THE SAS-A TELEMETRY SYSTEM

M. R. Peterson
D. L. Zitterkopf

The Small Astronomy Satellite has a PCM/PM telemetry system operating at 136 MHz. In the record mode multiplex data at 1 kHz are stored on an endless loop magnetic tape recorder for a maximum of one orbit or 96 minutes, and simultaneously transmitted at an output power of 250 mW. In the playback mode, the data recorded during the previous 96 minutes are transmitted at 30 kHz with an output power of 1.5 watts.

Introduction

THE SMALL ASTRONOMY SATELLITE TELEMETRY (TLM) subsystem design was required to fulfill two basic objectives: (a) satisfy the immediate requirements of the SAS-A mission, and (b) have adequate flexibility and capability to satisfy other experiments for follow-on launches with a minimum number of changes to the TLM subsystem. This article describes the SAS-A TLM subsystem and how it satisfies these two primary objectives.

The data requirements of the SAS-A and -B experiments were not unique. Because of the inclination and altitude of the SAS orbit, only one of the NASA STADAN network stations could be relied on to track and receive telemetry data. Therefore, to obtain experiment data continuously for an orbit, an on-board tape recorder was required with the capability of recording a minimum of one orbit or 96 minutes of data. The different data rates required the transmitter to have two output power levels, corresponding to the requirements during the real-time and playback transmission modes. Other requirements of the TLM subsystem were: (a) generate appropriate signals to synchronize the experiment with the TLM subsystem in a format agreed to by the experimenter, (b) be compatible with the NASA/STADAN telemetry receiving equipment,[1] (c) have the capability to process experiment data in analog and/or digital form, and (d) monitor and process information from within the spacecraft (i.e., housekeeping monitors such as voltages, currents, temperatures, and command status).

Weight and volume limitations prevented the use of extensive standby redundancy except for critical items, such as the crystal oscillator that is used as a master clock for the TLM subsystem. This redundant unit is switched and controlled by ground command. Within the limtations of total weight and volume, an obvious guideline for the design of the entire subsystem was that the effect of a failure or malfunction of a single component or connection be eliminated or minimized whereever possible.

System Description

The SAS-A TLM subsystem (see Fig. 1) is a PCM/PM system transmitting split phase encoded data at 136.68 MHz. There are two normal modes of operation, record and playback. In the record mode (see Fig. 2) the "real-time" digital data stream is filtered by the selected linear phase filter before modulating the operating transmitter. The real-time data are also recorded by an endless loop tape recorder for retransmission when the spacecraft is in view of the receiving station. The real-time bit rate is 1 kHz, and the minimum transmitter output power is 250 mW. As shown

[1] *Aerospace Data Systems Standards*, NASA GSFC X-560-63-2, Apr. 1968.

