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Technical Memorandum 33-554

Mariner Mars 1971 Data Storage Subsystem Final Report

R. Grumm

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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PREFACE

The work described in this report was performed by the Astrionics Division of the Jet Propulsion Laboratory.

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ABSTRACT

A digital tape recorder was used on the Mariner Mars 1971 spacecraft to record television and scientific data. Data were recorded at 132 kilobits/s and were reproduced at one of five available rates (16.2, 8.1, 4.05, 2.05, or 1.0125 kilobits/s) selected by ground command to be congruous with the spacecraft-to-earth communications link performance. The transport mechanism contained 167 m of 1.2-cm magnetic recording tape. A single motor was used to drive the peripheral drive transport.

During development of the design, "stick slip" problems were encountered, and the selection of 3M 20250 tape made by the Minnesota Mining and Manufacturing Company was an important part of the solution to this problem.

A design life of 2400 tape passes was achieved during the mission.

I. INTRODUCTION

In June of 1968, the engineering and scientific aspects of two major data storage options, namely, the Mariner Mars 1969 (MM'69) analog/digital hybrid and an all new digital recorder were evaluated, and the recommendation was made to develop an all-digital data storage subsystem (DSS) for the Mariner Mars 1971 (MM'71) mission.

The MM '69 DSS contained two endless-loop tape recorders with 111.25 m (365 ft) of 0.635-cm (1/4-in.) tape each. One of these recorders, the analog tape recorder (ATR), direct-recorded a 18.9-kHz amplitude-modulated carrier from the TV subsystem. During playback of the ATR, an analog-to-digital converter was used to digitize the magnitude of each positive peak to a 6-bit word. During playback, the tape speed was servo-controlled at 5.34 cm/s (1.71 in./s) to provide a playback data rate of 16.2 kilobits/s. The capacity of the ATR was 2.62×10^7 cycles or 1.57×10^8 equivalent bits.

The direct-recording process used to record the 18.9-kHz information is inherently inaccurate. Additional information was needed to establish the absolute levels of the signals. It was obtained by recording the digitized value of every seventh picture element on a digital recorder and formatting this value in the data automation subsystem (DAS) into a 16.2-kilobits/s data stream. A TV picture was recorded by recording the 18.9-kHz analog data on the ATR and the 16.2-kilobits/s digital data on the digital tape recorder (DTR). When the downlink performance permitted, the 16.2-kHz digital data to the DTR were also transmitted directly. In this case, playback of the DTR was unnecessary since the data were transmitted directly in real time. The ATR was played back directly to earth at 16.2 kilobits/s when the downlink performance permitted.

If the downlink performance would not support 16.2 kilobits/s, the data were returned by playing back the digital data on the DTR at 270 bits/s. The ATR data were then played at 16.2 kilobits/s and recorded on the DTR until the DTR was filled, at which time it was played back at 270 bits/s. When playback was complete, more data from the ATR were recorded on the DTR and played back. The capacity of the ATR was 1.57×10^8 bits and the DTR capacity was 2.3×10^7 bits, so several transfers were required to dump the ATR through the DTR.

The DTR transport was similar to the ATR transport. The DTR used saturation recording with a packing density of 531.1 bits/cm (1350 bits/in.) on four tracks across a 0.635-cm (1/4-in.) tape. Four passes were required to fill the DTR. The playback rate was servo-controlled at 270 bits/s.

The MM '69 flyby mission recorded about 70 pictures, which required fewer than 20 passes on each recorder.

The MM '69 TV/DSS combination was developed with the assumption that Mars was a low-contrast photographic subject. (The MM '69 system, as built, could distort high-contrast pictures.) The assumption of low contrast was consistent with the Mariner IV data and was considered acceptable for the relatively few pictures taken on the MM '69 mission. The low-contrast assumption was not necessarily valid, however, for the MM '71 mission, which would take many pictures under a wide variety of seasonal and lighting conditions on the planet.

Significant problems were encountered during testing and calibration of the MM '69 TV/DSS system. The basic cause of the problems was the high noise intrinsic to the direct-record process in the ATR. It was apparent that extensive processing would be required to assemble the playback data into pictures. This problem was manageable for MM '69 because of the few pictures taken. The MM '71 mission, however, anticipated taking several thousand pictures, and extensive processing of the pictures was impractical.

Large changes in the ground receiving station capability were anticipated for the MM '71 mission. Playback rates of 16,200 and 270 bits/s were available in the MM '69 design. The additional rates needed to optimize MM '71 data return were not technically feasible for ATR playback. Additional playback rates could be added to the DTR, but this would cause severe operational problems because of the ATR-to-DTR transfers required. From a reliability standpoint, two tape recorders in series with the TV data were undesirable.

Another factor, which alone was sufficient to prevent using the MM '69 transport for MM '71, involved the graphite-lubricated tape in the MM '69 transports: the tape degraded rapidly with use and clearly would not survive for the more than 2000 passes required for the MM '71 mission.

All of these factors made it apparent that the MM '69 DSS could not be reasonably modified for use on MM '71.

A feasibility model of a digital recorder was developed that had a storage capacity of 2×10^8 bits. The transport contained 146.3 m (480 ft) of 0.635-cm (1/4-in.) tape and had 12 tracks, with three tracks being recorded in four passes to fill the recorder. The tape speed during the recording of 130-kilobits/s serial NRZ data was 38.1 cm/s (15 in./s), with a motor speed of 11,250 rev/min. Playback rates of 2, 4, 8, and 16 kilobits/s, synchronous with an external clock, were provided. The weight was estimated at 18.2 kg (40 lb), and the power consumption was 25 W (record mode) (see Refs. 1 and 2). Capacity was defined as 1.8×10^8 bits, and five playback rates (1.0125, 2.025, 4.05, 8.1, and 16.2 kilobits/s) were used. The record motor speed was 5060 rev/min.

II. TECHNICAL DESCRIPTION

A. Functional Requirements

The function of the DSS is to maximize the return of scientific data by storing the recorded data for playback at times and data rates congruous with the downlink and Deep Space Network (DSN) performance. The DSS records on magnetic tape and has a nominal storage capacity of 1.8×10^8 bits, sufficient to record 32 complete pictures in the continuous-record mode. Stopping and starting the recorder between each picture and the next reduces the total storage capacity by a little more than one picture. The storage capacity was determined by estimating the maximum amount of data which could be played back during a typical day in the mission.

The five rates available for playback are 16,200, 8100, 4050, 2025, and 1012.5 bits/s. During the mission, the highest rate which can be supported by the spacecraft-to-earth communications link will be selected. The 16.2-kilobits/s rate is used early in the mission when the 64-m (210-ft) DSN antenna tracks the spacecraft, and the lower rates are used later as the distance to the spacecraft increases, or whenever a 26-m (85-ft) antenna is used for tracking.

B. DSS Characteristics and Components

Technical characteristics of the DSS are listed in Table 1.

1. Tape transport. The transport configuration is coplanar reel-to-reel, employing peripheral drive. It contains 167.6 m (550 ft) of 1.27-cm (1/2-in.) magnetic recording tape. The flight 2 transport mounted in the case but with the covers removed is shown in Figs. 1 and 2. Figures 3 and 4 are two views of the proof test model (PTM) transport outside of the case. The transport is shown in the upper left-hand corner of the block diagram presented in Fig. 5. Transducers to measure temperature and pressure and optical sensors to detect the ends of the tape are included in the transport.

2. Recording. The recorded data are split into two channels, which are recorded simultaneously on two adjacent tracks on the tape. Four tape passes across the heads are required to fill the eight data tracks. A ninth track is used as a tachometer and provides rate feedback for the playback servo. The locations of the data tracks on the tape are shown in Fig. 6.

The first tape pass of a nominal record sequence starts at the left end of the tape. From this starting point, data are recorded left to right on tracks 1 and 2. The tape reel rotation is counterclockwise (CCW) during the first tape pass.

Light-emitting diodes and n-p-n semiconductor optical sensors are used to detect transparent windows located near each end of the tape. The window in the upper half of the tape near the right end is detected at the end of the first pass. (Four windows are used for redundancy.) The response to the right end-of-tape (REOT) signal is to start clockwise (CW) tape motion.

