require checkout under many different temperature and voltage conditions. The DCS is particularly tedious to check out, even when high-speed clocks are used to shorten the cycle times. In fact, the DCS Test Set was a much more difficult piece of equipment to design than the DCS itself.

The various blocks in the system were checked out in parallel as far as possible. Once combined into the complete system, a dual-track audio tape recorder was used to perform system-level tests. Command tone sequences were recorded on one track and voice instructions regarding the test on a second track. This procedure greatly speeded the system testing with little investment in hardware and none in software development.

Acknowledgment

Tim McAdams (formerly of APL and now with Allen-Bradley Systems) contributed many valuable suggestions to the system design and performed the detailed logic design. The TRF receiver was designed by George Seylar of APL.

The SAS-3 Programmable Telemetry System

by M. R. Peterson

The SAS-3 telemetry system was designed to be an extremely flexible means of collecting and returning to earth data generated by a satellite-borne X-ray experiment. This article describes the concepts used to implement the programmable format telemetry system.

Introduction

In the past, APL telemetry systems for near-earth spacecraft have had a fixed format (i.e., data sampling order) such that the sequence in which data were sampled could be changed only to a limited extent near and after launch. Obviously, it would be advantageous for an experimental satellite made up of several different scientific sensors to be able to change the data sampling format as the requirements of the experimenter vary. Such a programmable system would allow data from malfunctioning sensors to be omitted or would permit more frequent sampling of data of great interest. The programmable telemetry system developed by APL for SAS-3 allows almost limitless changes in format by a ground control station so that the greatest amount of useful information can be obtained from the orbiting satellite.

To ensure that the terminology used herein is understood, the following definitions are given. A "minor frame," shown in Fig. 1, is the basic repetitive sequence of data in a pulse code modulation

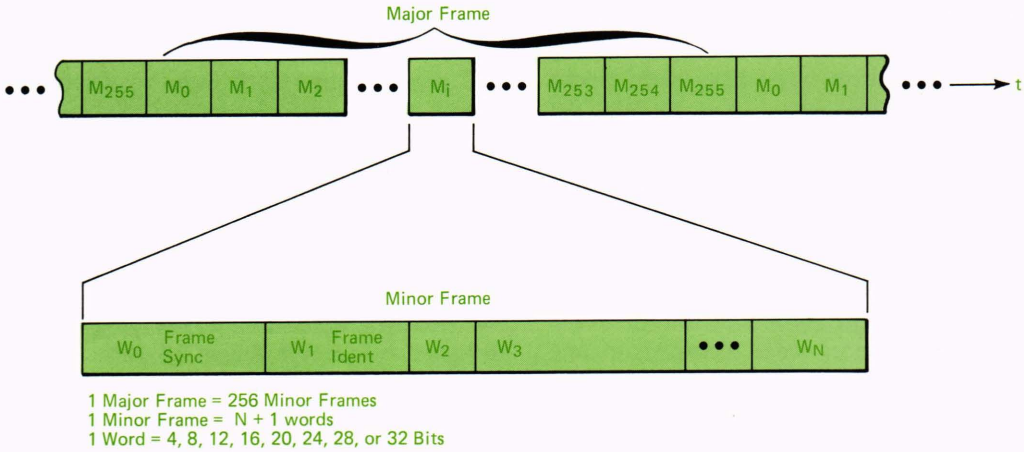

Fig. 1—Typical PCM frame layout of the SAS-3 telemetry system.

(PCM) data format. It contains two mandatory pieces of data, the frame synchronization code and the format identification code. This information is then followed by other data, shown in the figure as words 2 through N. For a particular satellite mission, the arrangement of the data within a minor frame may vary. However, the total number of bits in a minor frame must remain constant to ensure that the ground decommutation equipment can easily "lock on" to the data being transmitted.

