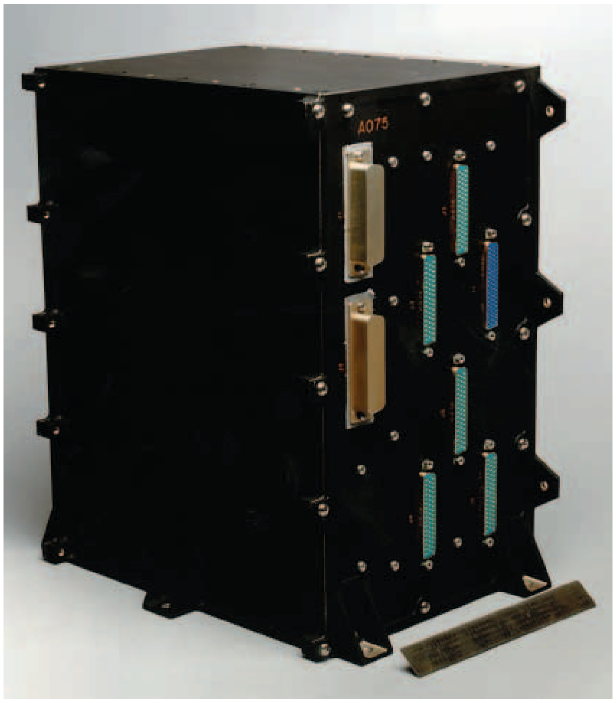

Figure 2. View of the command processor showing the connector panel.

The command processor has several unique features designed to support the complexity of the MSX mission. Multiple sequences of stored commands can be executed simultaneously, limited only by the 15,000-command capacity. Rule-based autonomous processing can check any of the housekeeping telemetry data and execute stored command sequences in response to logical and mathematical tests.

An innovative feature that time-stamps and logs commands as they are executed provides diagnostics to the flight operations team and the integration and test team. The log of the most recent 500 commands is subcommutated, at a low rate, into the command processor status telemetry. A history of the last 500 commands, including errors that occurred in processing, can be reconstructed by the ground support equipment using about 4 min of telemetry data.

The processor's software also provides uplink authentication, error checking, delayed command processing with resolution to 1 s in a year, and background memory scrubbing.

DATA HANDLING SYSTEM

The data handling system (DHS) collects data, formats downlink telemetry data streams, and keeps spacecraft time. It is fully redundant, with two mechanical assemblies that are mated together for flight. Figure 3 shows the redundant sides, DHS 1 and DHS 2, about to undergo an *x*-axis vibration test. The following paragraphs describe DHS functionality, some highlights of the 25-Mbps prime science formatter, and packaging design.

Functional Description

Spacecraft science and housekeeping data are gathered by the DHS and formatted to generate three serial data outputs. Each stream has selectable formats and can be turned on and off independently as required by the mission. These three streams are the following:

1. 25-Mbps (or 5-Mbps) prime science data stream containing imager, processor, and housekeeping data;