The logic change from CCW to CW motion causes the next pair of tracks to be selected. The second pass starts at the right end of the tape. During the second tape pass, tracks 5 and 6 are recorded and the reel rotation is CW.

The second tape pass ends at the first left end-of-tape (LEOT) window located in the lower half of the tape near the left end. The response to the LEOT signal is to start CCW motion. The logic change from CW to CCW motion advances the track selection logic to tracks 3 and 4 for recording the third pass. The third pass ends at the REOT. The fourth pass is recorded with CW motion.

The LEOT signal at the end of pass 4 (tracks 7 and 8) causes the direction control logic to switch to CCW motion on tracks 1 and 2 and, in addition, causes a "stop record" pulse to be generated. After this automatic stop, the DSS does not respond to "start record" commands from the DAS until the DSS is in the playback mode. This provides a means of automatically stopping the DSS when it is full and prevents recording over data recorded during the first tape pass. Only the DAS start record commands are inhibited after an automatic stop. Start record commands from the flight command-subsystem (FCS) and the central computer and sequencer (CC&S) are responded to without restriction whenever DSS power is on.

The early designs of the DSS included an erase head which erased each track pair just before recording. The erase heads were disconnected from the transport, removing power from the erase driver, but the erase circuitry in the electronics and case harness remains powered. The recording method is near-saturation direct-record. No bias is used. The record drive is sufficient to write over previously recorded data without a separate erase head.

Science bit sync at 132.3 kHz and data from the DAS are recorded alternately on the two record tracks. Bit sync is recorded on each track at 66.15 kHz. Data are recorded such that for a "1," a flux transition at bit sync time occurs on both record tracks simultaneously, while for a "0," a flux transition occurs on only one of the tracks.

3. Playback amplifiers and data detection. The playback (PB) head assembly (Fig. 5) has nine separate tracks. There are four pairs of playback tracks and one tachometer track (see Fig. 6). A single-stage preamplifier is provided for each of the head windings. The outputs of two of the data track preamplifiers are selected by the track selection logic to obtain the channel A and B playback signals. The selected channel A and B signals are separately amplified, differentiated, limited, and detected. The two detected data streams are combined at the input to the buffer.

The limited signal at the input to the data detectors is a 4-V peak-to-peak square wave. An integrate-and-dump circuit extracts data from the limited playback signal.

A phase-locked loop is used to derive the clocks from the limited playback signals. Clocks from the phase-locked-loop voltage-controlled oscillators (VCO's) time the integrate-and-dump circuitry. The loop filter response and the VCO countdown are switched by the bit rate selector. The derived clocks are used to clock the detected data into the buffer.

4. Buffer and data combiner. The A and B data channels are combined at the input to the buffer. Nominally there is a 180-deg phase difference between the A and B data signals. The timing is established during the recording process, when the data are alternated between the two selected tracks, and requires very precise construction and alignment of both the record and playback heads. A sum of the negative tolerance analyses of the heads and their alignment indicated that the A and B playback signals could be in incorrect phase. To circumvent this possibility, skew compensation circuitry was incorporated in the record electronics to add compensating lag or lead of 90 or 180 deg into the phase A record logic. It was not needed for the PTM and flight transports, and the compensation circuitry was wired for zero compensation.

The A and B channels are clocked into the buffer with frequency and relative phase as readoff of the tape. The playback data are clocked out of the buffer by the selected clock, which is derived from a stable crystal oscillator (master oscillator in Fig. 5). The buffer is required because the tape speed cannot be kept accurate enough to maintain the phase difference between the data read from the tape and the selected clock at less than 1 bit. The buffer has a capacity of 32 bits and nominally stores 16 bits (half full). This permits a phase difference between the playback data from the tape and selected clock of up to 16 bits, either lagging or leading, without loss of data.

The buffer also serves as an integrating phase detector, which is used as part of the tape speed servo system. An analog signal proportional to the number of bits stored in the buffer is generated. This signal is +5 V when the buffer is full, 0 V with the buffer half full, and -5 V when the buffer is empty. Since a 10-V signal is equivalent to 32 bits, the buffer may be said to have a gain of 312 mV/bit as a phase detector. The analog signal and the level signal from the buffer and data combiner to the summing junction are shown in Fig. 5.

The buffer level analog signal appears at the summing junction only if both of the data phase-locked loops have acquired data. Lock of both data loops is determined by comparing tape clock A and tape clock B from the data detector. When clocks A and B are phase-coherent for a period of about 100 ms, a data loop sync signal is generated and the buffer level signal is enabled. The data loop sync signal is also sent to the telemetry conditioner.

5. Motor and driver. The motor is a two-phase hysteresis synchronous motor. The phase difference between the two motor windings is 90 deg, and each is powered by a separate driver. Direction is controlled by changing the relative phase between the two windings.

In the record mode, the motor current switches full dc voltage to the drivers. Each driver operates as a saturated switch, chopping the dc motor voltage to produce a square wave output which is capacitor-coupled to the motor winding. The capacitor values are selected to tune the circuit near resonance and provide a motor current which appears nearly sinusoidal. In the record and slew modes, the current is about 2 A peak to peak in each winding and the motor operates synchronously at 5060 rev/min.

In the playback mode, the dc input to the motor drivers is controlled by a power amplifier in the servo electronics. With reduced power applied, the rotor of the motor slips from its synchronous speed. The servo provides precise control of the motor speed by controlling the power to the motor.

6. Servo design. In the playback mode, the motor is operated asynchronously. The dc voltage to the motor driver is controlled by the servo power amplifier (shown near the center of Fig. 5). The enable record speed input to this amplifier causes full power to be delivered to the motor in the record and slew modes. In this case, the dc motor voltage is about 15.2 V. In the playback mode, the enable PB speed signal enables the input from the summing junction and tape speed is servo controlled. In the absence of an enable signal (ready mode), the amplifier input is clamped near zero. In playback, the dc motor voltage is normally in the range from 6 to 8 V, with an available maximum of about 14 V.

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The transport speed is unpredictable with a fixed input during asynchronous operation. In playback, it is necessary to keep the motor continuously under servo control. Normal record sequences during the mission will result in gaps in recorded data between pictures in run-up and run-down areas, and in the turnaround areas near the end of tape. Since gaps in the data cannot be tolerated by the playback servo, a separate track on the tape is provided to derive a continuous tachometer signal to control tape speed when the recorded data rate falls outside the data phase-locked-loop capture range.

A tachometer channel separate from the data channels also simplifies data acquisition. The acquisition times of the data phase-locked loops are relatively slow, making it necessary for the tape speed to stay within the capture range of the phase-locked loops for a finite period of time. In the MM '71 design, a discriminator operating from the amplified and limited tachometer is used for speed control. During acquisition, the data loops are out of lock, so the buffer level signal is not present at the summing junction. Operating only from the tachometer signal, the servo is designed to bring the tape speed well within the capture range of ±15% of the phase-locked loops.

There is nominally some frequency error with the velocity feedback provided by the tachometer channel which would result in continual errors in the playback data rate unless corrected. The necessary correction is provided by the buffer level signal. Upon acquisition of the data loops, the buffer level signal is summed into the motor power amplifier, providing phase feedback. The servo gains are sized such that the phase error never exceeds ±16 bits. This keeps the transport speed and phase in the range that can be compensated for by the buffer's storage capacity.

The discriminator includes a selectable countdown, which is used to determine tape speed for the five playback rates. The discriminator provides correct information to the servo with any frequency from the tape between 0 (tape stopped) and 67 Hz (record speed). Between these limits, the discriminator output increases monotonically.

The gain of the transport as part of the servo system is not constant over the operating range defined by dc motor voltages between 4.5 and 14.5 V (gain of transport = tachometer output frequency/dc motor voltage). The servo amplifier is mechanized such that the loop gain with motor voltages below 8 V is twice that above 8 V.

7. Mode controller. There are four operating modes: ready, record, playback, and slew. The mode controller contains two magnetic latching relays, whose positions are decoded to generate the logic signals which determine the operating mode. The relays are set and/or reset by commands from the DAS, FCS, and CC&S. A state diagram of the commands and logic used to switch among the four operating modes is shown in Fig. 7.