Ordinarily there are data that are subcommutated within a particular word slot of the minor frame; i.e., a complete sample of the data source takes more than a minor frame to complete. As shown in Fig. 1, the SAS-3 telemetry system allows for a subcommutator length of 256 minor frames. The sequence of the 256 minor frames is referred to as a "major frame."

System Concept

There are several ways to implement a spacecraft telemetry system. The method used on the SAS-1 and -2 was to decide upon a data format before launch and then implement the *fixed format* by logic design and "hardwired" interconnections.[1,2] This fixed type of implementation minimizes size, weight, and power. However, it is inflexible in that the experimenter cannot change the telemetered format once the spacecraft achieves orbit. In fact, it is difficult to change the format even before launch, because a new circuit board has to be designed and fabricated. This means that the experimenter has to decide upon a format long before launch. As is often the case with scientific payloads, subtle but important changes in the basic design of the experiment become desirable. If the experimenter cannot change the format correspondingly, the experiment's effectiveness may be compromised. On the other hand, if the fixed format is changed by hardware modification, time is lost and the hardware reliability may be decreased.

A second data collection technique is the *adaptive format* telemetry system, in which the data are examined by some predetermined algorithm stored as software in the system controller. Based on the algorithm, the data are left unchanged or are compressed by processing or discarding. The system then transmits the processed data to the ground for further processing and interpretation. The adaptive format telemetry system has the advantage of recovering the greatest amount of usable data from the spacecraft while requiring the least intervention from a ground control station. However, while it allows the experimenter to change the format both before and after orbit is achieved, the adaptive system requires a complicated controller (equivalent to a medium-size digital computer) in the spacecraft to implement the sampling algorithm. Furthermore, an often overlooked disadvantage is the cost of programming the controller.

A third method, used on SAS-3, represents a combination of the two just described and is called

[1] M. R. Peterson, "The Small Astonomy Satellite Telemetry System," *Proceedings, National Telemetering Conference,* Los Angeles, April 22–30, 1970, 139–145.

[2] M. R. Peterson and D. L. Zitterkopf, "The Small Astronomy Satellite-A Telemetry System," *APL Technical Digest,* 10 Nos. 4 and 5, March-June 1971, 11–18.

a *programmable format* telemetry system. The programmable format system does not process, compress, or in any way change the data generated by experiment sensors in orbit. Like the fixed format system, it is relatively easy to design and build since a simple satellite-borne controller can readily be constructed using available integrated circuit technology. This allows the complicated controller to remain on the ground and, like the adaptive system, it permits the data sampling format to be changed both before and after launch as the experimenter desires. The size, weight, and power required by the programmable system are a compromise between the requirements of the fixed and adaptive systems.

A considerable amount of time was expended during the initial design phase to ensure that the SAS-3 system would be simple and would provide the flexibility required by a scientific payload. Before launch, the experimenter is able to select both the desired order of sampling data sources and the sampling frequency. After orbit has been achieved and the data received from the spacecraft are examined, the suitability of the data sampling order and rates can be determined. If a better data format will provide more meaningful data, it can be altered by changing the sampling format program stored in the format generator, which in the case of SAS-3 is the simple controller. Furthermore, if any of the data sources malfunction, the sampling can be eliminated from the format by changing the sampling format program. This maximizes the useful data returned from orbit. Obviously, the programmable system also allows the data format to differ from one spacecraft to another without changing hardware.

To minimize software cost, a simple instruction set was developed that has five basic instructions or operation codes. They are given in Table 1, along with a brief description of the actions they perform. The instructions provide the required flexibility for the system, which does not possess computational capability. They were expanded into an assembly language and an "assembler" was written to be run on the XDS Sigma 5 ground-based computer.

