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ON THE DESIGN OF PFM TELEMETRY ENCODERS

by H. D. White, Jr.

Goddard Space Flight Center
Greenbelt, Maryland

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SUMMARY

Pulse Frequency Modulation (PFM) is a time-division-multiplex telemetry system, especially suitable for small satellites because of its efficient use of transmitter power as a function of bit rate. The Explorer XII (Energetic Particles) satellite utilized a practical PFM system in which the analog-to-digital conversion was done essentially on the ground.

The encoding techniques used in PFM satellite telemetry systems are described herein, with emphasis on the simplicity of synthesizing and mechanizing the encoding. Several encoders are discussed (e.g., the Explorer XII and the UK-1 encoders, and a general-purpose digital data processor). In addition, checkout and bench-calibration techniques that facilitate integration between experiments and the encoder are included.

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INTRODUCTION

Pulse Frequency Modulation (PFM) is a time-division-multiplex telemetry system, especially suitable for small satellites because of its efficient use of transmitter power as a function of bit rate. A typical PFM encoder receives both analog and digital information from the satellite experiments (Figure 1). The encoder electronically commutates the information, either one analog parameter or 3 digital bits at a time, and encodes it into a series of time-multiplexed PFM bursts and blanks. The

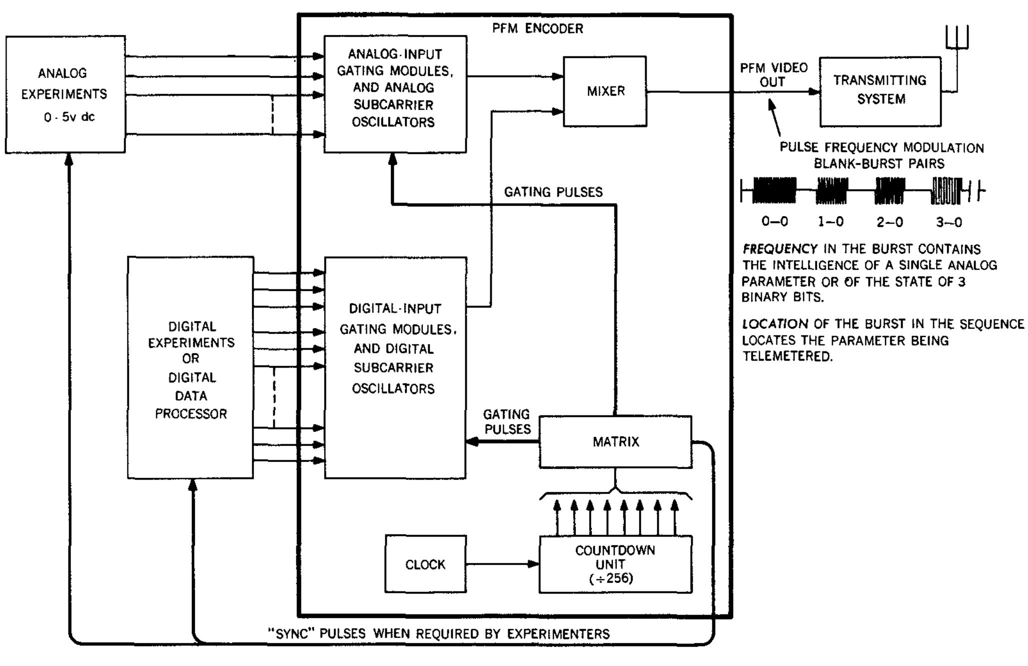

Figure 1—PFM encoder

*Presented at the 1962 National Telemetering Conference, Sheraton-Park Hotel, Washington, D. C., May 23, 1962; published in the Proceedings, Vol. 1, paper no. 3-4.

pulsed frequency bursts are derived from a set of pulsed subcarrier oscillators with a variable frequency range of 5 to 15 kc. The burst frequency contains the intelligence of a single analog parameter or of the state of 3 binary bits. The location of the burst in the telemetry sequence identifies the parameter being measured. The encoder also generates any required synchronizing (timing) pulses for the experiments.

The timing for the PFM system is obtained by counting down a clock frequency in a string of binary counters (called a countdown unit). The states of the binary counters in the countdown unit are then sampled by appropriate logical circuit elements in a matrix to produce the required commutation-gating pulses and synchronizing pulses.

From the theoretical signal-to-noise standpoint, the PFM system has certain marked advantages over some of the other commonly used satellite telemetry systems (Reference 1). In addition, this system has practical advantages in the simplicity of satellite encoding, which will be illustrated in the discussions that follow.

BASIC PFM SYSTEM AND FORMAT

General Description

A characteristic of the PFM system is that both the basic format and bit rate may be changed easily to accommodate different satellite missions.

The basic PFM telemetry system is a particular form of time-division multiplexing in which the intelligence being telemetered is contained in the frequency of a sequential series of 10-millisecond pulses *(bursts)* separated by 10-millisecond intervals *(blanks)*. The blanks precede the bursts. The pulse frequency is derived from a set of pulsed variable-frequency subcarrier oscillators, each having a frequency range of 5 to 15 kc.

The satellite telemetry system works in conjunction with a ground data-reduction system in which a bank of 120 contiguous bandpass filters, each 100 cps wide, are used to reduce the system noise bandwidth to that approximating one of the 100-cps filters. The entire bank of filters covers the frequency range of 4 to 16 kc.

Essentially, the PFM burst activates one of the 120 contiguous filters. If only one pulse frequency is present at a time, only one of the 120 filters will be excited. The filter having the greatest signal is determined by means of an auction circuit. All the other filters, containing noise only, are biased off; and the one filter containing signal plus noise is gated to the output. With reasonable signal-to-noise conditions, the filter output can be passed on to a discriminator for making more precise measurements; the magnetometer data of Explorer X (1961 κ) were sometimes read to a precision of 10 bits by this technique.

For the general use of PFM, a discriminator is not used; the signal is quantized into one of the hundred discrete 100-cps values in the 5 to 15 kc range by recording only the number of the particular filter that contains the greatest signal. Thus the basic analog accuracy of the standard PFM system is approximately 1 percent from the input of the satellite encoder to the recorded filter number on the ground. For the PFM encoders presently on board satellites, a 1-percent accuracy of analog information channels is the best that can be achieved. But, as noted, a 1/10-percent precision is possible with the use of discriminators at the filter band output.

Some interesting features of this system become apparent. If a 1-percent accuracy is assumed equivalent to almost 7 bits, then analog information is sent 7 bits at a time in a single PFM burst and, effectively, the analog-to-digital conversion is done on the ground. In regard to the satellite telemetry system, two important considerations result:

(1) The complicated analog-to-digital conversion is not required within the satellite.

(2) For a given bit rate, the transmitter power may be substantially reduced over that required for the same accuracy in an uncoded PCM system.

Analog Subcarrier Oscillator

The analog oscillator (Reference 2) is the name applied to the device that converts an input voltage of 0 to +5 volts* dc into a frequency output of 15 to 5 kc. Zero volts corresponds to approximately 15 kc, while 5 volts corresponds to approximately 5 kc. The analog oscillator is designed to operate in the temperature range of −10°C to +60°C.

Several inputs may be gated into a single oscillator. To maintain a 1-percent system accuracy, it is necessary to calibrate each analog experiment with its associated oscillator. The input impedance to the oscillator, when several inputs are commutated into it, is approximately 250 kilohms at approximately − 2.3 volts when the analog parameter is being telemetered, with a slightly active network at a high impedance when the oscillator is gated off. If the output impedance of the experiment is reasonably low (less than 1 kilohm), the input impedance of the encoder has a negligible effect on the output frequency of the oscillator. The input impedance of the analog oscillator, when only one input is applied (e.g., no commutation of inputs), is greater than 2 megohms at approximately +7 volts when the analog parameter is being telemetered, with a slightly active network at a high impedance when the oscillator is off.

The usual procedure followed in analog oscillator allocation is to give each experimenter his own oscillator. If the experimenter has many analog inputs (as in the case of the UK-1), the oscillator(s) is placed in the experimenter's package (approximately one for each eight inputs); this reduces the interface and calibration problems. When an experimenter has only a few inputs (as in Explorer XII† or the Interplanetary Monitoring Probe), the oscillator is placed in the encoder; this reduces the number of leads required. A main criterion for the oscillator is that its most likely failure be *off*, instead of *on*. Thus, when each experimenter has his own oscillator, a catastrophic event in an experiment affects only that one experiment. If an experimenter desires 1-percent analog data, the interchange of oscillators requires a recalibration.

*Or 0 to −5 volts dc in the UK-1.
†(1961 υ1) satellite.

Digital Subcarrier Oscillator

A pulsed digital oscillator that accepts 3 bits of information and encodes this as one of eight discrete frequencies in the band from 5 to 15 kc has been developed at Goddard Space Flight Center. The eight possible frequency levels correspond to the eight possible combinations of 3 bits. Thus digital information already in a digital form may be easily encoded and transmitted 3 bits at a time.