In the ready mode, 2.4-kHz power is applied to the DSS, but the tape is not in motion and the erase and record heads are not energized. The playback mode data are played back through the flight telemetry system (FTS) from the track selected by the tape pass sequencer logic and at a rate determined by the bit rate selector. In record mode, the 132.3 science data from the DAS are recorded on the tracks selected by the pass sequencer logic. In slew mode, the tape is moved at record speed, without erasing stored data, in the direction determined by the tape pass sequencer.

The capability exists of providing a high-power slew mode by exchanging the 16A10 structural subassembly for a high-power slew subassembly plug-in replacement. Necessary electrical connections, including a DC-87 command, are provided at the 16A10 connector. A relay is provided in the 16A6 subassembly to permit switching the motor to the high-power slew subassembly. In the nonenergized position, the DSS logic is as shown in Fig. 7. Telemetry indications of the high-power slew mode are provided. (This mode is not shown in the state diagram.) The responses of the DSS to all commands and events are listed in Table 2.

8. Tape pass sequencer. The tape pass sequencer provides the logic signals which select the appropriate track pair and direction of tape motion (see Table 3). The state diagram for the tape pass sequencer is shown in Fig. 8. The LEOT and REOT signals are generated by the end-of-tape sensors in the transport. These sensors employ gallium arsenide diode light sources and n-p-n planar light sensors to detect transparent windows in the tape. (See Fig. 6 for locations of the windows.) The windows are made by removing the oxide coating from the front of the tape and the coating material from the back. There are four redundant windows at each end of the tape. Redundant left and right EOT sensors are employed.

Commands from the FCS are available to provide operational flexibility and to back up the end-of-tape sensors and circuitry.

9. Telemetry conditioner and telemetry. The telemetry conditioner generates two 7-bit digital words containing DSS telemetry indications. Status channel words are read out synchronously with bit sync provided by the FTS.

Status channel 1 is word 218 in the engineering telemetry format. Channel 218 gives the status of the mode and pass selection logic. (It is coded as shown in Table 3.) This channel also indicates the status of the "full" logic if the DSS is in the ready, record, or slew modes. In the playback mode, bits 1 and 2 are used to monitor buffer overflows and empties.

Status channel 2 is word 304 in the engineering telemetry format. Its coding is shown in Table 4. This channel indicates the operating range of the buffer to the nearest quarter, the status of the bit rate selection logic status of bit sync loops, and the status of the high-power slew logic. Since the high-power slew mode is not incorporated, the third bit of this channel always indicates "high power not enabled."

The servo monitor signal sent to the FTS is a 0 to 100-mV range signal which provides a telemetry indication of the dc motor voltage. It is channel 217 in the engineering format.

A telemetry indication of transport pressure is provided by engineering word 403. This indication is sent to the FTS in the form of a resistance which is proportional to pressure. Zero pressure is zero resistance, and 2.0684 N/m^2 (30 psia) corresponds to 100 Ω.

An event is sent to FTS event counter 1 when the tape pass sequencer enables CCW motion. This occurs at a pass change or at power turnon if CCW becomes enabled.

An event is sent to FTS event counter 2 when the tape pass sequencer enables CW motion. This occurs at a pass change or at power turnon if CW becomes enabled.

10. Power converter. The power converter supplies the five dc voltages used in the DSS. The +4.5-V supply is used primarily for logic circuitry, the +12 and -12-V outputs for analog circuitry, and the +18-V supply for the motor power. Relays are powered from the +28-V source. The power converter operates from spacecraft 2.4-kHz power.

At power turn-on, the in-rush current is limited to below 150% of the steady-state power by the size of the input filter chokes and capacitors following the rectifiers in each dc supply.

11. Packaging. The DSS is packaged in 10 subassemblies mounted in spacecraft bay V. The PTM DSS, mounted in a chassis and held in its handling fixture, is shown in Fig. 9.

III. PROBLEMS

A. Stick-Slip

The term stick-slip is commonly, but somewhat inaccurately used to describe the category of problems associated with anomalous motion of the tape across the heads. It is beyond the scope of this report to present, define, or catalogue all of the terminology generated and used in connection with the MM'71 tape/head problem investigations. For the purpose of this report, the problems will be divided into four categories: (1) welding and sticking, (2) tape velocity transients, (3) signal breakup, and (4) high drag.

1. Welding and sticking. During testing of breadboard and prototype transports, there were several occurrences of tape sticks. Tape types 3M 20302, 3M 8106, and CEC 4 were observed to stick to the heads under certain conditions. After some of the sticks, it was possible to "shake" the tape loose by alternate reversals of the motor drive direction. Under some conditions, applying motor power to a transport with a stuck tape would result in the transport throwing a tape loop. The tape loop would become entangled in the mechanism and result in a catastrophic failure.

The main effort in the investigation of the tape weld problem was directed toward understanding the mechanism of sticking and making changes to preclude its occurrence. Additional effort was spent in reducing the probability of a tape loop being thrown in the event of a tape stick.

Transfer of material from the oxide/binder conglomerate onto the heads was identified as a major contributor to tape sticks. Examination of the heads on the BB 1 transport after a tape stick revealed a plastic coating, later identified as a urethane compound. A similar material had been found during a tape stick investigation conducted by the Goddard Space Flight Center on the Nimbus program. The Goddard investigation determined that the urethane was boiled from the tape surface by locally high temperatures at the point of contact between the tape and head. The condition was aggravated by high operating temperatures and high tape tension.

Three candidate tapes (3M 20250, 3M 990, and CEC W4) were chemically analyzed for highly volatile components in the oxide coating. Type 3M 20250 contained the least amount of volatiles. Throughout the test program there was never a case of 3M 20250 sticking. Therefore, one component of the solution to the tape sticking (welding) problem was the selection of 3M 20250 tape.

During the investigation, it was apparent that exposure to elevated temperatures greatly increased the probability of volatiles outgassing from the tape and precipitating a tape stick. For this reason, the test limits on the tape transport were lowered to 55°C for type approval testing and 45°C for flight approval testing.

The erase heads were removed from the transport, eliminating two head assemblies and thereby reducing the surface area available for the head to stick to. In addition, this permitted the reduction of tape tension.

A parking place was provided near the LEOT primary window by clearing the oxide coating from the tape. This window was located such that, after an automatic stop from record speed, the tape would stop with the window across the heads. Thus, the heads would rest on the Mylar-tape base material. This eliminated the possible sticking of the heads to the oxide/binder material during long periods of nonuse.

Modifications were included in the transport to minimize the chance of loop throwing (catastrophic) in case of a stick which can be broken by motor power. The peripheral belt thickness was changed from 22 to 38 μm (0.86 to 1.5 mils). The tape length was increased to 182.8 m (600 ft) to permit use of 7.6-m (25-ft) leaders (usable tape remained unchanged); both capstans were coated with a polymer to increase the static coefficient of friction; and the torque transmissibility of the drive train was increased. These changes increased the amount of pull which could be delivered to the tape without throwing a loop.

Some changes were made in the techniques and materials used to clean heads to make sure all contaminants were removed (and none introduced) during cleaning. Tighter controls on the manufacture and inspection of the heads were introduced to ensure that the shields and core lamination glue gaps did not protrude into the tape.

Early in the investigation, the outlook for a good solution to the tape-stick problem was bleak. A decision was made to provide an emergency mode to apply high power to the motor to break a stick which would stall the motor with normal power. In this mode, called high-power slew, greatly increased power was gradually applied to the motor. A command (DC-87) was assigned to initiate the mode. A relay was provided in the 16A6 subassembly to switch the motor from the normal driver to the emergency power driver. The high-power driver was located in subassembly 16A10. A prototype 16A10 was built and tested on the PTM. As the tape-stick problem began to yield to the investigative effort, the need for a high-power slew mode brute force approach diminished. Flight versions of the 16A10 high-power drives were never built, but the case harness and DSS still contain the circuitry required to plug them in.

2. Tape velocity transients. Early in the program, it was observed that the tape would occasionally stop briefly and then return to normal speed. The events appeared singular in nature and not related to spurious signals from the electronics or defects observable on the tape. This phenomenon, which caused the term stick-slip to be introduced into the program, was eliminated when a larger flywheel was installed on the motor to reduce flutter. The inertia of the drive train was increased sufficiently to power through any brief tendencies to stick. Actually, the steps taken to reduce tape sticking previously described constitute part of the solution to velocity transients. In any case, the phenomenon originally called stick-slip disappeared early in the investigation.