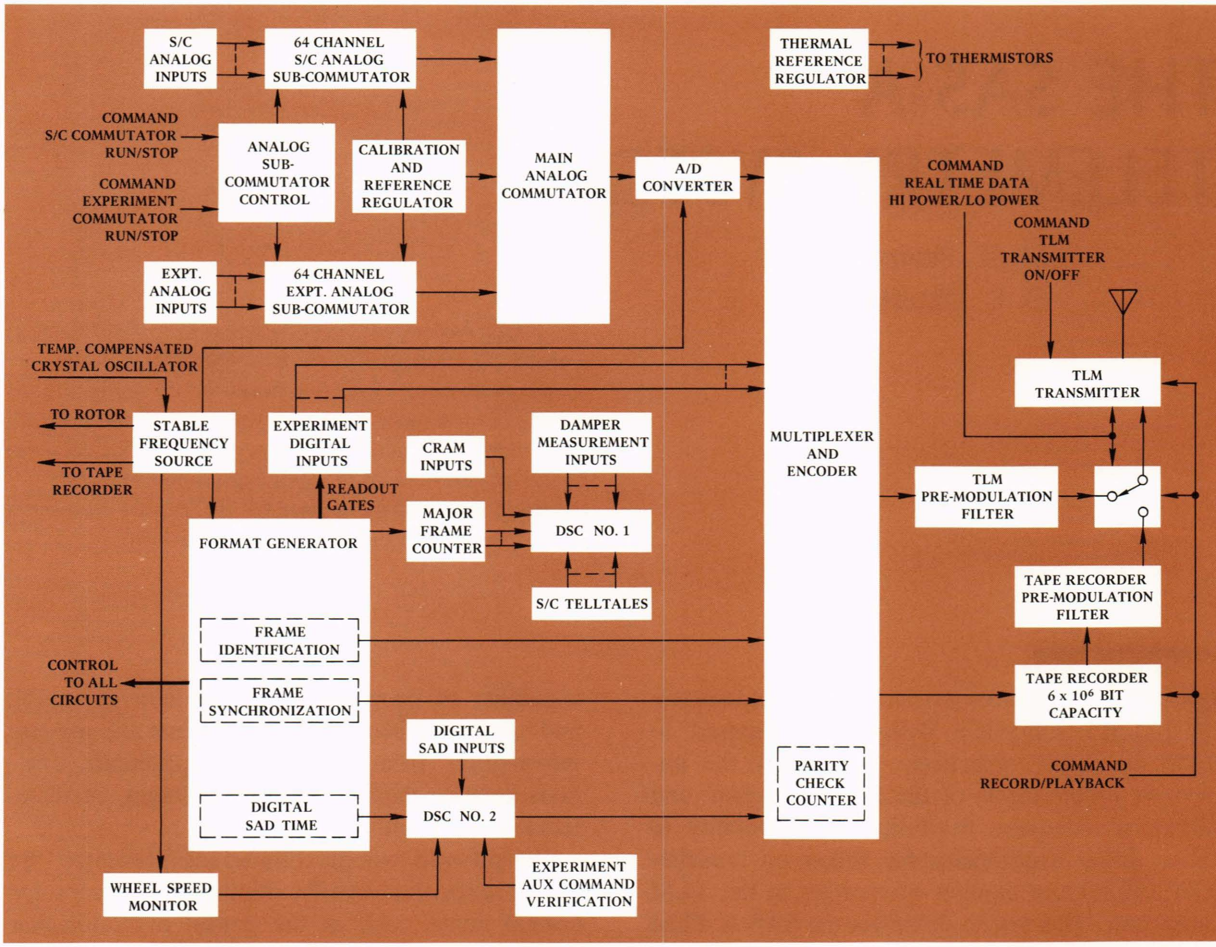

Fig. 1—Telemetry system block diagram.

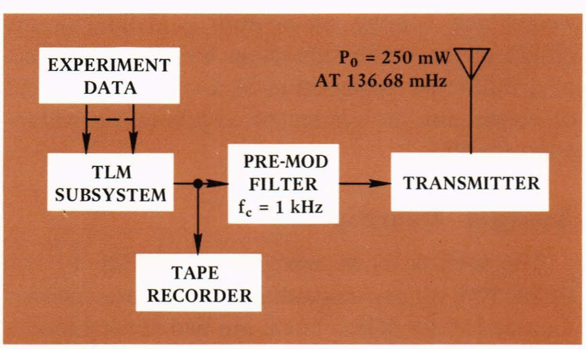

Fig. 2—Telemetry system in record mode.

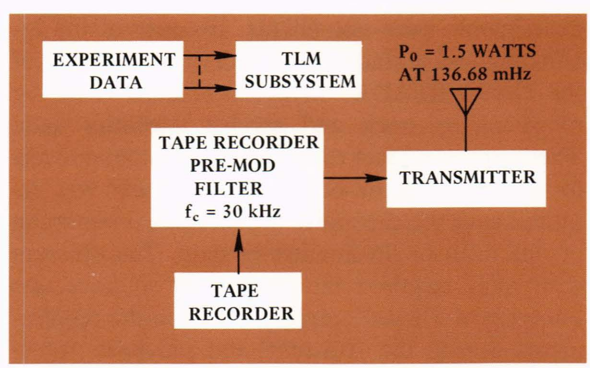

Fig. 3—Telemetry system in playback mode.

in Fig. 1, the transmitter can be turned off (by ground command) if it is necessary to conserve power for a particular spacecraft operation. However, the normal operating mode is with the transmission on, and adequate power remains in the carrier (while the real-time data are being transmitted) to satisfy the requirements of the orbit tracking and predicting (NASA Minitrack) facilities.