Digital-input gating modules have been developed to accept accumulator outputs 3 bits at a time, read them out as a discrete frequency, and then take the next 3 bits and read them out (18-bit and 15-bit accumulators have been read out in this manner in the UK-1 encoder). To use this feature, the two binary states must be 0 volts at less than 56 kilohms output impedance, and – 4 to – 5 volts at less than 56 kilohms output impedance from the experiment's accumulator. In the Interplanetary Monitoring Probe (IMP), the accumulation and read-out is done in the encoder in a digital data processor. The digital data are read out 3 bits at a time in a PFM burst.

Basic Format and Frame Synchronization

As previously stated, PFM is a time-division-multiplex system. The basic format consists of 256 channels arranged 16 channels in a frame, with 16 frames in a sequence. Frame synchronization is achieved by two methods, as follows:

1. The first channel of all frames (designated as 0 - all) consists of an asymmetric blank-burst interval, where a 5-millisecond blank is followed by a 15-millisecond burst. All the other channels consist of symmetric blank-burst intervals where a 10-millisecond burst follows a 10-millisecond blank. The system is synchronous in that all blank-burst intervals total 20 milliseconds.

2. The frequency in channel zero for all frames (0 - all) is also devoted to frame synchronization. The exact format is as follows:

Channel - Frame	Information Telemetered
0-0	000 digit
0-1	4.5 kc
0-2	001 digit
0-3	4.5 kc
0-4	010 digit
0-5	4.5 kc
0-6	011 digit
0-7	4.5 kc
0-8	100 digit
0-9	4.5 kc
0-10	101 digit
0-11	4.5 kc
0-12	110 digit
0-13	4.5 kc
0-14	111 digit
0-15	4.5 kc

Since each channel takes 20 milliseconds, a complete telemetry sequence of the 256 channels takes 5.12 seconds.

Information Nomenclature

An X-Y nomenclature is used to designate the location of a sample in the sequence, where X is the channel number and Y is the frame number. For example, "0-all" means channel 0 for every frame and "3-4" means channel 3 during frame 4. The 16 channels and the 16 frames are each labeled 0 through 15. This nomenclature also is used in the location of synchronizing pulses from the encoder.

Information Rate

In the basic PFM system the sampling rate is 50 cps, which amounts to 20 milliseconds for a blank-burst pair. Since an analog channel contains approximately 7 bits (1-percent accuracy through the system) and a digital channel contains 3 bits (1 of 8 possible frequencies), the information rate depends on the ratio of analog channels to digital channels. The following examples are given:

Channel Ratio			Information Rate
All analog	= 50×7	=	350 bits/sec
All digital	= 50×3	=	150 bits/sec
1/2 analog 1/2 digital	= 50×5	=	250 bits/sec

Synchronizing Pulses Supplied to the Experimenter

No standard synchronizing (timing) pulses are available in a given encoder because the possible combinations of pulses are extremely large. The pulses from the digital data processor to the experimenter constitute the only exception.

For a given satellite encoder, the experimenter's requirements are analyzed during the initial design planning stage and the experimenter requests those "sync" pulses necessary to program his experiment.

For the most part, any synchronizing pulse can be easily generated in the encoder if it is to start at the beginning of any channel (i.e., the beginning of the blank) and end at the end of any channel. These pulses are, of course, synchronized with the encoder. The experimenter must specify his requirements at a suitable stage of the design because changes are very difficult after the encoder is built. The use of welded modules, as discussed in the next section, limits changes.

Construction Utilizing Standard Modules

The construction now used in the basic PFM encoder has been the result of a gradual development. The first PFM modules, used in Explorer XII, were printed-circuit modules of binary counters and subcarrier oscillators. Many of the components, however, were directly mounted on printed-circuit boards. The UK-1 encoder, which followed, was so complex that the packing density had to be substantially increased; and therefore an almost all welded-module construction was used. The welded modules were mounted by soldering to the printed-circuit boards.

Certain advantages of welded modules other than increased packing density became apparent. One of these advantages was that each module was separately checked out with dynamic tests so that, when the modules were interconnected, every individual component had been dynamically tested before final test. This reduced the system test time considerably and increased reliability in that cards, once assembled, never have to be disassembled because of the initial installation of a faulty component. Another advantage that proved significant was that the increased packing density resulted in fewer circuit boards which, in turn, resulted in fewer interconnecting cables.

The disadvantage of welded modules is that changes and repairs are not easily made. Fortunately, the encoder contains very few critical circuits and will operate over wide changes in parameters. Standard modules are now available, and more have been developed for the Interplanetary Monitoring Probe (IMP). The welded technique construction will be carried one step further on the IMP encoder than was done on the UK-1 encoder: All interconnections between the welded modules will be welded instead of soldering the welded modules on printed-circuit boards.

PFM ENCODER FOR EXPLORER XII

Four digital oscillators and five analog oscillators were used in the Explorer XII encoder (Figure 2). One oscillator was used for each experiment, and two oscillators were used for the 16 performance parameters. Since eight of the 16 channels were digital and the other eight were analog, the bit rate was approximately 250 bits per second. Neither welded construction nor modular techniques were extensively used.

Commutation of analog input lines to a single analog oscillator was achieved. The three magnetometer inputs were gated into the magnetometer analog oscillator, and the three ion-and-electron (I&E) inputs were gated into the I&E analog oscillator. Performance parameters PP_0 through PP_{15} were split up, with PP_0 through PP_7 gated into a single analog oscillator and PP_8 through PP_{15} gated into another analog oscillator. The clock was not crystal controlled, and the countdown unit and matrix were both made exclusively of germanium transistors. Figure 2 shows that each digital experiment supplied only three input leads to the encoder. Thus the digital experimenters commutated the outputs of their accumulators, 3 bits at a time, into the encoder.

The encoder was packaged in three 5×7 inch printed-circuit cards. One additional 5×7 inch card was used to package the performance parameter signal-conditioning circuitry and an encoder power converter.

Designed to operate in a temperature environment of from 0° to +50°C (tested from −10° to +60°C), the power drain of the encoder and converter was approximately 270 milliwatts. The weight of the three encoder cards after potting, plus the encoder power converter, was approximately 3 pounds.

As Figure 2 indicates, the Explorer XII PFM encoder is relatively simple and illustrates the starting point of the basic PFM system. Figure 3 shows that channel zero was not devoted to frame synchronization.

The encoder operated well and was built on schedule. Much of the design philosophy was dictated by expediency in that little time was available for development. Thus much of the circuitry and packaging techniques were similar to those used in Vanguard III (1959 η1).

PFM ENCODERS FOR THE UK-1 SATELLITE

Figure 4 is a block diagram of the UK-1 encoder, which was required to telemeter the information on 100 input lines from the various British experiments. In addition, two encoders were required: one called the high speed (HS) encoder, and the other called the low speed (LS) encoder. The output from the HS encoder directly modulates the transmitter (real-time data). The output from the LS encoder is tape-recorded for one complete orbit at 1/48 the information rate of the HS system. On command from a ground station, the taped output is played back 48 times faster than the recorded speed. The taped playback then modulates the transmitter. Thus the output from both systems (HS and LS) will have the same bandwidth when received at a ground station.

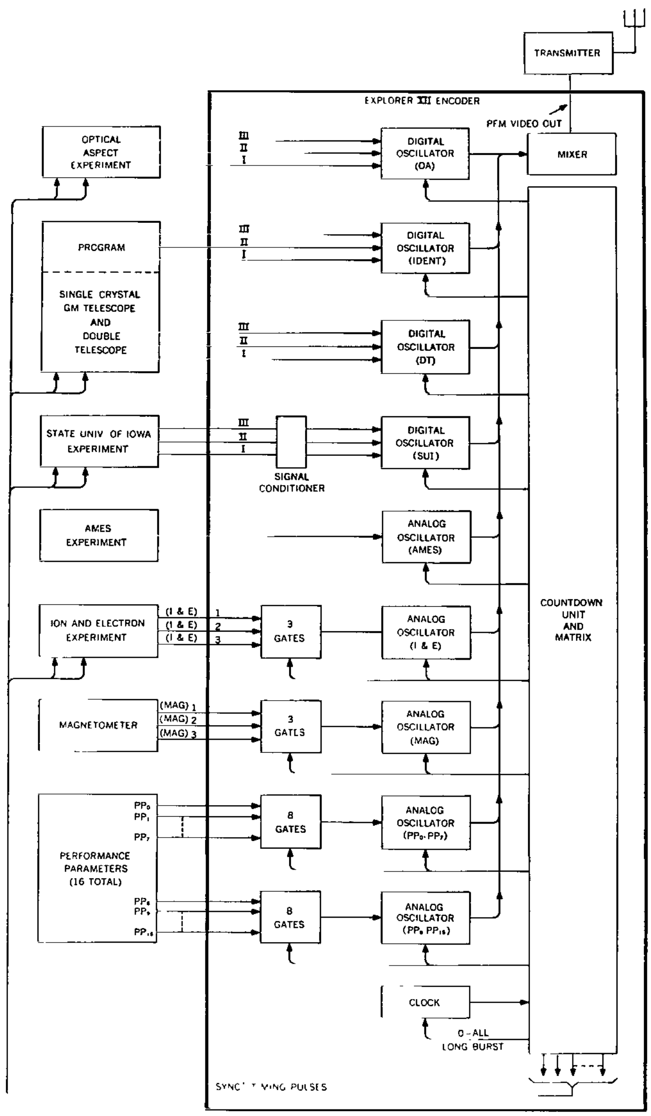

Figure 2—Explorer XII PFM encoder

Design Criteria

In order to meet the size and weight requirements of the UK-1 payload, the design approach for this encoder had to differ somewhat from the encoder used in the Explorer XII. The payload experiments are divided among three British universities: The University College of London (UCL), the Imperial College (the cosmic-ray experiment), and The University of Birmingham (the electron density experiment). The number of information lines required from each experimenter was such that it was desirable to locate the subcarrier oscillators and input-gating circuits in the experimenters' electronic stacks: two oscillator cards for UCL, one oscillator card for the electron-density experiment, and one oscillator card for the cosmic-ray experiment.