3. Signal breakup. Early in the program, it was observed that the tape would occasionally chatter across the heads instead of moving smoothly. The playback signal was highly distorted with random frequency- and amplitude-modulation components and appeared to be broken (hence the term, signal breakup). Sometimes the tape sliding across the heads would cause the servo to become unstable, and an oscillation would occur. Data could

not be recovered in either case, so the conditions were catastrophic when they occurred.

An understanding of the fundamentals of tape-to-head static and dynamic friction characteristics was needed. A study and test program with the Illinois Institute of Technology Research Institute was instituted to provide the engineering data required for a solution to the problem. The critical parameters were identified as tape type, tape speed, wrap angle, tape tension, coefficients of static and dynamic friction, and head material. The relationships between these parameters were identified such that the tape selection could be verified and the appropriate tension and wrap angle could be determined.

Several transport changes were made with the common objective of solving stick (weld) and stick-slip (velocity transients) problems. Removal of the erase heads reduced drag on the tape and helped eliminate signal break-up. Changes to the peripheral belt, addition of 7.6-m leaders, and coating the capstans, lowered and stabilized tape tension and thus contributed to the solution.

4. High drag. During the stick-slip investigation, a large increase in the power required to drive the motor was observed on several occasions. Although sufficient motor power was available for the servo to control the tape speed satisfactorily, the servo system would become unstable and frequently go into oscillation. It was determined that the gain of the transport as part of the servo system would increase as the tape drag increased. To compensate for this increase, the electronic gain was decreased for motor loads greater than nominal; i. e., with DC motor voltages greater than 8 V, the servo gain was decreased 6 dB.

These anomalous increases in drag have not been observed with 3M 20250 tape.

B. Skew

Shortly after the breadboard No. 2 transport had been refurbished to become the prototype, it was noted that there was an excessive time displacement error between certain pairs of the playback channels. The specific cause of this problem was found to be an improper size screw in the head assembly, which caused deflection of the heads. The problem was solved by replacing the screw with one of the correct size.

However, during the investigation it was found that tolerances on the heads and their mounting could sum up unfavorably and cause the playback phase A and B signals to have excessive phase shift for recovering data. The head and transport suppliers were unwilling to decrease the tolerances, so skew compensation capability was added to the record electronics. A jumper wire was provided on the 16A2 subassembly to introduce phase lag or lead of either 90 or 180 deg in the phase A record signal. Head tolerances and alignment on the PTM and flight transport were well within specification and no compensation was needed.

C. Peripheral Drive Belt Failure

On 14 January 1971, the P-belt on the SN 003 (refurbished PTM) transport failed while the unit was being tested. An examination revealed that the P-belt was split along its length, causing an appendage of the belt to become entangled in the reel and tension idler module, and finally jamming the drive mechanism.

During the investigation, it was found that the combination of belt width and crown radius of two idlers caused a concentration of lateral stress fatigue at the point at which the belt developed a longitudinal split. The P-belt did not conform to the surface of the crowned idler over the full width of the belt, and the edges were lifted from the surface of the crown. The slit of the failed belt is believed to have been at the point near the edge where the belt started to lift from the crown. Analysis indicated that there is a high stress concentration at that location. Design changes were introduced into the transport to improve conformity of the belt to the crowned idlers. This was accomplished by increasing the crown radius of the idlers to 15 cm and reducing the P-belt width to 0.94 cm. These changes reduced the lateral stress fatigue on the P-belt.

Lateral stress fatigue alone does not adequately explain the failure, as it occurred on a relatively new belt. Furthermore, all attempts to reproduce only the fatigue failure by life testing have been unsuccessful. It was concluded that the failure most probably resulted from material fatigue on a belt that had an anomalous weakness prior to use which had escaped detection.

Belt material, manufacture, inspection, handling, and installation were reviewed. As a result, the belt manufacturing operation was moved to a cleaner room, tighter production controls were established, inspections were improved, and an approved solvents list for belt cleaning was established. These changes resulted in greater uniformity of the belts and reduced the rate of rejection due to defects. The changes and associated investigation did not reveal a probable cause of the anomalous condition which must have existed in the failed belt. An extensive life test program was conducted, and the failure was not duplicated.

The number of changes that could be incorporated into the flight belts was limited by the schedule time available. A parallel belt building program was established for the purpose of making superior belts which would serve as backups for the remote possibility of some belt disaster late in the program. In addition, and perhaps more important, the development work required to build a better belt would expand knowledge in all areas of belt manufacturing and lead to the discovery of any flaws which might have existed in the manufacture of the flight belts. At the time of this writing, the development of a better belt is continuing, primarily for the Viking program. This program has greatly improved belt making technology but has not uncovered any alarming defects in the processes used to fabricate the MM'71 flight belts. Support from JPL Divisions 35 (Engineering Mechanics) and 38 (Propulsion) was invaluable in improving belt technology.

D. Motor Cogging Flutter

The MM'71 DSS has a tendency to make bit errors for the first few minutes of playback when initiated from the slew mode at 4, 2, and 1 kilobits/s, especially near the REOT. The problem at start of playback was just barely observed on the flight 1 DSS and is not evident on the PTM DSS. The bit errors are caused by a flutter component at the motor cogging frequency. This flutter component appears to be about the same amplitude in all three transports, although flight 2 has the most severe symptoms. The problem appears to be intrinsic to the transport design.

Cogging of the motor when it is operated asynchronously at the playback speeds is the source of the flutter. Excitation to the stator windings of the motor generates a magnetic field which appears to rotate at 5060 rev/min. During synchronous operation, the motor rotor aligns with this field and turns at 5060 rev/min. When the motor is operated asynchronously, the rotor slips with respect to the rotating field. The cogging rate is the difference between 5060 rev/min and the actual shaft speed. The frequencies of the cogging flutter for the five playback rates are tabulated below.

PB rate, kilobits/s	Cogging frequency, Hz	Shaft speed, rev/min
16.2000	222.4	612.8
8.1000	237.7	306.4
4.0500	245.3	153.2
2.0250	249.2	76.6
1.0125	251.1	38.3

A model analysis of the transport drive train was written and programmed, using estimated values for the tape-to-head friction. It is evident from the results that resonance in the drive train could be amplifying the flutter generated by motor cogging. Because studies to determine the needed data about head-to-tape friction were not conducted, the analysis was not completed.

The test history of the transport was studied, and it was determined that the condition appeared to be stable and would therefore not worsen. The symptoms appear only after certain sequences, and operational measures taken to avoid the condition have little impact on the mission. In fact, the problem was discovered rather late in the program because the sequence causing it was rarely used during test. It is not expected to be a handicap during flight operations.

E. Direct-Access Isolation Amplifiers

Amplifiers and line drivers are located in the flight hardware for the purpose of amplifying the monitored signals and to prevent noise from the support equipment (SE) and direct-access (DA) cable from interfering with DSS operation. The concept was good, but the mechanization caused some problems. The IC circuits (Motorola MC 1539) selected for the analog amplifiers (at least those from the production lot used in the DSS) have some spurious gain characteristics in the region above 100 kHz. As a result, they tend to be unstable and oscillate in certain DSS test configurations.

The loads on the amplifier circuit are connected in such a way that changes in the load can change the feedback compensation. There was some evidence that the amplifiers were affected by noise on the DA lines.

The occasional erratic performance in the isolation amplifiers was an annoyance, but the performance of the DSS was not degraded. The solution would have been to use a new type of IC and provide better isolation between the load and the feedback and compensation circuitry. This change to flight hardware was deemed too costly and risky since the problem was not serious.

F. Solder Joints

Throughout the construction of the PTM and flight hardware, there were problems with solder joints at the point where the connector assembly is connected to the printed circuit boards. Poor wetting of the tinning on the leads from the connector assembly was the apparent result of a vapor honing process used to remove enamel from the wires. The visible portions of many of these connections did not meet specified requirements. Part of the corrective action was to scrape the leads after the vapor honing process to improve the quality of the solder joints. Much rework on the flight hardware was required. No material review board action was needed as all joints were satisfactorily reworked.