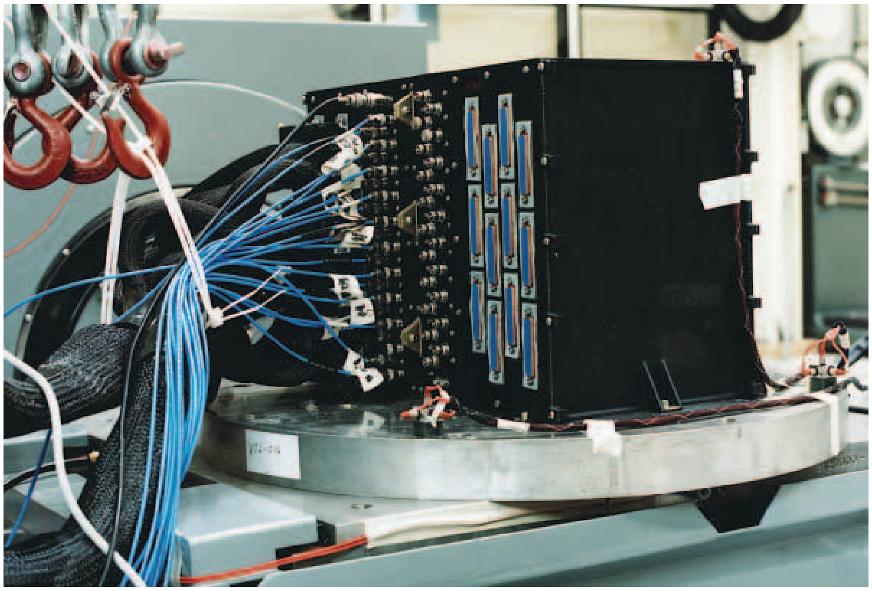

Figure 3. View of the data handling system (DHS) showing redundant DHS 1 and DHS 2 mated in flight configuration. In this photograph, the DHS is mounted on the vibration table with the bench test equipment cables attached.

transmitted in real time or stored on one of the spacecraft tape recorders

2. 1-Mbps snapshot science and housekeeping wideband downlink data stream; transmitted in real time
3. 16-kbps narrowband downlink data stream containing spacecraft housekeeping and memory dump data; transmitted in real time

A state machine in the DHS collects one complete set of housekeeping data every second. The housekeeping data include

1. Single-ended analog monitors (123)
2. Differential analog monitors (76)
3. Digital discrete (“telltale”) channels (48)
4. Temperature transducer channels (96)
5. Low-range temperature channels (31)
6. Serial digital housekeeping channels (24)

Spacecraft mission elapsed time and Universal Time are kept in the DHS. They are based on precise 1-Hz pulses derived from the 25-MHz ultrastable crystal oscillators. Copies of these times are placed in each housekeeping data set and are distributed to other subsystems for synchronizing events external to the DHS. Selected critical housekeeping data parameters are stored in a DHS random access memory buffer. Called the “full orbit memory,” this buffer is dumped by command to a ground station. Finally, the full set of housekeeping data is provided by dedicated interfaces to the command processors. Software in the command processors uses the contents for synchronization and for fault protection and autonomous control.

Power is applied to only one of the redundant sides of the DHS. Power consumption from the 28-V spacecraft power bus is 20 W with prime science off and 40 W with the prime science running at 25-Mbps. Each source of data has independent, isolated interfaces to DHS 1 and DHS 2. Operationally, each data source has to be commanded to know which DHS side is powered. This is an important part of the overall cross-strapped design that eliminates single-point failures and prevents failure propagation.

Prime Science Formatter

The prime science formatter processes real-time, high-rate imager data, as well as stored spacecraft processor data, and formats the data into a serial 25-Mbps output. Any of several allocations of prime science bandwidth between instruments can be selected by command. These are chosen to accommodate the expected operating modes of the instruments. They are hardwired into the logic of the formatter hardware.

Imager data are transferred using clock and gate signals generated by the prime science formatter and distributed to the data sources. To compensate for propagation delay effects resulting from the data path (cable and electronics) and to permit formation of a contiguous output data stream, the formatter automatically senses the total data gathering delay for each high-speed imager data source and uses the results to continuously equalize the path delays. (A patent has been awarded for this innovation.[1]) High-speed emitter-coupled logic technology is used to implement the 25-Mbps processing logic.

Package Design

The two data handling systems, DHS 1 and DHS 2, are electrically identical. Mechanically, for better thermal design, they are mirror-image assemblies bolted together. One DHS flight unit consists of five multilayer printed circuit boards, a motherboard, and an internal wiring harness. Each unit has dimensions of 25 × 22 × 32 cm and a mass of 10 kg. Figure 4 shows the wide/narrowband telemetry processor board configured with connector savers for bench test.