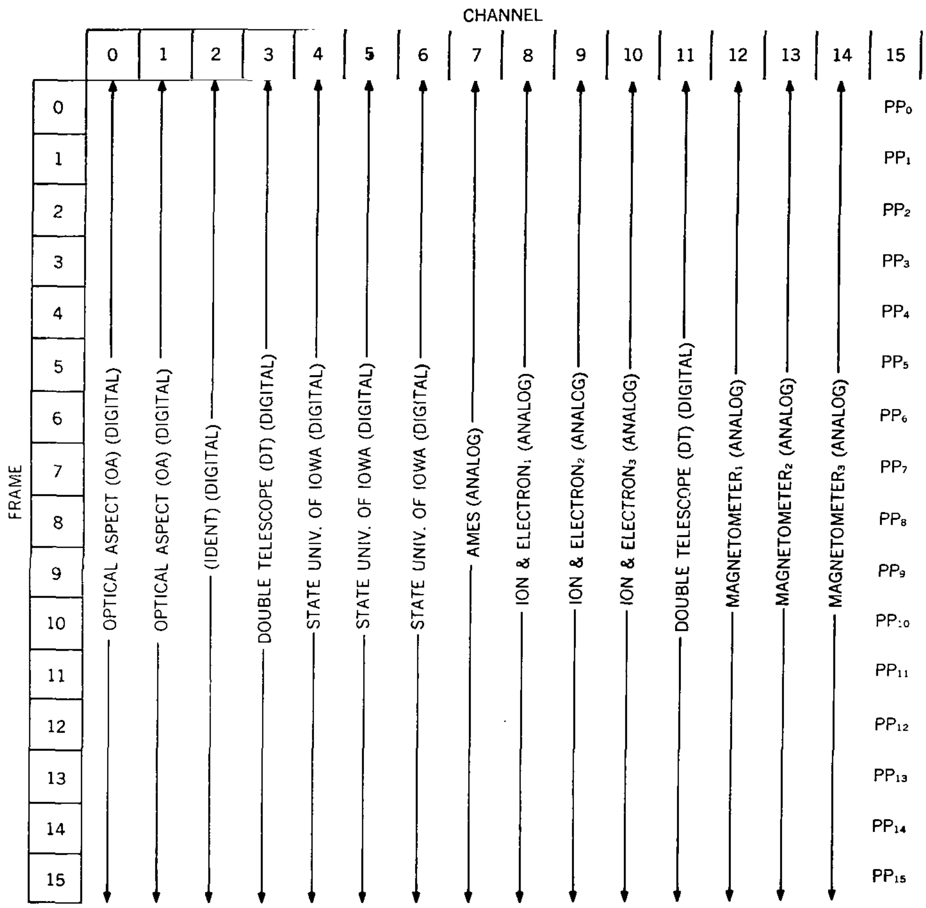

Figure 3—Explorer XII telemetry channel allocation

Figure 5 shows the placement of the subcarrier oscillator cards. This configuration has two advantages: (1) The information lines from the experiment remain short; and (2) the experiment electronic stack is a nearly self-contained unit, which facilitates system integration.

During the initial design phases of the experiments and of the encoder, the Atlantic Ocean separated the two systems; thus an integration problem could easily have resulted. Matrix simulators (simple to build, ship, and use, but of unsophisticated design) were sent to the United Kingdom with appropriate pre-prototype subcarrier-oscillator cards and test specifications. The interface between the experiments and the encoder worked very well with this technique. Much of the success must be accredited to the outstanding cooperation and keen interest shown by the UK experimenters, particularly Dr. A. P. Willmore, of the University College of London.

Subcarrier-Oscillator Cards

Figure 6 illustrates most of the circuitry used in the subcarrier-oscillator cards. The card contains two analog-oscillator modules, one digital-oscillator module, one 8-negative analog-input-gate