Future programs considering a similar packaging approach should incorporate design changes to eliminate this problem. As a minimun, the wires in the connector assembly should be stranded (pre-tinned) and set in a soft potting compound. Changes in the thickness of the board should be considered.

G. Conformal Coating

During the final assembly of several subassemblies, it was found that a buildup of excessive conformal coating was causing mechanical interference in the final sandwiching process. It appeared that the manufacturing personnel were overreacting to rejections due to thin conformal coating. Actually a thin coat of conformal coating is desirable, but there was no inspection technique available to distinguish between a thin coat and no coat at all.

H. IC Circuit Failure

During the fabrication and testing of circuit modules, several failures of SE424Q IC's were observed. Static discharges were suspected and the following precautions were taken: (1) a copper ground plane was installed on the floor of the test station, (2) a copper ground plane was installed on the test bench, and (3) the scope, chair, and test technician were grounded. All grounds were connected to the building ground. The test technician was grounded via a wrist strap. No failures were observed after these precautions were taken.

I. Tape Guidance

A slight amplitude modulation was observed on the playback signal of the flight 002 transport in August of 1970. This condition gradually worsened, and the transport was unsealed in December to investigate the condition. It was found that the tape was riding against the flanges of the tape idlers located on each side of the heads, distorting the tape.

Mechanical measurements made to determine the precise dimensional relationships of the various elements in the tape path showed all elements to be within specification. Tracking of the tape was corrected by using shims to adjust the relative alignment between the flanges and the heads. The shimming of the heads and idlers was done as required to optimize the tracking of the tape on all transports. This tracking adjustment is now part of the standard procedure of assembling a transport.

J. Transposed Playback Bit Sequence

On a few occasions, the prototype, flight 001 and flight 002 subsystems were observed to play back data in a transposed sequence. For example, a series of bits recorded in 12345678. . . order were played back in the transposed order of 21436587. . . or 132547698. The problem was caused by a design error in the circuitry intended to permit recovery of data during transients in dynamic skew which exceeded 1/2-bit time. The electronic design was changed such that data bits were taken from each data track in strict chronological order as they were read from the tape. These changes were incorporated in Engineering Change Request 14548. No transposed playback sequences have been observed since then.

IV. CRITIQUE

The most significant improvements of the MM '71 DSS over the MM '69 (and earlier) DSS are the use of all-digital recording and of a reel-to-reel transport.

The endless-loop transports used on MM '64, '67, and '69 were initially developed for flyby missions requiring few tape passes. They are poorly suited for long missions requiring many tape passes, having life times in the range of a few hundred passes. The lifetime of the MM '71 reel-to-reel transport is specified as 2400 tape passes, with some margin of safety.

A major weakness in the MM '69 DSS was the use of the analog record-reproduce process to store information carried in the amplitude of the recorded signal. This process caused continual problems throughout the development, testing, and calibration of the MM '69 DSS. The problems were of a fundamental nature and did not yield to the development efforts to improve performance. Therefore the recommendation was made to avoid the use of the analog recording process on future missions.

Several serious problems were encountered and solved during the development and testing of the MM '71 reel-to-reel transport. None were of a nature that would restrict use of the MM '71 transport concepts on future missions.

A benefit of the difficulties encountered was that they resulted in development being done on previously unsolvable problems. An example is the progress made in belt construction. At the beginning of the program, the process for making polyester belts for tape transports included some secret step which was carefully guarded by the companies that produced them. The failure of the belt on the SN003 transport caused this situation to change. The basic properties of the belt material required for good belts are now well understood, nondestructive tests on the belt material to uncover latent defects are available, and improved fabrication techniques are in view (Ref. 3).

The belt failure also led to the relocation of the crowned idlers that was contradictory to an industry rule of thumb that crowned idlers must not be adjacent in the belt path.

The tape welding problem caused a study to be made and a mathematical model to be constructed of the tape-tension-determining elements in the transport. Stick-slip resulted in a much better understanding of the design factors necessary to ensure smooth sliding of the tape across the heads, as well as in a redesign of critical elements of the servo. The flutter problems caused a modal analysis program to be written and resulted in improved techniques for measuring flutter being developed.

Problems with the MM '71 transport yielded to investigation, and solutions were found and implemented. Use of similar transports on future missions is enhanced by the technological base formed in the process of solving the MM '71 problems.

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3. Cuddihy, E. F., "Analysis of the Failure of a Polyester Peripheral Drive Belt on the Mariner Mars 1971 Flight Tape Recorder," JPL Quarterly Technical Review, Vol. 2, No. 1, Jet Propulsion Laboratory, Pasadena, California, Apr. 1972.

GLOSSARY

ATR	analog tape recorder
CC&S	central computer and sequencer
CCW	counterclockwise
CW	clockwise
DA	direct access
DAS	data automation subsystem
DSS	data storage subsystem
DTR	digital tape recorder
EOT	end of tape
FCS	flight command subsystem
FTS	flight telemetry subsystem
IP	isolated pulse
LEOT	left end of tape
LSB	least significant bit
MM '69	Mariner Mars 1969
MM '71	Mariner Mars 1971
MSB	most significant bit
PRI	primary
PTM	proof test model
REOT	right end of tape
SE	support equipment
SEC	secondary

Table 1. Technical characteristics

Parameter	Performance
Storage capacity	1.8×10^8 bits
Data input rate	132.3 kilobits/s
Playback rates	16.2 kilobits/s
	8.1 kilobits/s
	4.05 kilobits/s
	2.025 kilobits/s
	1.025 kilobits/s
Weight, subassemblies 16A1 through 16A10	11.09 kg (24.4 lb)
Weight, harness	1.864 kg (4.1 lb)
Power (measured)	
Playback	16.1 W
Record	26.7 W
Slew	26.0 W
Ready	12.4 W
Tape speeds	
Record	49.38 cm/s (19.44 in./s)
Playback	
16.2 kilobits/s	6.1 cm/s (2.4 in./s)
1.0125 kilobits/s	0.381 cm/s (0.15 in./s)
Run-up time to record speed	1.0 s specified maximum
	0.4 s nominal (room temperature)
Run-down time from record speed	2.7 s (room temperature)
Tape type	MT 20250 (Minnesota Mining and Mfg.)
Tape dimensions	167.6 m (550 ft) × 1.27 cm (1/2 in.)
Tracks	9 (4 pair of data tracks plus a tachometer track)

Table 2. DSS response to commands and events

Source				Response
DAS	CC&S	FCS	DSS	
	16G	DC-16		Start recording from any mode.
Start record				Start recording from ready mode only if DSS tape full logic is reset.
Stop record				Switch to ready mode from record mode only.
	16H	DC-3		Start playback from any mode and reset tape "full" logic.
	16F	DC-4		Switch to ready mode from any other mode.
		DC-39		Start tape slew from any mode.
	16J			Advance from any tape pass to tape pass 4 and start slew mode.
		DC-22	REOT[a]	Switch to tape pass 2 from 1 or switch to tape pass 4 from 3. If in CCW slew, switch to ready mode.
		DC-23	LEOT[b]	Switch to tape pass 1 from 4 or switch to tape pass 3 from 2; if on pass 4 in record mode, set the tape to full logic. If in CW slew, switch to ready mode.
	16A	DC-56		Select 16.2-kbps playback rate.
	16B	DC-57		Select 8.1-kbps playback rate.
	16C	DC-58		Select 4.05-kbps playback rate.
	16D	DC-59		Select 2.025-kbps playback rate.
	16E	DC-60		Select 1.0125-kbps playback rate.
		DC-87		High-power slew command.

[a]REOT indicates the EOT event occurring at the extreme CCW rotation of the tape reel.

[b]LEOT indicates the EOT event occurring at the extreme CW rotation of the tape reel.

Table 3. DSS status, channel 1 format (telemetry word 218)

Bit[a]	Value[b]	Indication
1 (MSB)[c]	+4.5	Buffer did not empty since last readout, in playback. Tape full in ready, record, or slew mode.
	0	Buffer emptied since last readout, in playback. Tape $\overline{\text{full}}$ in ready, record, or slew mode.
2	+4.5	Buffer did not overflow since last readout, in playback. Tape $\overline{\text{full}}$ in ready, record, or slew mode.
	0	Buffer overflowed since last readout, in playback. Tape full in ready, record, or slew mode.
3	+4.5	Tape pass 1 or 2.
	0	Tape pass 3 or 4.
4	+4.5	Tape pass 1 or 3.
	0	Tape pass 2 or 4.
5	+4.5	Playback, record, or ready mode.
	0	Slew mode.
6	+4.5	Record, slew, or ready mode.
	0	Playback mode.
7 (LSB)	+4.5	Playback, slew, or ready mode.
	0	Record mode.