The assembler transforms a desired sampling format (written in assembly language) into a binary code that will in turn generate the format once the code has been loaded into the variable format generator via the spacecraft command system. In addition to generating the binary code, the assembler provides outputs to the ground-based decommutation program that allows the Sigma 5 computer to recognize which format is being received on the ground and automatically to decommutate, process, and display the data that are

TABLE 1

SAS-3 TELEMETRY SYSTEM OPERATION CODES

1. Read Data from a Digital Source
   Mnemonic: RBDS, bits   address, m
   Read [bits] from digital source [address] through multiplexer [m]. The parameter "bits" may assume the following values: 4, 8, 12, 16, 20, 24, 28, 32.
2. Initiate an Analog-to-Digital conversion
   Mnemonic: IAD, asc   address
   Initiate analog-to-digital conversion on [analog subcommutator], channel [address]. If [address] contains the letters FCTR, the contents of the frame counter will be used for the analog channel. If [address] is a number, that number will be used for the analog channel.
3. Set Scratch Registers
   Mnemonic: SSRO, x   address
   SSR1, x   address
   Set scratch register (zero or one) to [address]. If [x] = 1, increment the frame counter 1 count and load the Telemetry Verify Register (TVR). (The TVR contains the frame count and the contents of the storage at the location specified by the frame count.) This operation is used for five purposes: (1) to increment the frame counter at the start of each minor frame; (2) to allow a number to be read into the data stream to identify a particular format; (3) to permit the experimenter to read into the data stream a code of his own choosing if the standard 24-bit frame-synchronization code provided is not suitable; (4) as a diagnostic aid if a portion of the memory should fail; (5) as a control input for some subsystem.
4. Jump
   Mnemonic: JMPU   address
   Jump unconditionally to [address].
   Mnemonic: JMPO, S_n address
   If [sense line $S_n = 0$], jump to [address].
   Mnemonic: JMP1, S_n address
   If [sense line $S_n = 1$], jump to [address].
   Mnemonic: JMPS, y
   This instruction is used to perform software digital or analog subcommutation. The number of channels that are to be subcommutated is indicated by "y". Its value may be
   $y = 2m$ $(m = 1, 2, 3, 4)$
   The address where the subcommutator starts is "address". Its value is set by the programmer.
5. Repeat
   Mnemonic: RPT, bits   length
   Repeat the last preceding RBDS operation the number of times specified by [length]. The parameter "length" may assume the following values: 3, 7, 11, 15, 19, 23, 27, 31.
   The parameter "bits" must be the same number as "bits" in the last preceding RBDS statement.

being telemetered. The assembler has proved most useful to the program and makes the job of generating format programs extremely simple.

The fact that writing format programs is so convenient became an unexpected advantage when the time came for system integration and test. During system testing it is necessary to verify the response of the experiment and spacecraft to various commands. Since the sampling rate normally is not rapid, the verification process was expected to be lengthy. However, by designing new formats that rapidly sampled the verification information, the time required for this part of the integration and test period was shortened by a factor of ten. The ease of changing the sampling format attests to the usefulness of the programmable concept.

Another indication of the utility and flexibility of the programmable format is that the GEOS-3 telemetry subsystem was derived from the SAS-3 system. The fact that the GEOS-3 telemetry subsystem could use some SAS-3 hardware and the SAS-3 assembler and decommutation programs allowed a tight design and development schedule to be met.

The most important use of the SAS-3 programmable format system occurred in June 1976. A year after launch, the M.I.T. experimenter successfully changed the format so that data from sensors that had malfunctioned could be replaced by other, more useful data.

System Operation

Operation of the SAS-3 programmable sampling format is explained by Fig. 2, a simplified block diagram. Both analog and digital data can be telemetered from any satellite. Since the order in which the digital data are to be sampled is not known in advance, the "switch" shown in the multiplexer of Fig. 2 can be set to any of 64 input positions by the RBDS instruction of the format generator. It is then possible to accept data from each digital input in increments of 4, 8, 12, 16,