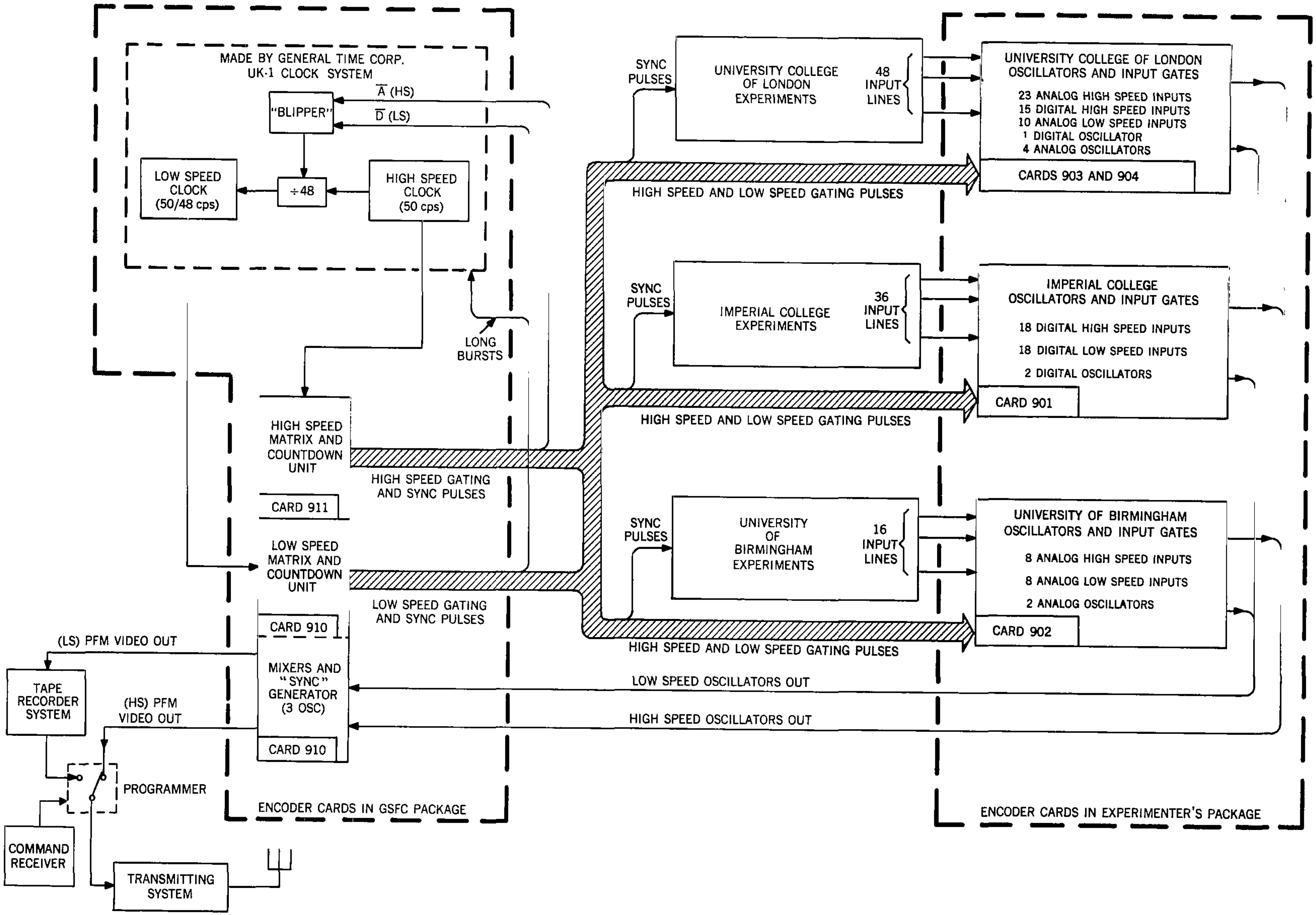

Figure 4—UK-1 PFM encoder

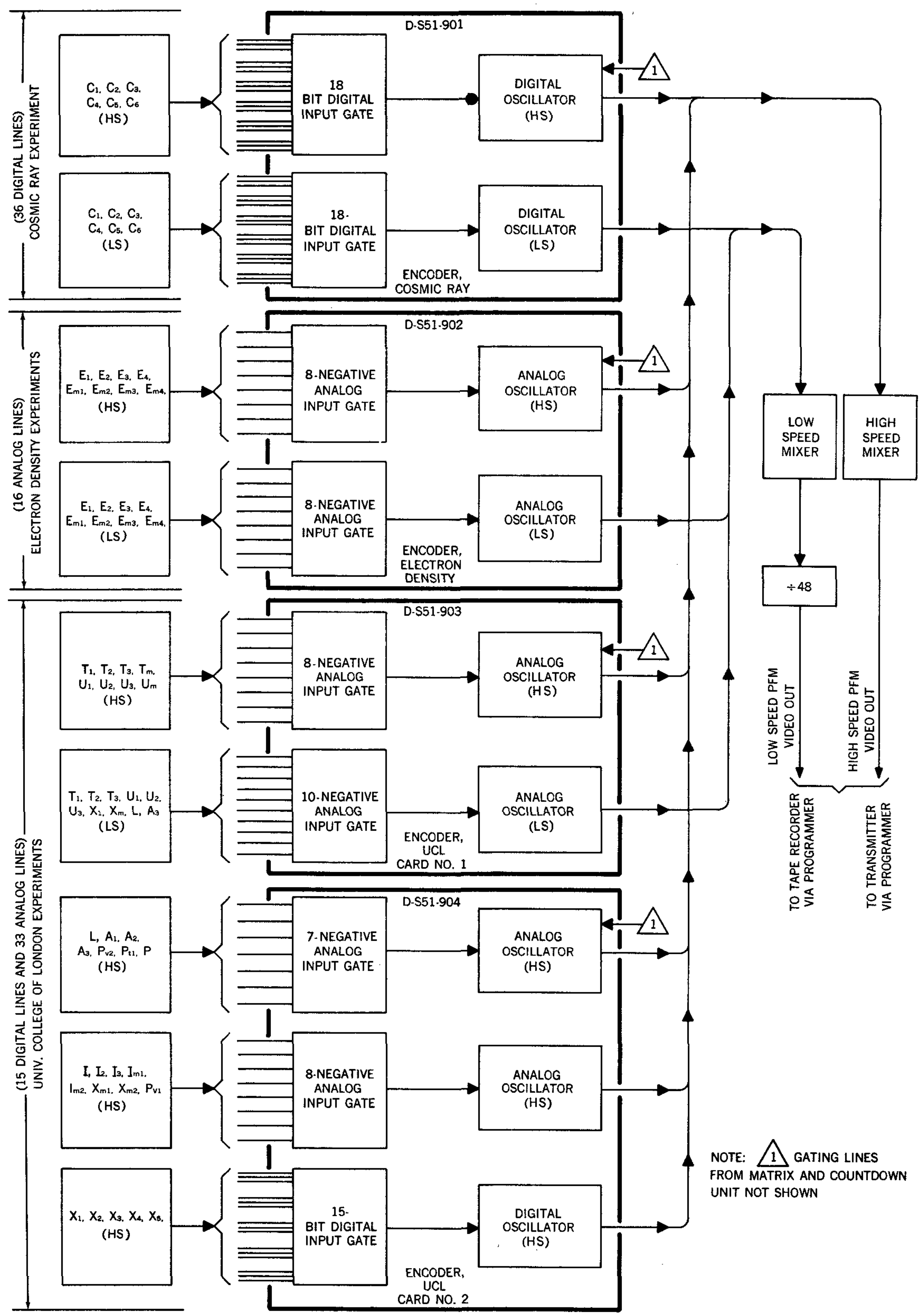

Figure 5—UK-1 encoder cards located in experimenters' stacks

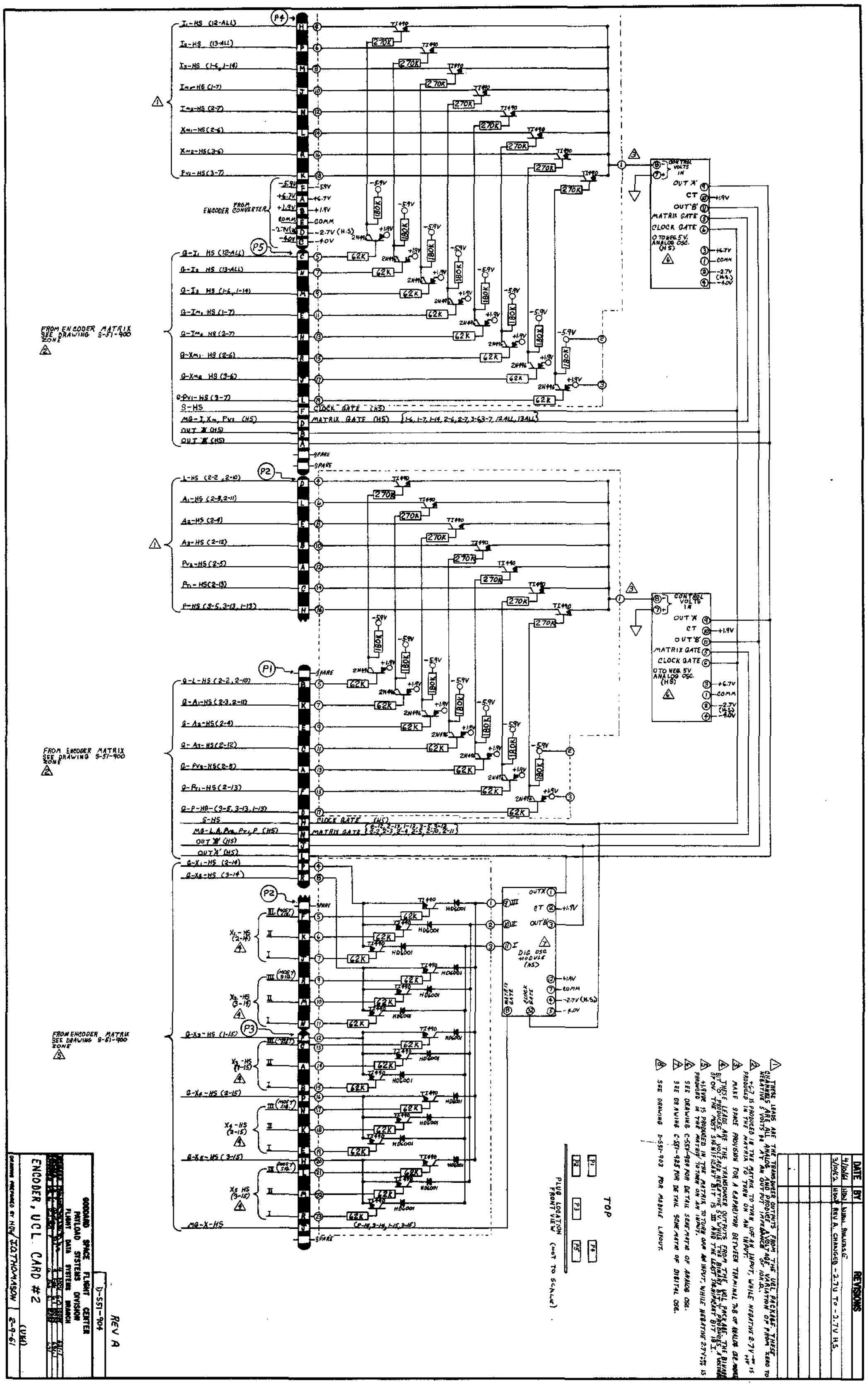

Figure 6—UK-1 encoder, UCL card 2

module, one 7-negative analog-input-gate module, and one 15-bit digital-input-gate module. Thus the card handles the information from 15 analog lines and 15 digital lines from some of the UCL experiments. All gating modules are of welded construction and are mounted on a 5-inch-diameter printed-circuit card. The card size was chosen to fit with the rest of the cards in that particular UCL electronic stack. In the analog gating modules the n-p-n transistors perform the switching functions with about a 30-millivolt drop when *on* and essentially an open circuit when *off*. The p-n-p transistors invert the standard logic feeding the cards, which accounts for the fact that the analog lines from the UK-1 experiments go from 0 to – 5 volts dc.

No measurable crosstalk has been observed from adjacent inputs when the system is in operation. There is, however, a 0.1 percent jitter in the encoding and decoding system that may mask slight crosstalk effects. The linearity and accuracy over the temperature range of 0° to +40°C is of the order of 1 percent. The long-term repeatability (1 month) is of the order of 1/2 percent, and the short-term repeatability is approximately that of the 0.1 percent jitter.