The subsystem is placed in the "playback" mode (see Fig. 3) by ground command. In this mode, the transmitter output power is increased to a minimum of 1.5 watts, and the 30:1 playback

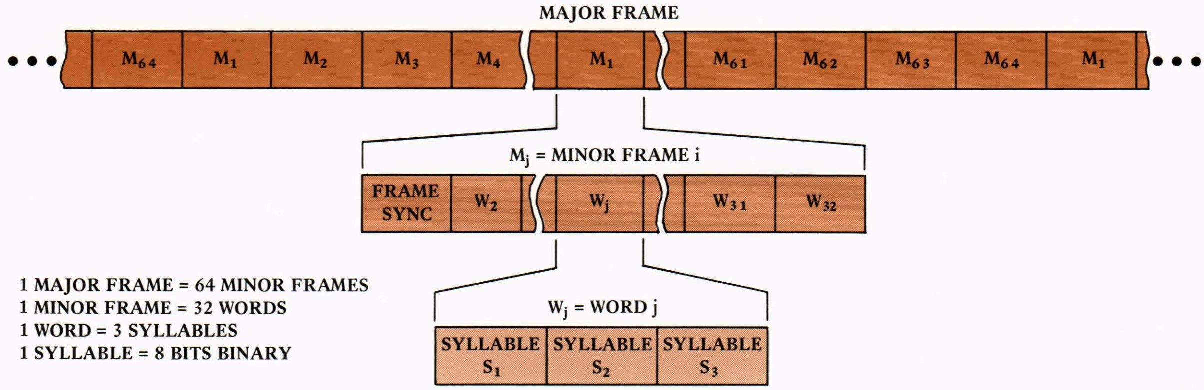

Fig. 4—Telemetry system typical PCM frame layout.

ratio of the tape recorder results in a playback data rate of 30 kHz. At the end of the playback cycle (approximately 3.4 minutes), the recorder issues a signal to the command subsystem, which returns the TLM subsystem to the record mode. If for any reason the recorder does not issue the end of playback signal or if it is desired to terminate the playback before the end of the cycle, the subsystem can be returned to the record mode by ground command. The 30-kHz data stream is filtered by a linear phase filter before modulating the transmitter. This filter is required to reduce the transmitted RF bandwidth.

There are two auxiliary transmission modes that can be selected by ground command. They are: (a) real-time data transmitted at 1 kHz, recorder in the record mode, and the transmitter in the 1.5 watt high power mode, and (b) real-time data transmitted at 1 kHz, recorder in the playback mode, and the transmitter in the 1.5 watt high power mode. Because the spacecraft power subsystem cannot support the high power 1.5 watt mode of the transmitter indefinitely at all satellite orientations, these modes are primarily for use in trouble shooting some possible malfunction, or in the event of a higher than expected noise environment.

A "minor frame" is the basic repetitive sequence of data in the SAS PCM format. As shown in Fig. 4, the 32 word minor frame sequence begins with a 1 word synchronization pattern,[2] and is followed by 31 words of data. Each word contains 24 binary digits and is divided into three eight-bit syllables. It takes 768 milliseconds to transmit a minor frame of data at a data rate of 1 kHz. Thus, there are 768 bits in a minor frame. Since there are three syllables per word and 32 words per minor frame, there are 96 eight-bit syllables per minor frame. The TLM format is also configured such that a sequence of minor frames, starting with minor frame 1 and continuing to minor frame 64, is defined as a "major frame." It takes 49.152 seconds (64 minor frames x 0.768 second/minor frame) to transmit a major frame at a data rate of 1 kHz. To aid the reader in remembering these definitions: The major frame is analogous to a paragraph, the minor frame is analogous to a sentence, and the minor frame is divided into words and then syllables and bits, as a sentence is divided into words, syllables, and letters.