KEY GENERATOR/TEMPEST ELECTRONICS UNITS

Figure 5 shows one KG/tempest electronics unit. It measures 10 × 24 × 26 cm, has a mass of 5.7 kg, and

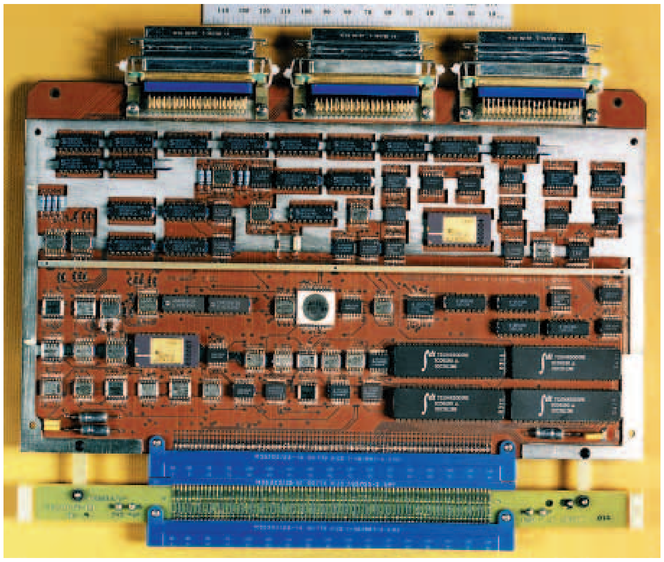

Figure 4. Component side view of the wide/narrowband telemetry processor board from the data handling system.

Figure 5. Front view of the key generator/tempest electronics unit, showing the connector panel.

consumes a maximum of 14.7 W. In flight, two of these units are stacked one on top of the other. Manufactured by the Cubic Corporation, they provide secure communications between the MSX spacecraft and the ground. Each of the two units consists of a multilevel housing with three encryptor modules, one decryptor module, and a power converter/regulator module. Table 2 identifies the data links and describes how they are used.

Each of the three encryptors accepts plain text data input at the specified data rate and provides an encrypted cipher text data output. The single decryptor accepts encrypted (cipher text) data input at 2 kbps and provides plain text command data output. Multiple outputs for the cross-strapped data paths are switched and buffered within the encryptor/decryptor modules. The redundant data paths are indicated on the C&DH System block diagram of Fig. 1. In addition, the encryptors and the decryptor contain serial data and housekeeping logic for command and status information. Finally, the power converter accepts 28-V spacecraft bus power and provides nine isolated, regulated, and filtered outputs that are distributed to the other modules.

POWER SWITCHING UNITS

The MSX spacecraft has three power switching units: units 1 and 2 and the ordnance control unit. Each is capable of controlling 64-relay commands. Together, the units provide switched power and signals for spacecraft operation. The ordnance control unit is dedicated to spacecraft ordnance functions. Separate ordnance function is required to protect against spurious ignition of ordnance devices. Measures taken include interlocked relay contact circuits, electromagnetic interference shielding, and dedicated connectors and harness wiring for ordnance functions. A total of 252 relays are used in the power switching units.

All three units contain a motherboard and six 18 × 18 cm plug-in cards (two driver/telemetry boards and four relay boards) mounted in a 23 × 23 × 25 cm chassis. Each unit has a mass of 7.3 kg. Two 50-pin "D" connectors are used on each relay board, one for power in and the other for switched power out. Four types of latching relays are used for the various switching functions and are selected according to the power requirements of the various users. The contact ratings range from 2 to 25 A. In addition, 2-A nonlatching relays are used to provide pulse commands. Figure 6 is a photograph of a completed power switching unit, ready for installation on the spacecraft. Figure 7 is a component side view of a typical relay board.

The two driver/telemetry boards in each unit provide redundant relay coil drive and relay contact position telemetry. Each board accepts an 8-bit parallel command word from one of the two command processors and decodes the command into the appropriate signal to operate the relays, whose drive circuits are configured in an 8 × 8 matrix. Latching relay control circuitry is made fully redundant by driving the two latching relay coils from separate matrix decoders. The boards also contain parallel-to-serial shift registers with output interfaces for the telemetry of relay contact position.