The method of gating does not provide a constant input impedance to the experiments, and it is not a passive network. It does, however, have the decided advantage of simplicity and, by making these cards an integral part of the experimenter's electronics package, some of the interface calibration problems are eliminated.

It should be noted that no common analog-to-digital converter is involved, since the quantization is done on the ground by the 120 comb filters. This entire job could, of course, have been done with four oscillators (one HS analog, one LS analog, one HS digital, and one LS digital) instead of the nine selected, by gating appropriate functions into one oscillator. This was not done for several reasons: First, it was desirable to give each experimenter his own oscillator (since only one oscillator is *on* at a time, there is not significant increase in power by having more than one oscillator); second, if it is assumed that the most likely oscillator failure occurs when *off*, not *on*, no single oscillator failure would be catastrophic. In addition, if an n-p-n input-gating transistor shorts out, crosstalk will result among that channel and the others associated with its oscillator. The oscillator configuration was chosen, then, as a compromise between size and (hopefully) reliability.

The general approach toward reliability was not to design toward the minimum number of components but to design toward the minimum number of catastrophic components. The choice of oscillators is an example of this approach in that, if an oscillator fails when *off*, only those experiments associated with that oscillator are lost. The same is true in the case of a shorted input-gating transistor. It also should be noted that an open input-gating transistor will result in the loss of only the analog channel associated with it. In the five complete UK-1 encoder systems that have been built to date, the input-gating transistors have not opened; but on one occasion an input-gating transistor shorted, probably as a result of an excessive voltage spike applied to the input channel.

Again, Figure 6 shows that 15 digital lines are gated 3 bits at a time and commutated into a single digital oscillator. This means that the accumulator for this particular experiment (UCL x-ray) is scanned 3 bits at a time by the encoder. The experimenter, therefore, was not required to shift out the contents of his accumulator 3 bits at a time as was done in the Explorer XII encoder. The next logical step will be taken in the Interplanetary Monitoring Probe (IMP) encoder, where the experiment accumulation will be done in the encoder. A digital data processor designed for this purpose will be described later.

Matrix Design

Figure 7 shows the schematic diagram of the UK-1 high speed (HS) matrix card, which functions to generate all the HS encoder gating functions and provide the necessary HS timing pulses required by the experiments. The card is entirely made up of welded modules, and all transistors are silicon. No attempt has been made to design a standard matrix with a standard format for different satellites. The main reason for tailor-making the matrix for each payload is that the number of input lines to be telemetered and the required number of synchronizing pulses vary considerably with different satellites, so that it has been thus far impractical to attempt to design an efficient all-purpose matrix card.

The X-Y nomenclature (discussed in the section "Basic PFM System") makes for rapid matrix design, however, since the Boolean equations may be written, by inspection, from the desired telemetry format. More important, perhaps, is the fact that an efficient telemetry format may be derived by use of the X-Y nomenclature and its easy conversion to a Boolean expression during the initial planning phases of the satellite. For example, say it is required to generate a function for channel 8 on frame 9 only: The X-Y nomenclature would be 8-9 and, by inspection, the Boolean function is $E\ \bar{F}\ G\ \bar{H}\ A\ \bar{B}\ \bar{C}\ D$, where $E\ \bar{F}\ G\ \bar{H}$ denotes the channel location and $A\ \bar{B}\ \bar{C}\ D$ denotes the frame location. All the equations may be written in this manner and "reduced" by Boolean algebra. The equations are reduced, not in their simplest form, but in terms of the simplest form consistent with the circuit logical elements used.

Some techniques for reducing and checking the equations, which may or may not be new, have been developed for this type of logical circuitry. This paper will not dwell on the mechanization and synthesization of the equations except to say that Boolean algebra is a powerful tool in this application. As an example, the high speed and low speed matrix equations were written and mechanized in less than 30 hours. Thus the tailormade matrix may be rapidly and accurately designed, and has great flexibility in that any format may be efficiently put together. Whatever timing pulses the experimenters need may be generated for them. This is often of considerable value in overall payload reliability in that encoder timing pulses supplied to the experiment may reduce the complexity.

Clock and Low Speed Encoder Design

Since two encoders are utilized in the UK-1 satellite, reliability can be increased if the two encoders are made independent of each other (provided the experiments do not depend on both encoders operating simultaneously). In this system, only the UCL x-ray experiment required synchronization between the encoders. The design philosophy was to make the two systems independent and very loosely "sync" them through the clock circuitry. In other words, the high speed and low speed count-down units were not hard-coupled to each other.

The 48:1 relation between the LS and HS encoders was reached by assuming that the tape recorder for the LS encoder could be acquired by an interrogating ground station for at least 2 minutes

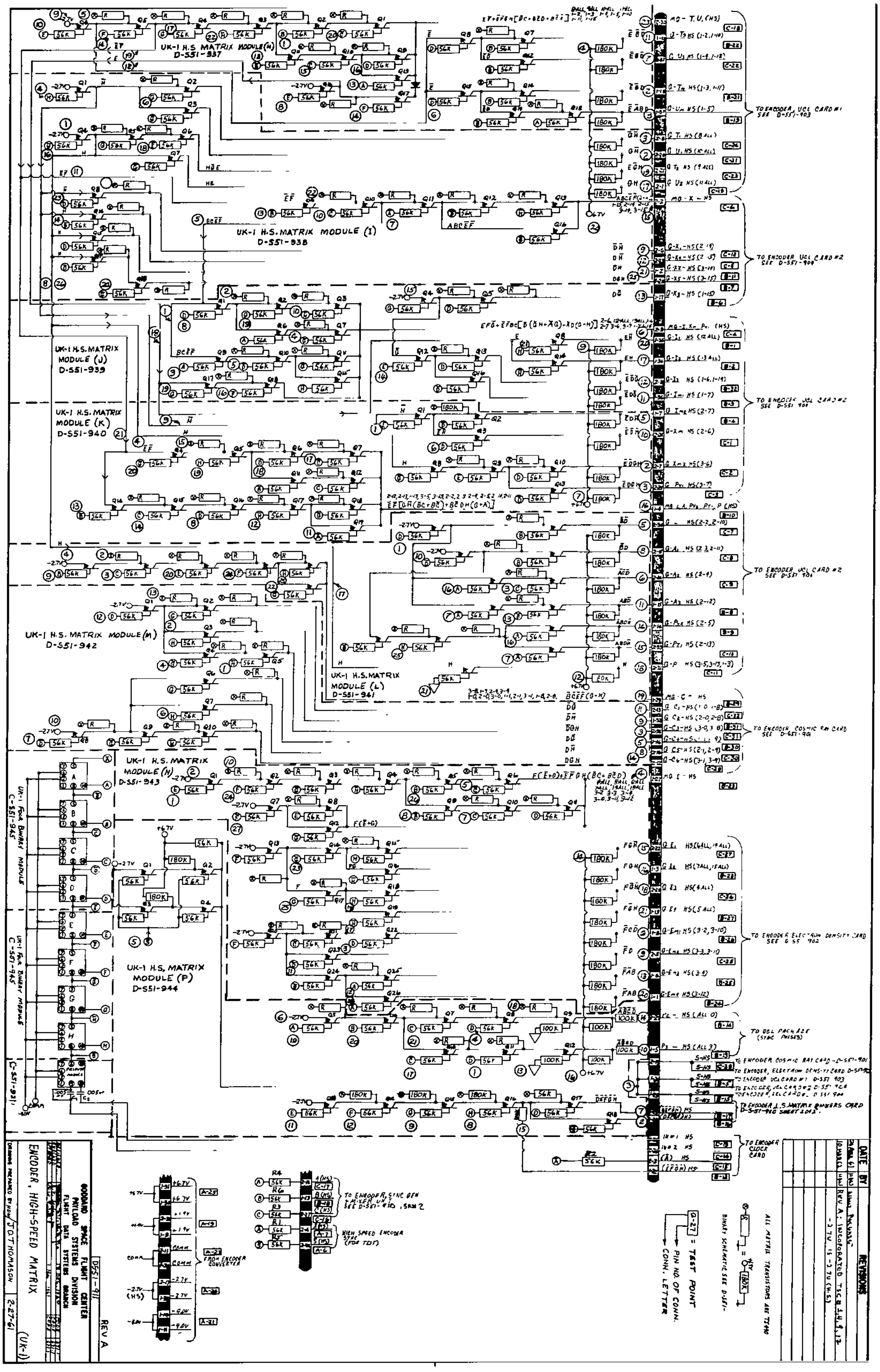

Figure 7—UK-1 encoder, HS matrix card

during playback. The orbit takes approximately 100 minutes; thus, the tape should be played back approximately 50 times faster than it was recorded. The 48:1 relation was chosen because it is easier to work with than 45:1 or 50:1. In addition, since the LS encoder is of 2-frame duration (32 channels) and the HS encoder is 16 frames (256 channels), a 48:1 reduction will cause exactly six high speed sequences to occur for one low speed sequence; thus they may be synchronized. Figures 8 and 9 depict the telemetry channel allocations for the LS and HS encoders, respectively.