Another representation of the SAS-A TLM format is given in Table 1. By examining the table, the reader will observe that there are four subcommutators within the TLM format. One 16-channel digital subcommutator (DSC #1) and one eight-channel digital subcommutator (DSC #2) are used to monitor and multiplex digital data such as telltales (which monitor command system status), outputs of various digital data registers not directly associated with the experiment data, and sundry go-no go monitor functions. Two 64 channel analog subcommutators (ASC #1 and ASC #2) are included to monitor housekeeping functions (voltages, currents, temperatures, etc.) in the experiment and control section of the spacecraft. The output of each analog subcommutator is converted from an analog voltage to an eight-bit binary number by an analog-to-digital (A/D) converter. One channel from each

[2] J. L. Maury, and F. J. Styles, "Development of Optimum Frame Synchronization Codes for GSFC PCM Telemetry Standards," *Proceedings of the NTC*, pp. 3-1 to 3-10, 1964.

TABLE 1

SAS-A TELEMETRY MINOR FRAME FORMAT

Word	*Syllable 1*		*Syllable 2*	*Syllable 3*
1.			FRAME SYNC	
2.		X-1		ASPECT
3.	PH1-1		PH2-1	PH1-2
4.	PH2-2		PH1-3	ASPECT
5.	PH1-4		FRAME IDENT.	PH1-5
6.		X-1		ASPECT
7.	PH1-6		PH2-3	PH1-7
8.	PH2-4		PH1-8	ASPECT
9.		X-2		ASC #1 (APL HSPKG. SAMPLE)
10.		X-1		ASPECT
11.	PH1-1		PH2-5	PH1-2
12.	PH2-6		PH1-3	ASPECT
13.	PH1-4		DM	PH1-5
14.		X-1		ASPECT
15.	PH1-6		PH2-7	PH1-7
16.	PH2-8		PH1-8	ASPECT
17.	DSC #1		DSC #2	ASC #2 (AS&E HSKPG.)
18.		X-1		ASPECT
19.	PH1-1		PH2-1	PH1-2
20.	PH2-2		PH1-3	ASPECT
21.	PH1-4		PARITY CHECK	PH1-5
22.		X-1		ASPECT
23.	PH1-6		PH2-3	PH1-7
24.	PH2-4		PH1-8	ASPECT
25.		X-2		ASC #1 (APL HSKPG. SAMPLE #2)
26.		X-1		ASPECT
27.	PH1-1		PH2-5	PH1-2
28.	PH2-6		PH1-3	ASPECT
29.	PH1-4		DM	PH1-5
30.		X-1		ASPECT
31.	PH1-6		PH2-7	PH1-7
32.	PH2-8		PH1-8	ASPECT

Note: Frame Synchronization, Frame Identification, ASC #1, DSC #1 and #2, and Parity Check are charged to the TLM subsystem; all other information is used by the experiment and as such is not discussed here.

of the four subcommutators is sampled during a minor frame. Each subcommutator advances one channel per minor frame; therefore, a complete cycle of the 16 channel subcommutator requires 16 minor frames; a complete cycle of the 8 channel subcommutator requires 8 minor frames; and a complete cycle of each of the 64 channel subcommutators requires 64 minor frames, or one major frame. (Note: The length of the 64 channel subcommutator defines the length of the major frame.) To identify which subcommutator channel is being sampled in a given minor frame, the subcommutators are synchronized to a binary counter (Frame Identifier, word 5 syllable 2 in Table 1) which is incremented at the start of each minor frame. By examining this binary information, the channel or minor frame number is determined.

The 64 channel analog subcommutators are normally synchronized to the Frame Identifier such that channel 1 occurs in minor frame 1, channel 2 in minor frame 2, etc. Therefore, channel 1 would be sampled once per major frame; or approximately once every 49 seconds. However, if a higher sample rate for a particular channel is desired for a given interval, it is possible to "stop" either of the 64 channel subcommutators on a particular channel by ground command, thereby assuring at least one sample of that channel every minor frame. The subcommutator will remain stopped on the same channel until released by another ground command. The transmission of the "stop" command must be timed such that if it is desired to stop the subcommutator in minor frame N (channel N), the command must be executed in the spacecraft during minor frame N−1. For example: If it is desired to stop the subcommutator on channel 16, the stop command must be executed while the subcommutator is on channel 15.

When the release command is received, the subcommutator is reset to channel 1 when the TLM subsystem cycles to minor frame 1.

Functional Description of Block Diagram

A brief functional description is given below of each of the fifteen main components of the SAS TLM subsystem shown in Fig. 1.