All latching relays are monitored. The telemetry data streams are daisy-chained between the three units such that one 160-bit data stream from each of the driver/telemetry boards is fed to one of the redundant data handling systems. Command decoding and telemetry logic is implemented using CD4000B series integrated circuits. Discrete transistors are used in the relay coil drive circuits.

The units operate with 28-V and 5-V inputs to each driver/telemetry board. The 28-V power, supplied by the spacecraft battery, is used for command decoding and relay operation, and the 5-V power is used for the telemetry circuits. Power consumption per unit is 630 mW.

Figure 6. Front view of power switching unit 1, showing the connector panel.

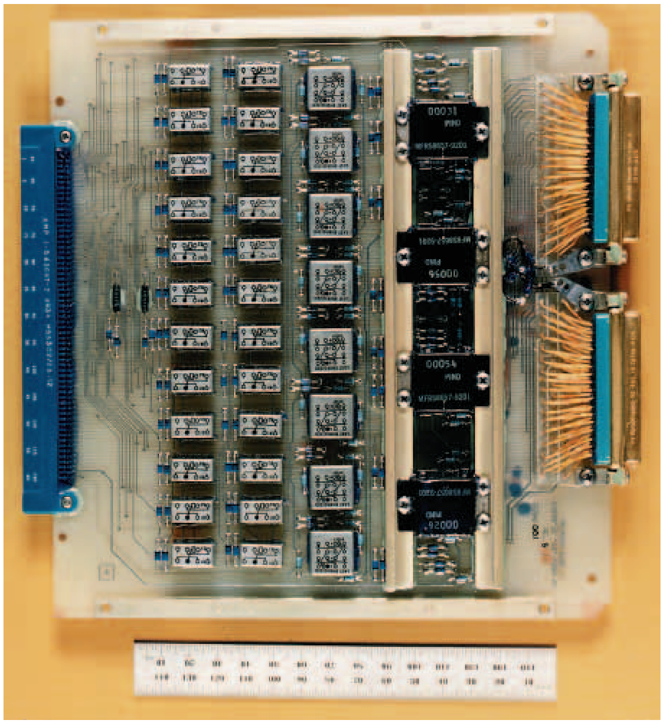

Figure 7. Component side view of relay 2 board from power switching unit 1.

SPACEBORNE TAPE RECORDERS

Purpose

Recording the prime science data ensures that no information is lost while MSX is out of contact with the ground receiving station. Each of the spacecraft's two tape recorders can continuously accumulate data at 25 Mbps for up to 36 min, or else data can be intermittently recorded at 5 Mbps for a maximum total record time of 3 h.

Upon command, the recorded data are played back to the ground at 25 Mbps. This process can take 36 min if the entire tape has been recorded. Since the MSX satellite takes about 13 min at most to pass over the APL ground station, the data are played back piecemeal until all information has been recovered.

Description

The two recorders were manufactured for APL by Odetics Corporation. Each carries 2.2 km of 2.54-cm tape that can record up to 54 Gb of data. The 36-cm diameter reels are stacked one above the other and contrarotate to minimize disturbances to the spacecraft attitude from recorder speed changes. To further reduce angular momentum transients and to eliminate the time and energy of rewinding, the tapes are played out backwards so the last datum recorded is the first recovered.

An error detection and correction system achieves an average bit error rate of less than 1×10^{-7}. Each recorder has three capstans, which are coupled by redundant Kapton belts to a servo-controlled, brushless DC motor with optical commutation. Four additional servo-controlled motors maintain tension and lateral position of the tape. The housing of each transport unit is pressurized with nitrogen to protect the tape, heads, and lubricated bearings from the vacuum of space.

Table 3 lists the characteristics of the MSX spaceborne tape recorders. Figure 8 shows a tape recorder with cables interconnecting the transport and electronics units, and Fig. 9 shows the transport unit with its cover removed.

SUMMARY

By any of the usual benchmarks of complexity, such as data volume, number of relays, harness complexity, stored command capacity, and number of lines of flight code, the MSX C&DH System was an enormous undertaking. The C&DH System meets the program requirements for high speed, massive onboard storage, and precise timing. Some innovative techniques were required to synchronize data from distributed sources at the 25-Mbps rate. A high level of mission operation

Table 3. Characteristics of the MSX spaceborne tape recorders.