The circuit elements in the LS and HS encoder are identical and therefore use the same circuit design for flip-flops, logical elements, analog oscillators, and digital oscillators.

The clock signal to the LS encoder is made 48 times slower than the HS clock signal. The LS oscillators are mixed to form a composite video in the 5 to 15 kc range and are divided by 48 to supply the proper frequency deviation to the tape recorder. Thus the LS encoder is merely slowed down by a factor of 48.

The clock was designed and manufactured to Goddard Space Flight Center (GSFC) specifications by the General Time Corporation, Stamford, Connecticut. A simplified block diagram of the clock is shown in Figure 4. The clock is controlled by a 20-kc crystal and is divided down to synchronize a free-running multivibrator at a lower frequency. The signal is further divided to give the desired 50-cps HS clock rate, which is then divided by 48 to give the 50/48 LS clock rate. An additional input from a so-called "blipper" circuit is inserted in this last divide-by-48 circuit. An output from the "blipper" circuit occurs once every low speed sequence (approximately 30 seconds) when the encoders are not in synchronization, to advance the "sync" by 20 milliseconds. It may therefore take up to 2 hours to achieve synchronization. Once encoder synchronization is obtained, it remains in sync. This is what is meant by "loosely" synchronizing the encoders; it is the desired result. All flight-unit clocks for the UK-1 have functioned well.

Fabrication

The six UK-1 encoder cards and associated bench test equipment were designed, and pre-prototype (see Figure 10) cards were built at GSFC. Detailed electrical test specifications were written, and the pre-prototype cards were checked out and calibrated at GSFC. A prototype and three sets of flight unit cards (total of 24 cards) were built, electrically checked out, integrated, and calibrated to the GSFC electrical test specifications by Electro-Mechanical Research, Inc. This company also fabricated all

FRAME \ CHANNEL	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	S	X_1	X_{m1}	E_4	E_1	E_2	E_3	X_1	C_1	C_2	C_3	C_4	X_1	A_3	C_5	C_6
1	S	X_1	X_{m1}	E_{m4}	E_{m1}	E_{m2}	E_{m3}	X_1	T_1	T_2	T_3	L	X_1	U_1	U_2	U_3

Figure 8—UK-1 low speed encoder, telemetry channel allocation

FRAME \ CHANNEL	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	S	C_1	C_2	C_3	E_3	E_4	E_1	E_2	T_1	T_2	U_1	U_2	I_1	I_2	E_1	E_2
1		C_4	C_5	C_6												
2		T_3	L	E_{m1}												
3		T_m	A_1	E_{m2}												
4		U_3	A_2	E_{m3}												
5		U_m	P_{v2}	P												
6		I_3	X_{m1}	X_{m2}												
7		I_{m1}	I_{m2}	P_{v1}												
8		C_1	C_2	C_3												
9		C_4	C_5	C_6												
10		T_3	L	E_{m1}												
11		T_m	A_1	E_{m2}												
12		U_3	A_3	E_{m4}												
13		P	P_{t1}	P												
14		I_3	X_1	X_2												
15		X_3	X_4	X_5												

Figure 9—UK-1 high speed encoder, telemetry channel allocation

the welded matrix modules, the subcarrier oscillators used in the prototype, and the three sets of flight unit cards. The power converters for all the encoders were designed and fabricated by GSFC.

The finished product for the entire UK-1 encoding system, therefore, was a joint effort of Goddard Space Flight Center, Electro-Mechanical Research, Inc., and General Time Corporation.

THE "IMP" PFM ENCODING SYSTEM

As an example of how the basic PFM encoding system may be modified to accommodate different satellite requirements in bit rate vs. range, the Interplanetary Monitoring Probe (IMP) encoding system is described briefly.

The IMP system, now in the initial design state, will consist of two parts: a digital data processor (DDP), and an encoder.

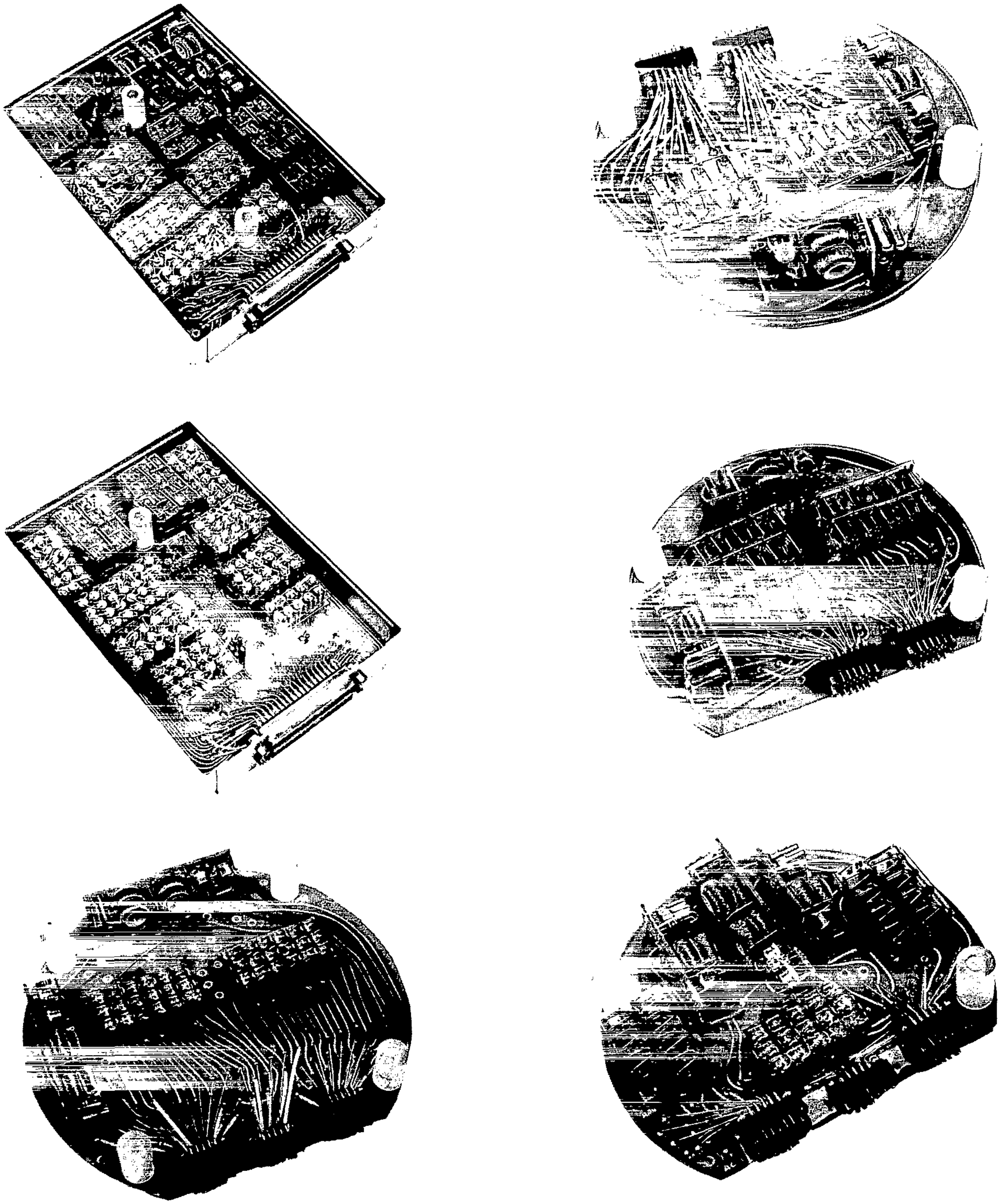

Figure 10—UK-1 encoder cards (pre-prototype). (Not to scale.)

Differences Between IMP and Basic PFM Systems

The IMP encoder is a modification of the basic PFM (Pulse Frequency Modulation) encoder system that was successfully flown on Explorer XII and on the UK-1 real-time HS encoder system. Table 1, and the list that follows, explains most of the modifications in the IMP system.

Table 1

Comparison of IMP and Basic PFM Encoder Systems

Function	Basic PFM System	IMP Encoder "Normal" Sequence
Sampling rate	50 cps	50/16 cps
Subcarrier frequency deviation	5 to 15 kc	5/16 to 15/16 kc
Sequence time	5.12 seconds	*81.92 sec
Information channel construction	10-millisec blank followed by 10-millisec burst	0.16-sec blank followed by 0.16-sec burst, or continuous 4.8-sec burst
Data handling	By experimenter	By Digital Data Processor

*In the IMP, sequences are subcommutated (see Figure 11).

The six main modifications in the IMP system are:

1. The sampling rate has been reduced by a factor of 16 (i.e., the basic PFM sampling rate is 50 cps, but the IMP sampling rate is 50/16 cps).