1. *Stable Frequency Source.* A redundant temperature-compensated crystal oscillator with a nominal frequency of 1.024 MHz ±0.001% is used as the basic timing source for the TLM subsystem. The operating oscillator is powered by a relay controlled by a ground command. The frequency variation of either oscillator is less than 1 part in 10^6 per orbit. This stability is achieved by passive temperature compensation since the expected temperature variation of the crystal is less than ±5% per orbit during normal operating conditions. In addition to providing the reference frequency for the TLM control electronics, other reference signals are derived for use by the momentum wheel speed monitor, the momentum wheel drive motor, and the tape recorder drive motor.

2. *Format Generator.* The format generator contains all the dividing and decoding circuitry which provides timing and control functions to all circuits within the TLM subsystem and experiments. The control functions include the address gates and readout gates, which multiplex all the data into the proper format. In addition to this function, the format generator also includes the circuitry that generates the frame synchronization word and the frame identifier syllable.

3. *Momentum Wheel Speed Monitor.* The momentum wheel speed monitor (WSM) measures the average rotational speed of the SAS momentum wheel by counting pulses from a 128 kHz stable frequency (derived from the TLM crystal oscillator) for 31 revolutions of the momentum wheel. These 20 bits, plus a telltale (which indicates if the reading is complete, or if the counter is still counting when the data is sampled) are transmitted in three eight-bit syllables.

4. *Major Frame Counter.* The major frame counter is used as a time code generator to relate spacecraft time to ground time. It is a 20-stage binary counter that is incremented every major frame (64 minor frames) or every 49.152 seconds, giving it the capability of a nonrepeating readout for approximately one year. By examining the major frame counter and the frame identifier, spacecraft time can be resolved to 0.768 second.

5. *Digital Subcommutators (DSC) #1 and #2.* The digital subcommutators are used to telemeter system data that can be sampled less than once per minor frame. Four of the 16 channels of DSC #1 are designed to accept serial input digital data, and 12 of the channels are designed to accept parallel input data. Of these 12 parallel input channels, four accept signals directly from integrated circuits compatible with the TLM subsystem integrated circuits. The remaining eight channels (8 channels x 8 bits/channel = 64 bits) handle positive or negative analog levels in addition to digital logic signals.

DSC #2, the eight-channel subcommutator, telemeters the momentum wheel speed monitor data, the state of the experiment auxiliary command subsystem, and information from the digital solar attitude detector (DSAD). The DSAD data consist of an elevation angle to the sun referenced to the spacecraft and the satellite time at which this elevation angle is measured (spacecraft time is referenced to the major and minor frame counters, and a word counter which resolves the DSAD time reading to ±0.012 second).

6. *64-Channel Analog Subcommutators.* The TLM subsystem includes two 64-channel analog subcommutators used to telemeter housekeeping information such as voltage, current, and temperature data from the experiment and control sections. Input voltages to the analog subcommutators may range from —50 to +50 volts; however, because of the characteristics of the junction field effect transistors used as switches, input voltages that exceed ±0.250 volt are attenuated so as not to exceed the rating of the commutator components.

Each of the analog subcommutators provides logic signals synchronized to channels 39, 40, 47, and 48. These signals are normally logical "1" and switch to a logical "0" during the time the subcommutator is on a particular channel. For example, the channel 39 signal is always a logical "1" until the subcommutator advances to channel 39, at which time the signal switches to a logical "0". The signal switches back to a logical "1" when the subcommutator advances to channel 40, but then the channel 40 signal switches from a "1" state to a "0" state. Some of these signals are being used in SAS-A as "power control gates" to switch power to devices that only have to be powered while their output is being sampled by the subcommutator. This reduces their power requirements from a duty cycle of 100% to a duty cycle of 1/64 (~ 1.6%).

7. *Main Analog Commutator (MAC).* The main analog commutator is similar in design to the 64-channel analog subcommutators; however, the input to the main analog commutator is merely the output of the two 64-channel analog subcommutators. The purpose of the MAC is to multiplex the outputs of the experiment and control section analog subcommutators to the input of the A/D converter.