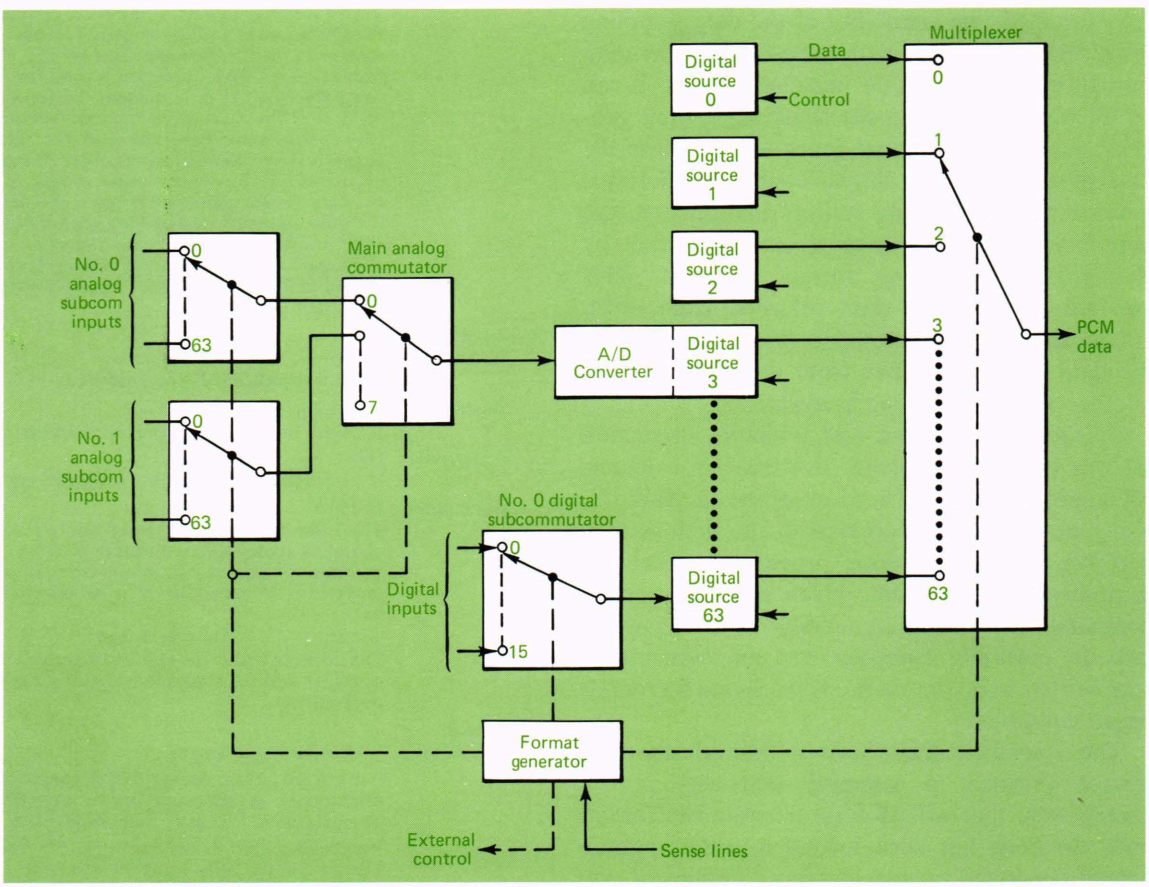

Fig. 2—Simplified block diagram of the signal flow of the telemetry system.

20, 24, 28, or 32 binary digits (bits); i.e., the switch can be programmed to dwell at any position for any of these increments.

The control inputs from external systems to the format generator labeled "sense lines" in Fig. 2 are used to force the telemetry system to change from one sampling format to another. They are assigned priority by the order in which they are sampled in a format program or, if desired, can be ignored.

The "external control" lines shown in Fig. 2 allow the format generator to communicate with external systems so that they may be synchronized with its data sampling operations. For example, the SAS-3 attitude control system sends to the analog-to-digital converter (ADC) an analog signal that was not to be telemetered but was to be converted from an analog voltage to a digital number and then used for attitude control. The IAD instruction (see Table 1) was used to make the analog-to-digital conversion. After conversion, the SSR instruction 0 or 1 (see Table 1) was used to store the binary number in the attitude control system.