Tape pass	Bit 3	Bit 4
1	+4.5	+4.5
2	+4.5	0
3	0	+4.5
4	0	0

Mode	Bit 5	Bit 6	Bit 7
Ready	+4.5	+4.5	+4.5
Record	+4.5	+4.5	0
Slew	0	+4.5	+4.5
Playback	+4.5	0	+4.5

[a]Bit 1 is the first bit clocked out of the DSS, bit 2 is second, etc.

[b]Voltage on DSS/FTS interface.

Sample time at 8-1/3 bits/s = 420
at 33-1/3 bits/s = 1680

[c]MSB -- most significant bit.

LSB -- least significant bit.

Table 4. DSS status, channel 2 format (telemetry word 304)

Bit[a]	Value[b]	Indication
1 (MSB)	+4.5	Buffer output bit 1-8 or 9-16.
	0	
2	+4.5	Buffer output bit 1-8 or 17-24.
	0	Buffer output bit 9-16 or 25-32.
3	+4.5	High power enabled.
	0	High power not enabled.
4	+4.5	Bit sync loops in lock.
	0	Bit sync loops out of lock.
5	+4.5	Bit rate select relay 3 reset.
	0	Bit rate select relay 3 set.
6	+4.5	Bit rate select relay 2 reset.
	0	Bit rate select relay 2 set.
7 (LSB)	+4.5	Bit rate select relay 1 reset.
	0	Bit rate select relay 1 set.

Buffer output bits	Bit 1	Bit 2
1-8	+4.5	+4.5
9-16	+4.5	0
17-24	0	+4.5
25-32	0	0

Bit rate, kilobits/s	Bit 5	Bit 6	Bit 7
1.0125	0	0	0
2.025	+4.5	+4.5	0
4.05	0	0	+4.5
8.1	+4.5	0	+4.5
16.2	+4.5	+4.5	+4.5

[a]Bit 1 is the first bit clocked out of DSS, bit 2 is the second, etc.

[b]Voltage on DSS/FTS interface.
Sample time at 8-1/3 bits/s = 42
at 33-1/3 bits/s = 168