Record speeds	18.8 cm/s and 94 cm/s
Playback speed	94 cm/s
Tape dimensions	2.54 cm × 2.2 km
Tape format	42-track IRIG standard
Power consumption	45 to 225 W, mode dependent
Mass, transport unit	57.6 kg
Mass, electronics unit	21.8 kg
Total mass	79.4 kg
Size, transport unit	50.8 × 50.8 × 33.0 cm
Size, electronics unit	30.5 × 50.8 × 38.1 cm
Number of parts	16,732

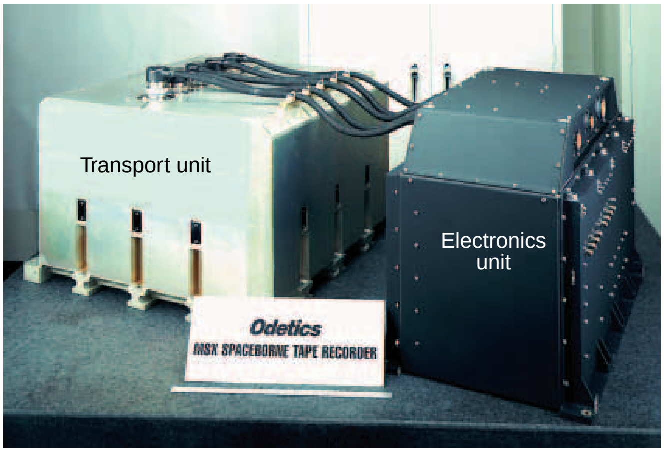

Figure 8. Spaceborne tape recorder, showing transport unit and electronics unit with interconnecting cables.

flexibility is incorporated into the command system software. Multiple command sources, uploadable autonomy rules, and stored commands are all accommodated. Hardware and software were fully tested and delivered on time to the MSX spacecraft for integration and test.

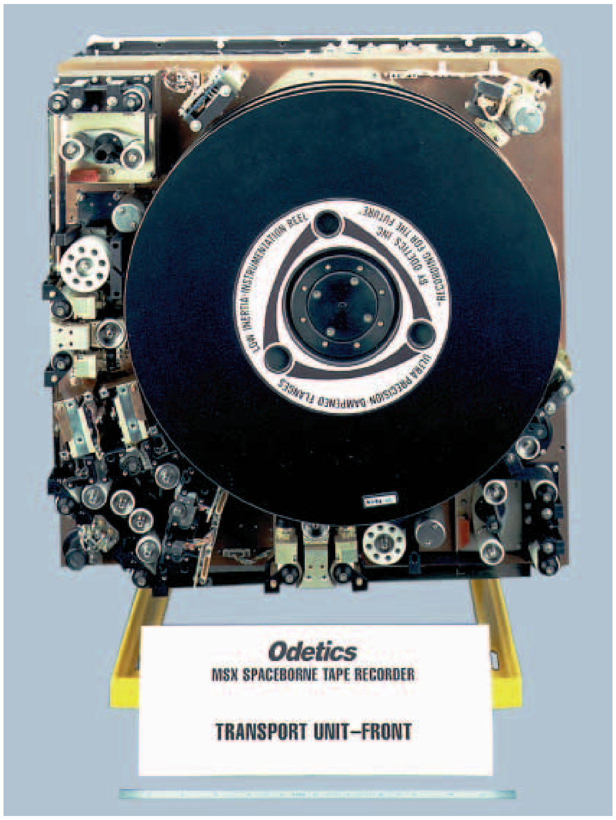

Figure 9. Spaceborne tape recorder transport unit with cover removed. The coaxial tape reels, tape path, and capstan assemblies are clearly visible.

REFERENCE

[1] Schwartz, P. D., "High Speed Propagation Delay Compensation Network," U.S. Patent No. 5,379,299 (3 Jan 1995).

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