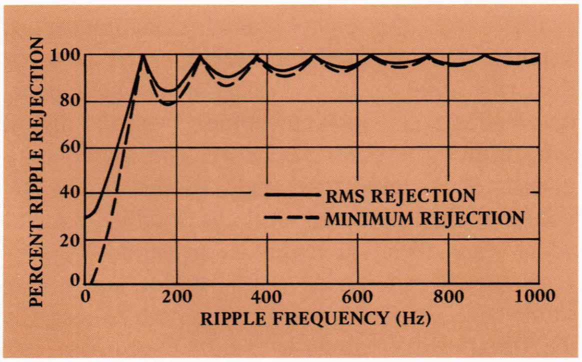

Fig. 5—Percent ripple rejection vs. ripple frequency of the A/D converter.

8. *Analog to Digital (A/D) Converter and Reference Regulators.* The A/D converter uses the dual slope integration technique to convert an analog input to an eight-bit binary output.[3,4] For an input of —0.254 volt or more negative, the A/D output is eight zeros; for an input of +0.254 volt or more positive, the A/D output is eight ones. The aperture time, or time during which the A/D converter samples the input, is 0.008 second. Figure 5 shows the percent ripple rejection vs. ripple frequency characteristics of the A/D converter. Complete rejection of unwanted signals at frequencies that are multiples of 125 Hz occurs because any sine wave with a period equal to or a multiple of the aperture period will contribute nothing to the output of the integrator. An analog voltage may be telemetered with the analog subcommutators, the main analog commutator, and the A/D converter with a maximum error of ±0.8% of full scale of the particular analog channel. This error is shared by the circuits in the following manner:

Contributor	*Errors, % of full scale*
Attenuators	±0.1
A/D converter linearity and reference voltages	±0.2
Commutator switches	±0.1
Resolution error (±1 bit in an 8 bit readout)	±0.4
	±0.8% maximum

The A/D converter also converts information from the star sensor into four bits of digital information. The sampling rate for this function is about 21 samples per second. The highest analog housekeeping sampling rate associated with the SAS-A TLM subsystem is approximately 2.6 samples per second. (The control section housekeeping TLM is sampled twice per minor frame, or 2 samples/0.768 second = 2.6 + samples/second.) This means that the highest signal frequency component that can be resolved without high aliasing errors is less than 1 Hz.

9. *Thermistor Reference Regulator.* The thermistor reference regulator supplies ± 0.500 volt at 4 milliamperes. A series connected combination of a thermistor and a fixed resistor is connected across the ±0.500 volt output, thereby creating a voltage divider whose characteristics vary as a function of the thermistor resistance (which changes with temperature). A separate resistor and thermistor combination is used for each temperature measurement desired, and the individual voltages are telemetered by using the analog subcommutators.

10. *Multiplexer and Encoder.* Using appropriate signals from the format generator, the multiplexer accepts all the various digital telemetry data (see Fig. 1) and combines them serially in the format illustrated by Table 1. Exclusive-or (modulo 2) addition (see Fig. 6) of the digital data and associated data readout gates is used in the multiplexer. This method of data combination provides protection from loss of the entire telemetry system output because of a failure of one of the input

[3] J. C. Loessi, *A Proposed Analog-to-Digital Converter for Small Earth Satellites*, APL/JHU TG 954, Oct. 1967.

[4] P. D. Olbert, *A Small Astronomy Satellite Analog-to-Digital Converter*, APL/JHU TG 1043, Nov. 1968.

gates, or a short to ground, or an open in the spacecraft harness. To provide a waveform free of switching transients, the multiplexed data are routed to the encoder. The encoder then converts the NRZ-C waveform to split phase coded data.[1] The encoder has two isolated outputs, one for the 1kHz premodulation filter and one for the tape recorder.