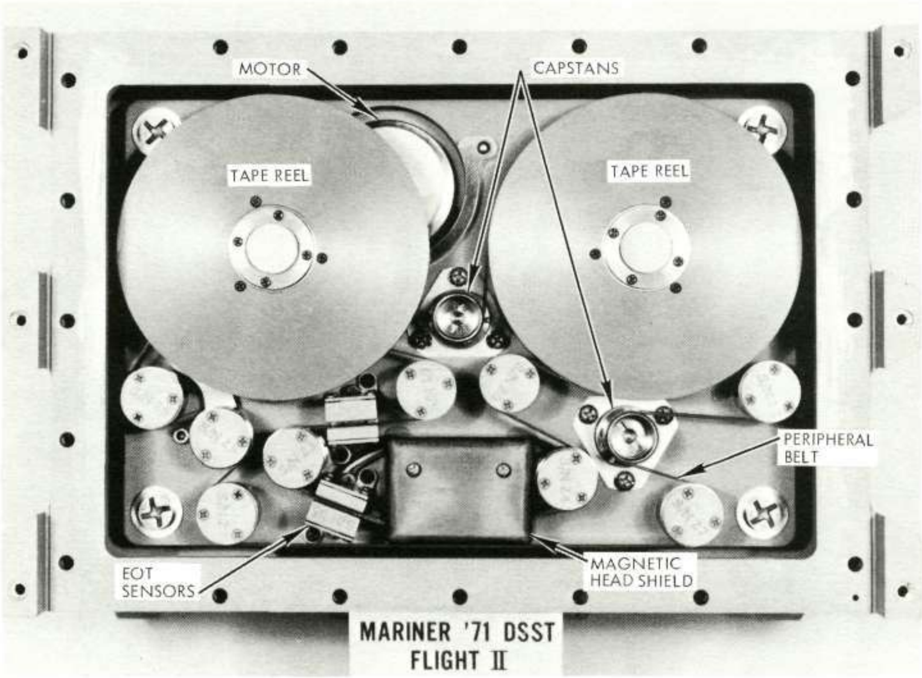


Fig. 1. Tape transport in case, top view

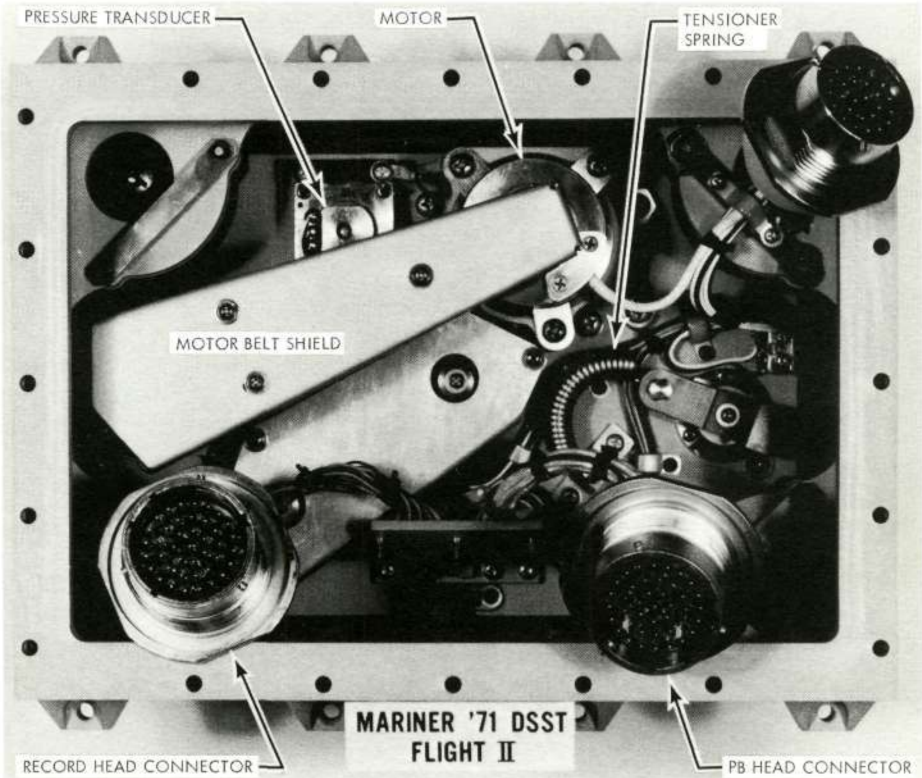


Fig. 2. Tape transport in case, bottom view

Fig. 3. Tape transport out of case, top view

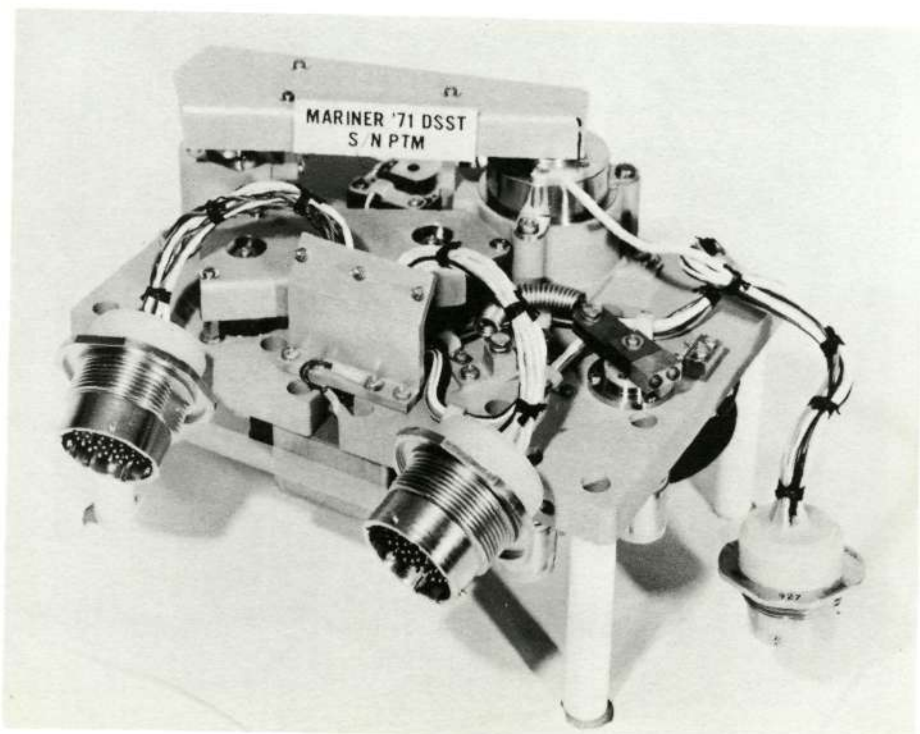


Fig. 4. Tape transport out of case, bottom view

FOLDOUT FRAME 1

FOLDOUT FRAME 2

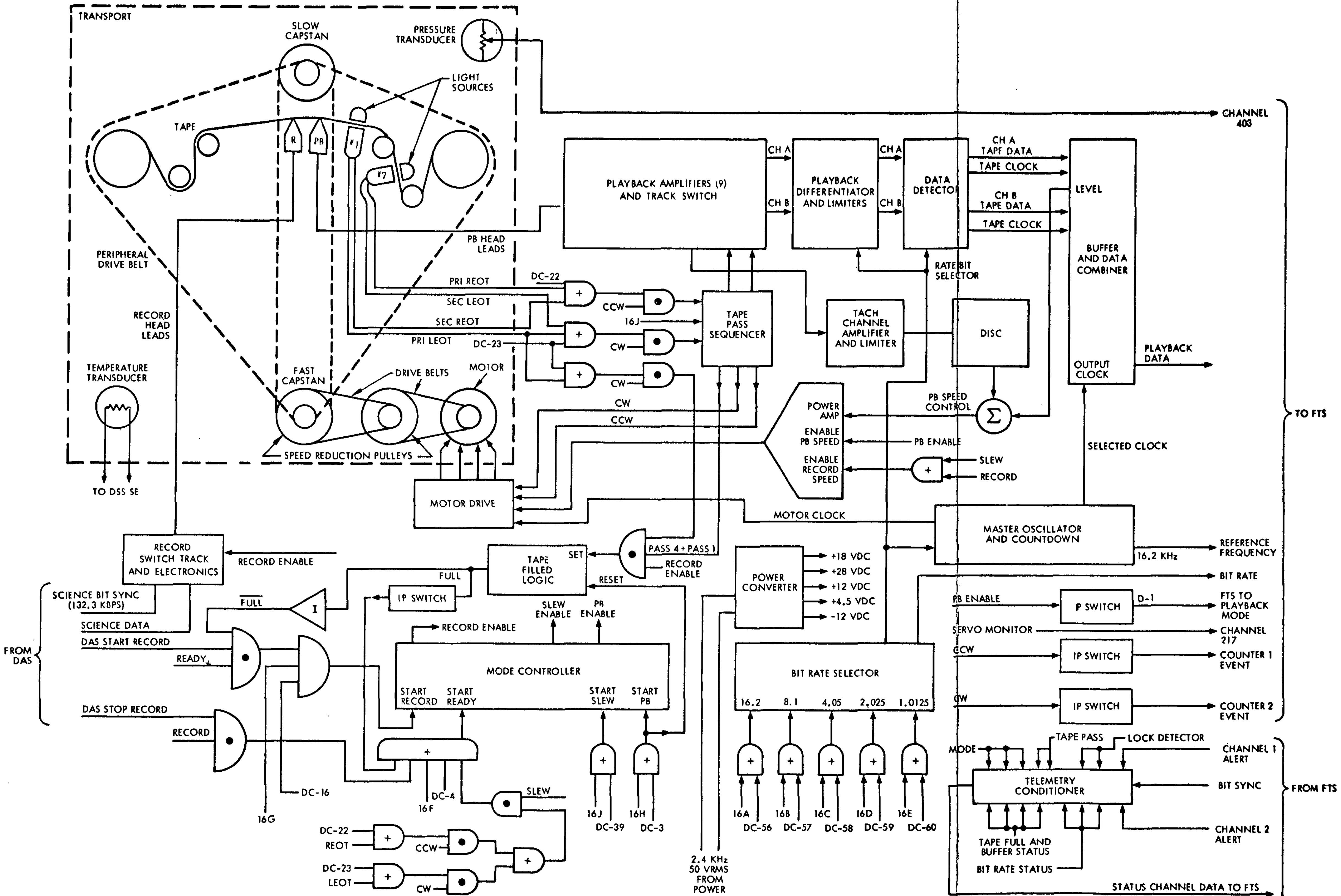
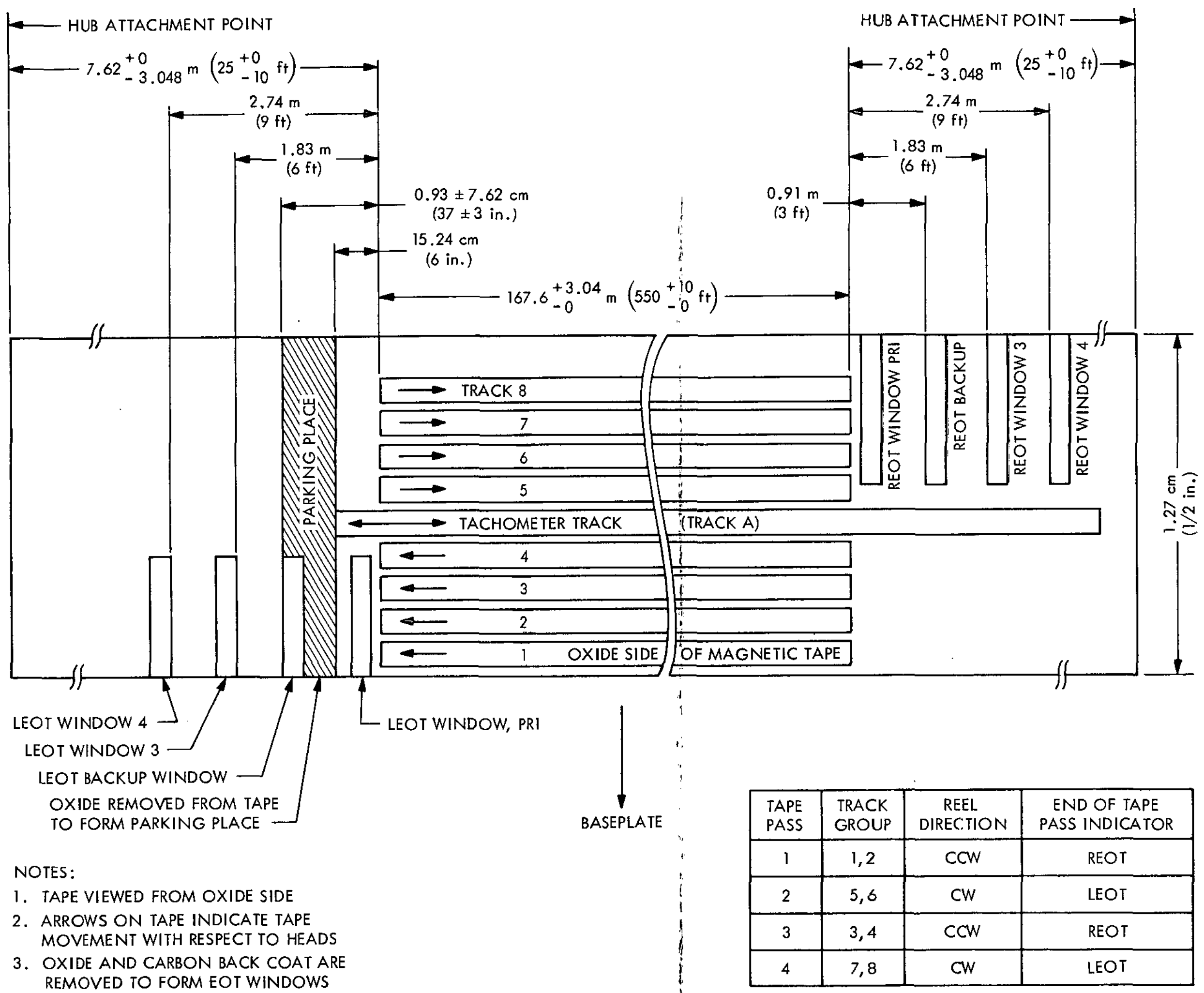