2. The subcarrier-oscillator frequency deviation has been reduced by 16 (the basic PFM frequency deviation is 5 to 15 kc, but that of the IMP is 5/16 to 15/16 kc).

3. The time for a complete sequence has been increased by 16 (the basic PFM sequence time is 5.12 seconds, but in the IMP it is $5.12 \times 16 = 81.92$ seconds).

4. Telemetry sequences are essentially subcommutated (i.e., three normal sequences are followed by a fourth sequence, the Rb sequence). (See Figure 11.) Another way of stating this is that the basic PFM system consists of 256 channels, while the IMP encoder consists of 1024 channels as far as the ground station is concerned. This sequence commutation is not done in the encoder but is done in the programmer, with control pulses supplied by the encoder.

5. The blanks have been eliminated in some of the analog frames. In the basic PFM system, each channel consists of a blank followed by a burst; in the IMP, channels 1 through 15 of frames 3, 7, 11, 13, 14, and 15 contain no blanks but are 4.80-second bursts. In all other frames of the normal sequences (0, 1, 2, 4, 5, 6, 8, 9, 10, and 12), channels 1 through 15 consist of 0.16-second blanks followed by 0.16-second bursts. The fourth sequence (Rb sequence) will probably consist of an

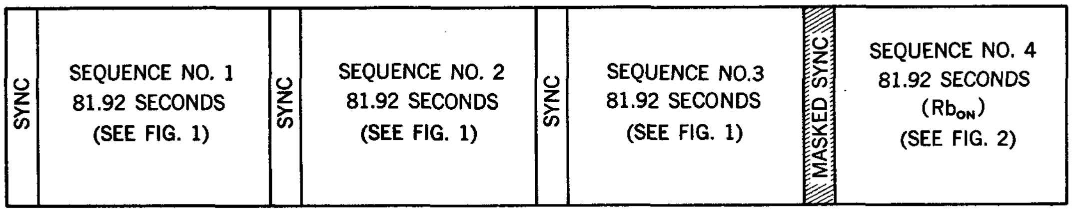

Figure 11—IMP telemetry sequence format

81.92-second burst but with an 80 percent attenuation of the Rb signal at the beginning of each frame to allow a "masked sync" in the transmitter output.

6. Much of the digital data handling (accumulation and digital subcommutation) has been placed in the encoding system in a device called the DDP (Digital Data Processor). In the basic PFM system, each experimenter did his own accumulation and sometimes did his own subcommutation while, in the IMP, much of it is done by the DDP.

IMP Format

Figures 11 through 13 are timing diagrams of the IMP format. The following definitions will be helpful:

Telemetry Sequence: The time for 256 samples in a normal PFM system, the time to commutate through all the experiments.

Normal Sequence: The telemetry sequence shown in Figure 12 (all experiments except for Rb).

Rb Sequence: The telemetry sequence shown in Figure 13. Three normal sequences are followed by one Rb sequence, as shown in Figure 11.

Sequence Time: 81.92 seconds for IMP normal sequence.

IMP Encoder Design Philosophy

As previously indicated, the basic PFM format is a 256-channel encoder (divided into 16 channels by 16 frames) with a 50-cps sampling rate and a video output in the range of 5 to 16 kc with a fixed synchronization frequency of 4.5 kc. Each sample consists of a blank followed by a burst.

Many of the modules necessary for this type of format have been developed for the UK-1. The basic design philosophy for the IMP encoder has been to use as many of these modules as possible and to develop new ones only when absolutely necessary. To slow the encoder down by 16 is no particular problem, since the clock frequency is merely changed to 50/16 cps and the oscillators are then "mixed" (only one oscillator is *on* at a time) into a composite video in the 5 to 15 kc range. This composite video is then divided by 16 to give the desired 5/16 to 15/16 kc range. A slowdown by 48 was accomplished in the UK-1 LS encoder by this technique.