In this space it is not possible to describe more fully the operation of the SAS-3 programmable format telemetry system. However, additional information is available.[3, 4]

System Description

The SAS-3 telemetry system shown in more detail in Fig. 3 is a pulse code modulation/phase modulation (PCM/PM) system. Because of the low inclination and altitude of the SAS-3 orbit, only the NASA Space Tracking and Data Acquisition Network station at Quito, Ecuador, can reliably track and receive telemetry data for a part of each orbit. Therefore, to recover the experiment data over the entire orbit requires data storage provided by two endless-loop tape recorders that were furnished to APL by NASA/GSFC. The recorders operate with a 20:1 playback-to-record ratio. This ratio requires the transmitters to operate at two different power levels. The tape recorders can record data simultaneously, although in practice only one is on at a time. Furthermore, the recorders can be "dumped" at the same time, one via the VHF link and the other via the S-band link.

Actually, two format generators are provided SAS-3: one with fixed and the other with variable format. There are three reasons for having both: (1) The variable storage may lose information if power is lost. If this happens, it is desirable to have an operating system available immediately, without reprogramming, so that telemetry data are available when power is restored. (2) While reloading the variable storage, it is desirable to have telemetry data. (3) The availability of two independent storage media permits a backup mode should one fail.

The storage of the variable format generator is an 8192-bit read-write random-access core memory (RAM). Early in the program it was decided to build the RAM from low-power COSMOS circuitry. However, the COSMOS units were not available early enough, so an APL-developed core memory was used. Because of the requirement for low power, the core memory was designed as a serial-access rather than a parallel-access device; therefore, operation of the format generators (and hence the telemetry system) is limited to a bit rate of approximately 16 kHz.

The storage of the fixed format generator is an 8192-bit field-programmable read-only memory (PROM) consisting of 16 Harris Semiconductor HPROM-0512 integrated circuits. The fixed and variable storage memories were each divided into two pages having 4096 bits of storage. Each page was configured as 256 16-bit words (program steps) and with identical sampling format programs determined by the experimenter early in the SAS-3 development. This was done for reliability, since it was uncertain if the fusable links in the PROM's would tend to "heal" themselves and return to the unprogrammed state of logic "0." In fact, the concern proved unnecessary; prelaunch tests and the performance of the units during spacecraft checkout and after launch have demonstrated their reliability.

Although each page of the variable storage could also be loaded with identical sampling format programs, a more useful step was taken on SAS-3: each page was loaded with a *different* set of sampling format programs, further demonstrating the system's flexibility. One page contained format programs for monitoring data associated with launch vehicle lift-off and early orbit opera-

[3] M. R. Peterson, "Design Specification for SAS-C Telemetering System," APL/JHU Report 7233-9904, June 1973.

[4] M. R. Peterson, "A Programmable Sampling Format Telemetry System," *Proceedings, International Telemetering Conference,* Washington, DC, October 9–11, 1973, 350–361.