Fig. 5. DSS functional block diagram



TAPE PASS	TRACK GROUP	REEL DIRECTION	END OF TAPE PASS INDICATOR
1	1,2	CCW	REOT
2	5,6	CW	LEOT
3	3,4	CCW	REOT
4	7,8	CW	LEOT

Fig. 6. Track pattern and end-of-tape window placement

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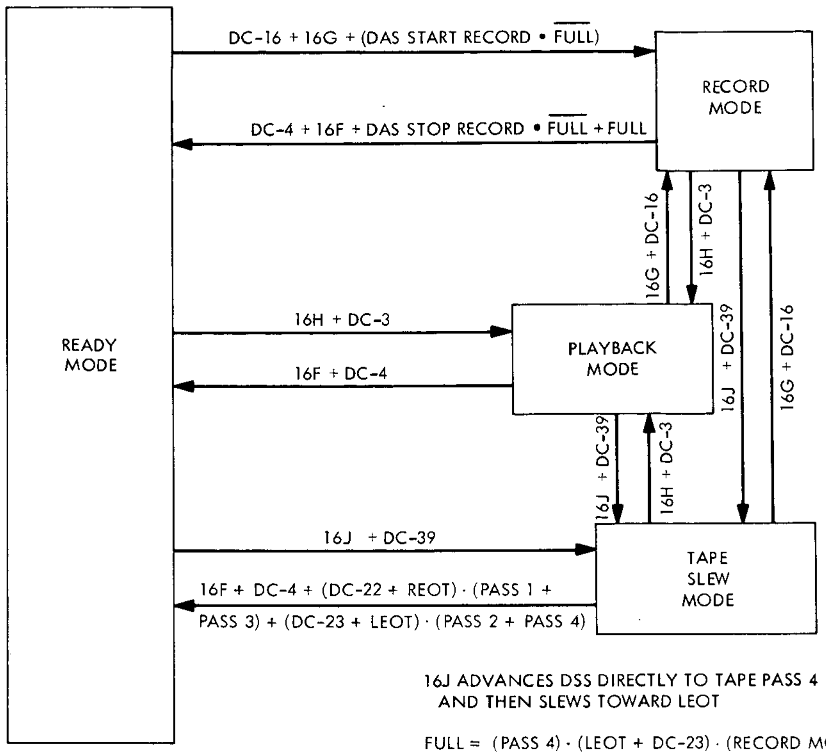


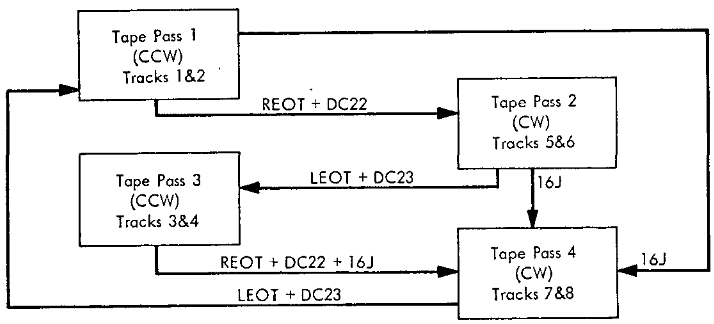
16J ADVANCES DSS DIRECTLY TO TAPE PASS 4 AND THEN SLEWS TOWARD LEOT

FULL = (PASS 4) · (LEOT + DC-23) · (RECORD MODE)

FULL LOGIC RESET BY 16H + DC-3

FULL LOGIC RESET = $\overline{\text{FULL}}$

Fig. 7. DSS mode diagram



CW = Clockwise tape reel rotation

CCW = Counterclockwise tape reel rotation

REOT = EOT at extreme of CCW rotation (right end of tape)

LEOT = EOT at extreme of CW rotation (left end of tape)

16J also selects slew mode

Fig. 8. DSS tape pass sequencer state diagram

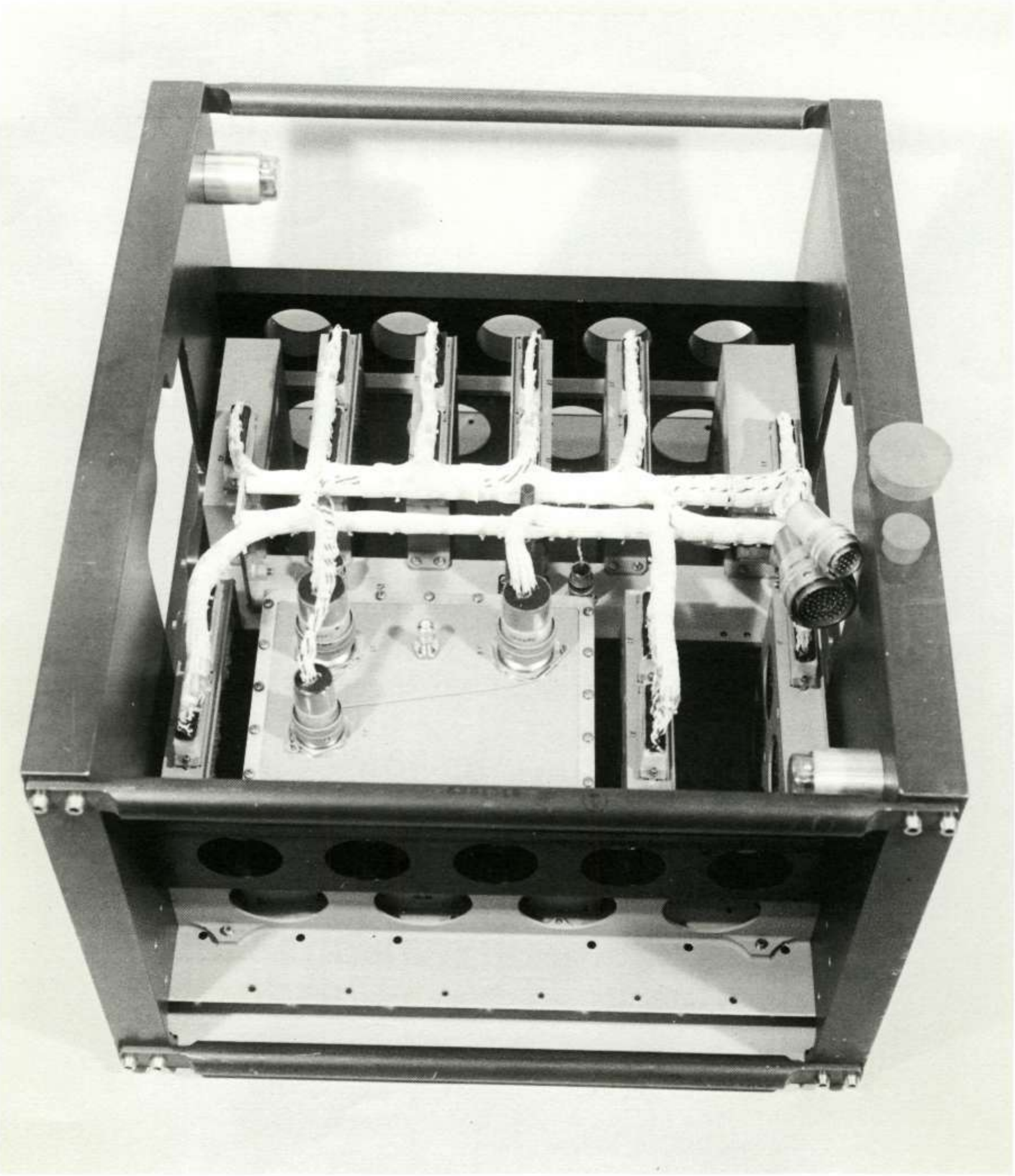


Fig. 9. Proof test model DSS mounted in a chassis and held in its handling fixture

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