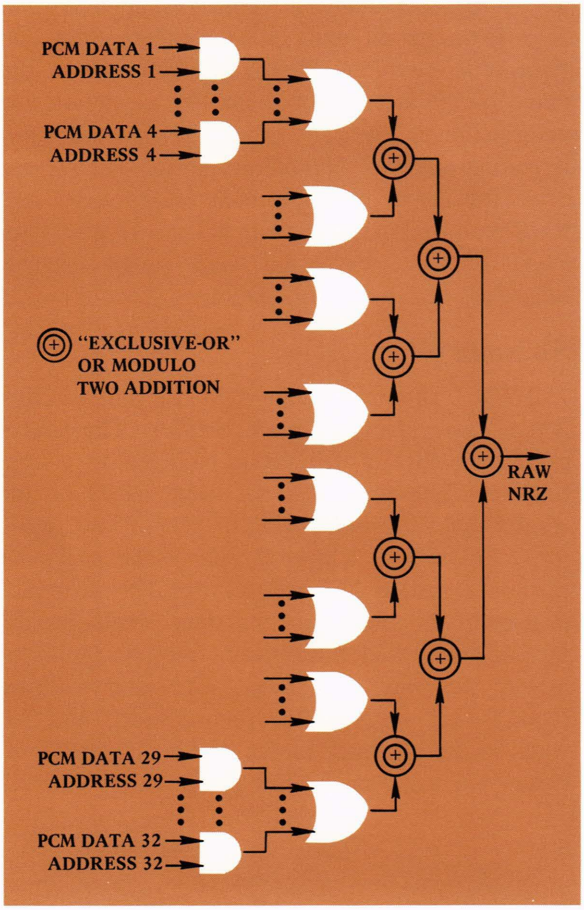

Fig. 6—Logic diagram for SAS multiplexer.

11. *Parity Check Counter*. When a ground station receives the telemetry data, it is possible for the station to detect certain errors introduced by the transmission link or the station's receiving equipment. This is accomplished by using the parity check data, the result of a parity check counter in the TLM subsystem that generates a (744,736) shortened cyclic code[5] (see Fig. 7). Eight parity bits are transmitted for every 736

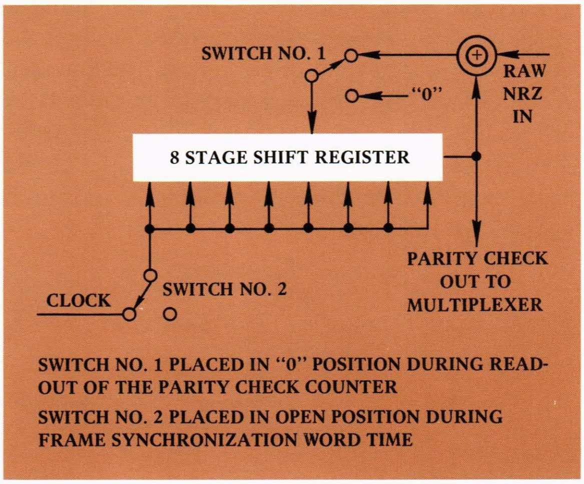

Fig. 7—Parity check counter.

data bits. The frame synchronization bits, which are of a known constant pattern, are not included in the parity check. The code makes a check on the complete minor frame except as noted above, and will detect all odd number of errors, i.e., 1, 3, 5, 7. . . . In addition to this property, the code will detect all burst error patterns of length ≤ 8, 99.2% of the burst error patterns of length 9, and 99.6% of all the burst error patterns of length ≥ 10. The parity check coding is performed in such a manner that the telemetered data can be recovered without performing the parity check on the ground.

12. *Premodulation Filters*. There are two five-pole linear phase filters in the subsystem; their purpose is to control the spectrum from the transmitters during both the real time and playback modes. (Refer to Fig. 1.) The real-time premodulation filter has a —3 dB point at 1 kHz and the playback premodulation filter has a —3 dB point at 30 kHz. The filters are DC coupled designs, which eliminates a possible voltage spike when switching from real time to playback, or vice versa. Such a voltage spike, inherent in an AC coupled design, could possibly over-modulate the transmitter, causing the carrier to disappear and the ground receiving equipment to lose phase lock.

13. *Tape Recorder*. The data storage tape recorder is an endless loop recorder provided to APL by NASA. It has a record/playback ratio of 1:30 ±0.5%. The capacity of the recorder is approximately 6 million bits with a packing density of 1667 bits/inch of tape. This gives a record time capability of approximately 100 minutes and

[5] W. W. Peterson, *Error Correcting Codes*, The M.I.T. Press: Cambridge, Mass., 1961.

a playback time of approximately 3.4 minutes, +4%, —0%. The operating recorder accepts the split phase coded data directly from the encoder. A phase-lock loop is included in the playback electronics to minimize playback flutter and wow. This phase loop can be removed from the circuit by a ground command. The recorder output is split phase coded data.