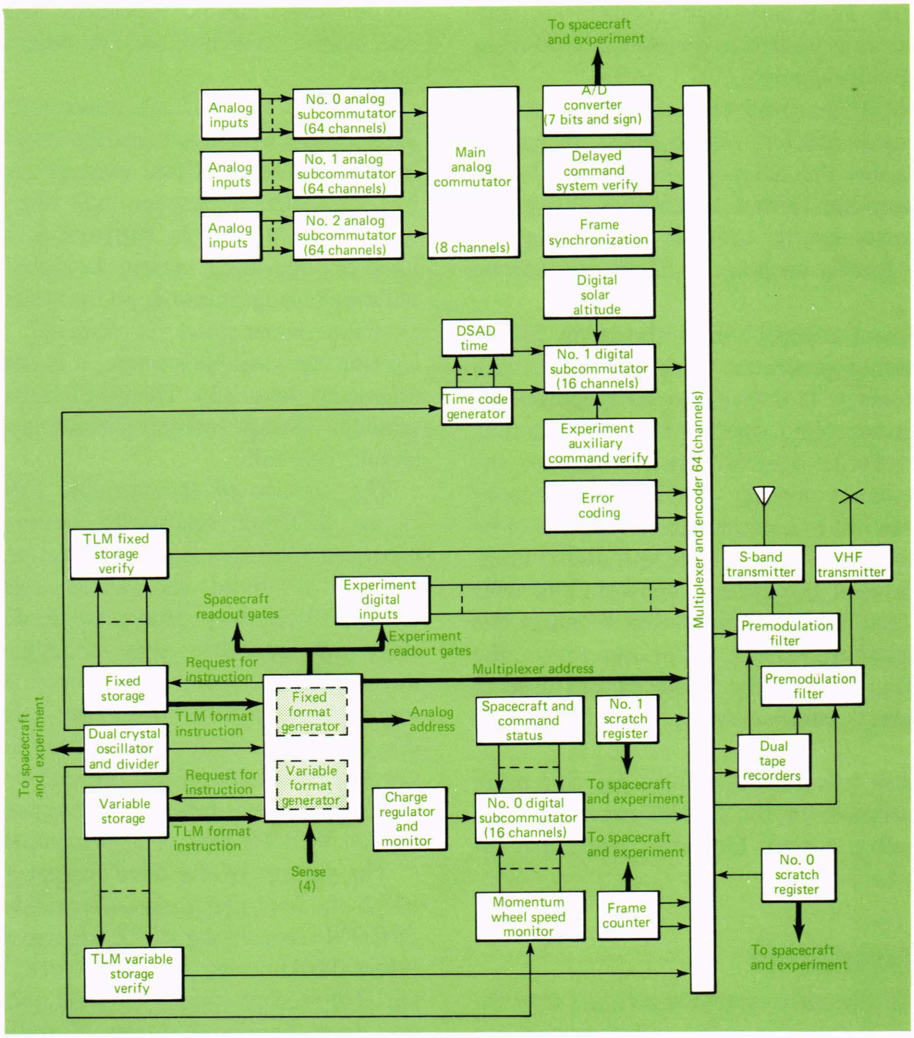

Fig. 3—Signal flow block diagram of the telemetry system.

tions. The other page was loaded with the format programs to be used by the experimenter after the spacecraft was stabilized and ready for operation.

The multiplexer and encoder will accept 64 serial digital inputs coded as NRZ-C. To provide a waveform free from switching transients, the multiplexed data are routed to the encoder, which converts the NRZ-C waveform to split-phase coded data.[5]

Timing for the telemetry system, experiment, and control section is provided by an ultrastable crystal controlled oscillator employing a 5.025-MHz crystal initially set to within ±2 parts in 10^7 and stable to 1 part in 10^{10} per orbital revolution over a temperature range of 30° to 120° F. It has redundant crystals and associated circuitry in the center of the package, with temperature control provided by redundant proportionally controlled heaters. The timing source makes possible operation at any one of eight different bit rates, ranging from approximately 125 to 16,000 bps, selected by ground command. In addition, the timing source provides the reference for the time code generator, which is a 24-stage binary converter used to relate spacecraft and ground time.

The system design provides two 16-channel digital subcommutators and three 64-channel analog subcommutators, all of which are hardware. Although SAS-3 has only three 64-channel analog subcommutators, the system is designed so that this number can be increased to eight if the

[5] "Aerospace Data Systems Standards," NASA/GSFC Report X-560-63-2, July 1971.

need should arise on other spacecraft. In addition to the hardware subcommutators, up to 16 of the digital inputs to the multiplexer or 16 of the inputs to the analog subcommutators can be subcommutated by using a software subroutine stored in the variable storage. The ADC uses the dual-slope integration technique to convert an analog input to an 8-bit binary output.

When a ground station receives the telemetry data, it is possible to detect errors introduced by the transmission link or the station's receiving equipment. This is done by using the error coding data that result from a parity-check counter in the telemetry system. The error coding allows the telemetered data to be recovered without performing the error check on the ground. A more comprehensive description of this type of error coding is available.[6]

Command Requirements

The telemetry system primarily requires relay commands for switching power and signals to its various parts. In addition, it requires two "data command" services.

The short data command service allows 24 data bits (address and instruction) to be shifted serially to the telemetry system format generator from the spacecraft command system. It is used for loading single locations in the variable format generator.

The second data command service is termed the "long load" mode, in which a number of 24-bit words are shifted serially to the format generator. This service permits loading of the entire variable storage in 96 s at a 64-bps rate.

The telemetry system modes of operation are described in more detail elsewhere.[4,7]

Redundancy

Since the primary concern with regard to satellite-borne experiments is the integrity of the data, certain parts of the telemetry system were made redundant (Fig. 4). Redundancy of the power converter, timing circuitry, multiplexer, and tape recorder is provided by having two identical sets of each item. Format generator redundancy is provided by having both fixed and variable format generators. The RF link redundancy is provided by two VHF transmitters with turnstile antennas.

Acknowledgment

The author would like to acknowledge the significant contribution of John Rosema in designing the circuit of the format generators and of W. Harold Goodnight in writing the assembler and decommutation programs.

[6] W. W. Peterson, *Error Correcting Codes*, M.I.T. Press, Cambridge, MA, 1965.

[7] "SAS-C Satellite Operator's Manual," APL/JHU Report S2-0-156, January 1975.

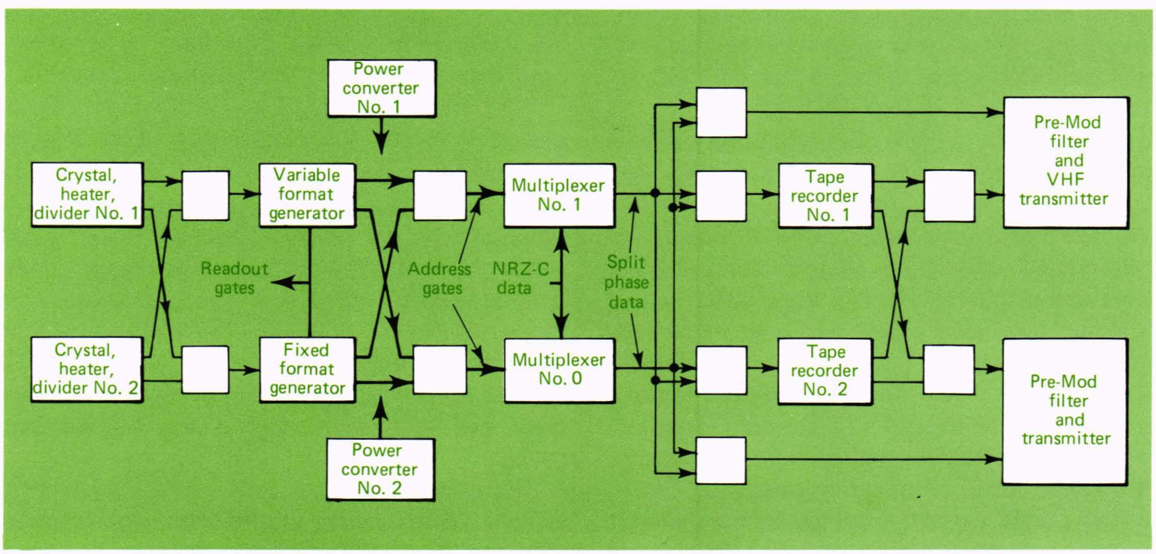

Fig. 4—Redundancy of the telemetry system. (combining circuitries are indicated by unlabeled boxes).