TABLE 2
WORST CASE TELEMETRY AND TRACKING SYSTEM MARGIN

	Record Mode	*Playback Mode*
Transmitter power*	+24.0 dBm	+31.8 dBm
Modulation loss (data and carrier)	—4.3 dB	—4.3 dB
Spacecraft cable loss	—0.5 dB	—0.5 dB
Spacecraft filter loss	—1.0 dB	—1.0 dB
Spacecraft antenna gain	—6.0 dB	—6.0 dB
Free space path loss (340 n. mile orbit at 10° elevation)	—141.3 dB	—141.3 dB
Polarization loss (if received with diversity combination)	0 dB	0 dB
Ground antenna gain	+17.0 dB	+17.0 dB
Received signal power	—112.1 dBm	—104.3 dBm
Noise power density (dBm above 1Hz)†	—164.7 dBm	—164.7 dBm
Received bandwidth (dB above 1Hz)	+30.0 dB	+44.8 dB
Received noise power	—134.7 dBm	—119.9 dBm
Received signal power	—112.1 dBm	—104.3 dBm
Received noise power	—134.7 dBm	—119.9 dBm
Signal-to-noise ratio	+22.6 dB	+15.6 dB
Signal-to-noise ratio	+22.6 dB	+15.6 dB
Signal-to-noise ratio for Bit Error Probability of 10^{-5}	+11.0 dB	+11.0 dB
Data margin	+11.6 dB	+4.6 dB
Minitrack margin above —120 dBm at receiver input‡	+3.0 dB	+10.8 dB

* Playback power is 1.5 watts including loss due to isolator and occurs at low voltage and +10°F (—12°C).
† Based on a 2400°K system temperature and 1 Hz bandwidth.
‡ Based on spacecraft antenna null of —17 dB, ground antenna with + 16 dB gain, and 45° elevation.

14. *Telemetry Transmitter*. The transmitter is phase-modulated and transmits at a frequency of 136.68 MHz ±0.002%. The output power (into a 50 ohm load) in the low power mode is 250 mW, and is 1.5 watts in the high power mode. These power levels are at lower temperatures and input voltages than predicted for normal spacecraft operation, and thus represent worst case power levels. An isolator inside the transmitter protects the power amplifier from overload caused by a high VSWR which may occur when the telemetry antenna is in the folded position during launch.

15. *Turnstile Antenna*. The turnstile antenna is mounted at the end of the —Y axis solar blade. The antenna radiates a cardioid-shaped pattern with left-hand circular (LHC) polarization and right-hand circular (RHC) polarization. In the plane of intersection of these two cardioids, the polarization is linear. A ground station using polarization-diversity combining equipment will receive the nearly isotropic sum of the LHC and RHC polarized signals, that is, will receive telemetry data at nearly the same signal strength regardless of satellite orientation.

Summary

Table 2 summarizes the data transmission link worst case calculated performances. The spacecraft filter loss of 1.0 dB is included as a contingency. The filter was not used, based on the results of RFI testing during spacecraft integration tests. Figure 8 is a photograph of the processor portion mounted in a test fixture. The processor portion of the telemetry subsystem (excluding the tape recorder and transmitter) requires approximately 2.5 watts of power. The tape recorder requires 1.2 watts in the record mode and 3.0 watts in the playback mode. The transmitter consumes 1.6 watts in the low power mode and 7.2 watts in the high power mode. The weight of the processor is 8.8 pounds, the tape recorder weighs 6.0 pounds, and the transmitter weighs 1.4 pounds.

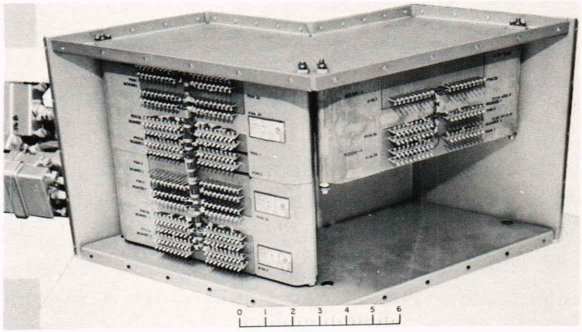

Fig. 8—Telemetry system assembled in test fixture.