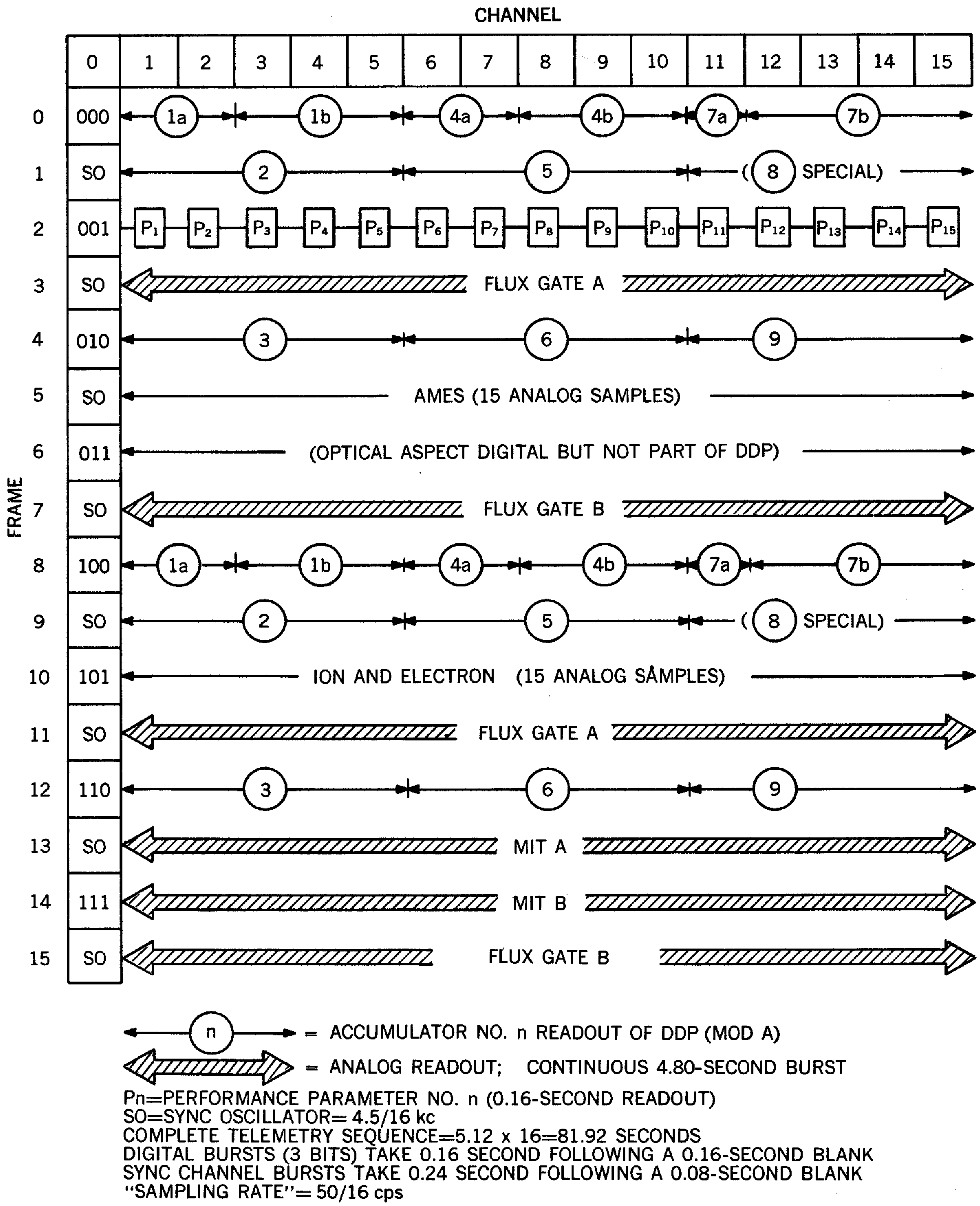

Figure 12—IMP telemetry channel allocation for sequences 1, 2, and 3

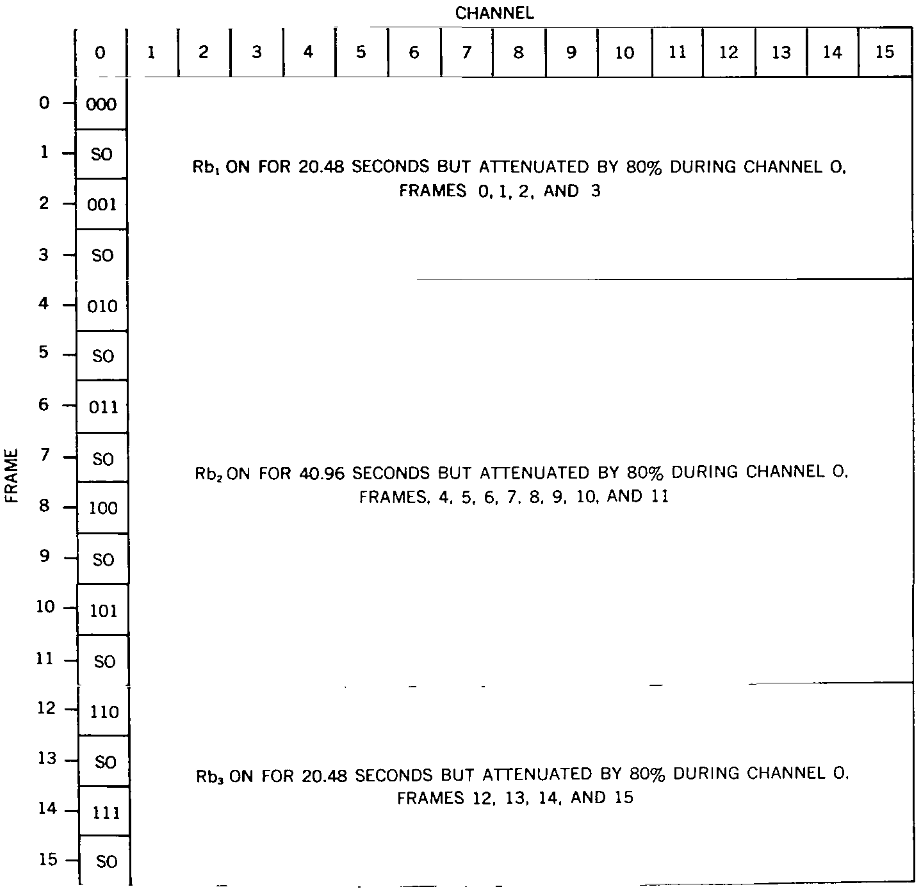

Figure 13—IMP telemetry channel allocation for sequence 4 only

The UK-1 low speed information was then recorded on a tape recorder *in the satellite*. Upon command, the tape was played back 48 times faster than it was recorded so that the ground station received information in the 5 to 15 kc band while the encoder output, as mentioned, was 5/48 to 15/48 kc. As of this writing, the UK-1 satellite has successfully completed environmental tests, and the encoding scheme works well.*

The divide-by-16 circuit at the output of the mixer is a mixed "blessing" in that it decreases reliability but does provide a chance to make the output video coherent when using simple, proven, noncoherent oscillators.

Figure 11 shows that the telemetry sequences are actually subcommutated; in addition, during the Rb sequence it is necessary to carry the sync-frequency channel (0-all) through while the Rb signal is attenuated by 80 percent. Basically, there are two ways to handle this problem. One is to generate

*Since this report was written, the spacecraft was successfully launched from Cape Canaveral on April 26, 1962 on a three-stage Delta rocket.

the entire sequence format in the encoder; this would result in a 1024-channel encoder instead of the "standard" 256-channel encoder. The resulting complexity of the encoder would be rather large because extra switching functions would have to be added to each encoder matrix function. In addition, the DDP would have to be redesigned and the existing 256-channel decoding test equipment would have to be modified.

The other approach to the problem is indicated in Figure 14, where a video-out signal is generated as if the encoder were a normal 256-channel device. In other words, the video-out signal is present even during the Rb sequence. An additional countdown by 4 is added to the 256-state countdown unit, and the additional binary counters (A1 and A2) are utilized to generate synchronizing pulses that indicate the occurrence of sequence 4 and to initiate control circuitry for the Rb experiment. The switching is then done in the IMP programmer to result in the sequence shown in Figure 11.

Digital Data Processor

The Digital Data Processor (DDP) has been designed to accept inputs either from the digital type of experiment (e.g., counting experiments) or from the type of experiment that measures the magnitude of random discrete phenomena, such as randomly occurring pulse heights, and requires the storage of this data until it is telemetered. In the latter type of experiment, the experimenter will be required to supply a pulse train where the number of pulses supplied is proportioned to the value of the parameter being measured. In the counting experiment, the experimenter must supply a line that contains a pulse whenever his probe is activated by the event he wishes to count. Some signal conditioning is done inside the DDP. Each accumulator will accept pulses up to a 500-kc rate. Some of the accumulators are reset after each read-out while others are not reset. Every accumulator is frozen during read-out.

Another function of the DDP is to supply a digital clock with a storage capacity approximately 32,000 times the telemetry sequence time. This output will be telemetered at least once per telemetry sequence.

Essentially the DDP will consist of 12 accumulators, read out twice per telemetry sequence (see Figure 12). The accumulator capacities in the DDP are: three of 6 bits, three of 9 bits, and six of 15 bits. One of the 15-bit accumulators will be used as the digital clock. The total capacity of the DDP, then, is 135 bits.

The logical design is such that the entire DDP may consist of three identical cards (see Figure 15). The three cards are called sets 1, 2, and 3, respectively. Each of the three cards contains: four accumulators (45 bits); a PFM digital oscillator; and a generalized matrix that supplies the scanning, freeze, and reset functions necessary for accumulator operation. The accumulators are packaged 3 bits at a time with their associated output gate circuits. Thus, each of the cards is a self-contained unit; and connecting different countdown functions to the plug (external to the card) will generate different scanning, freeze, and reset functions via the generalized matrix. Three sets of Boolean equations were written, simplified, and arranged so that the generalized matrix would solve the three sets of equations with the same hardware.

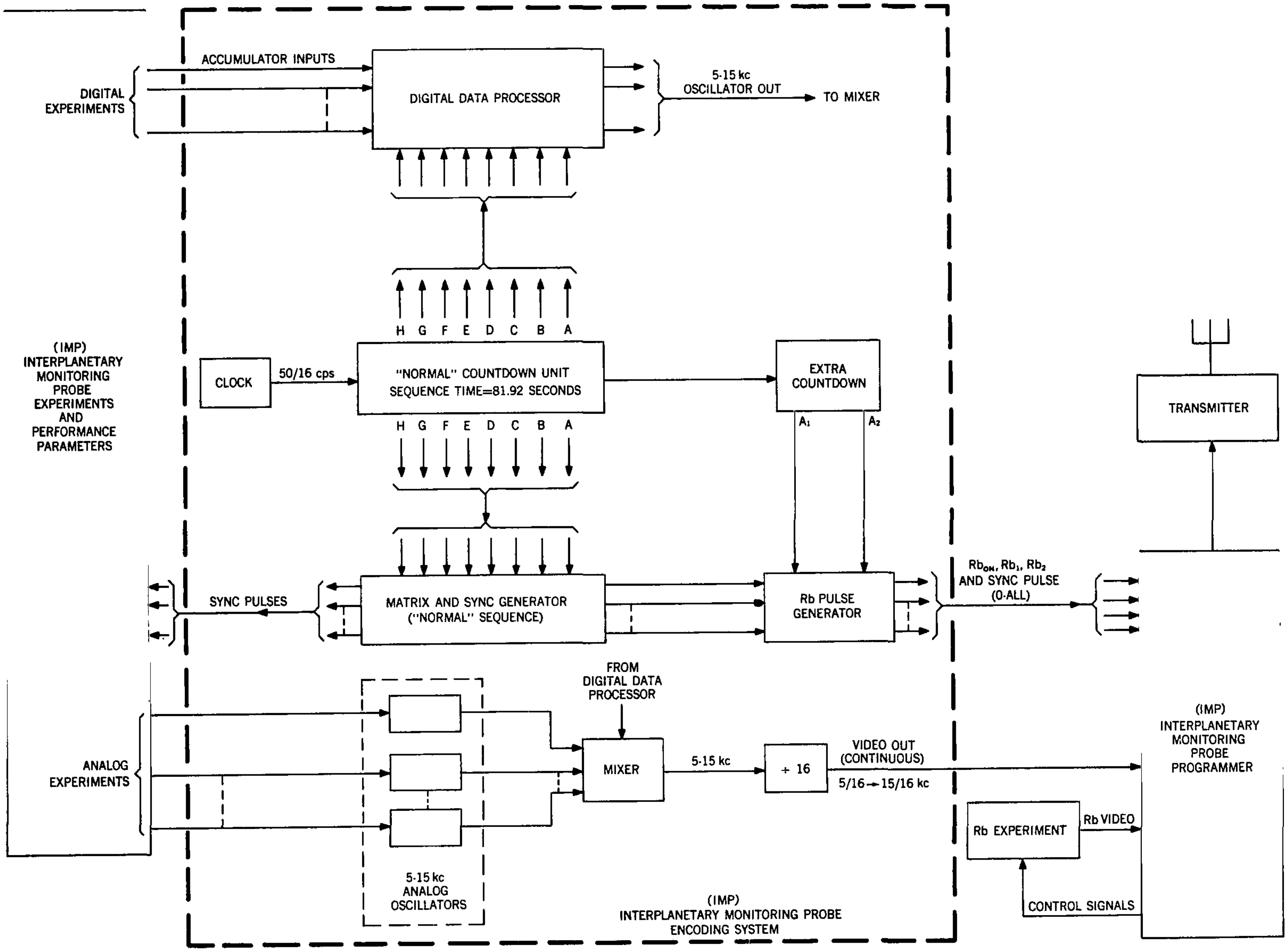

Figure 14—IMP encoding system

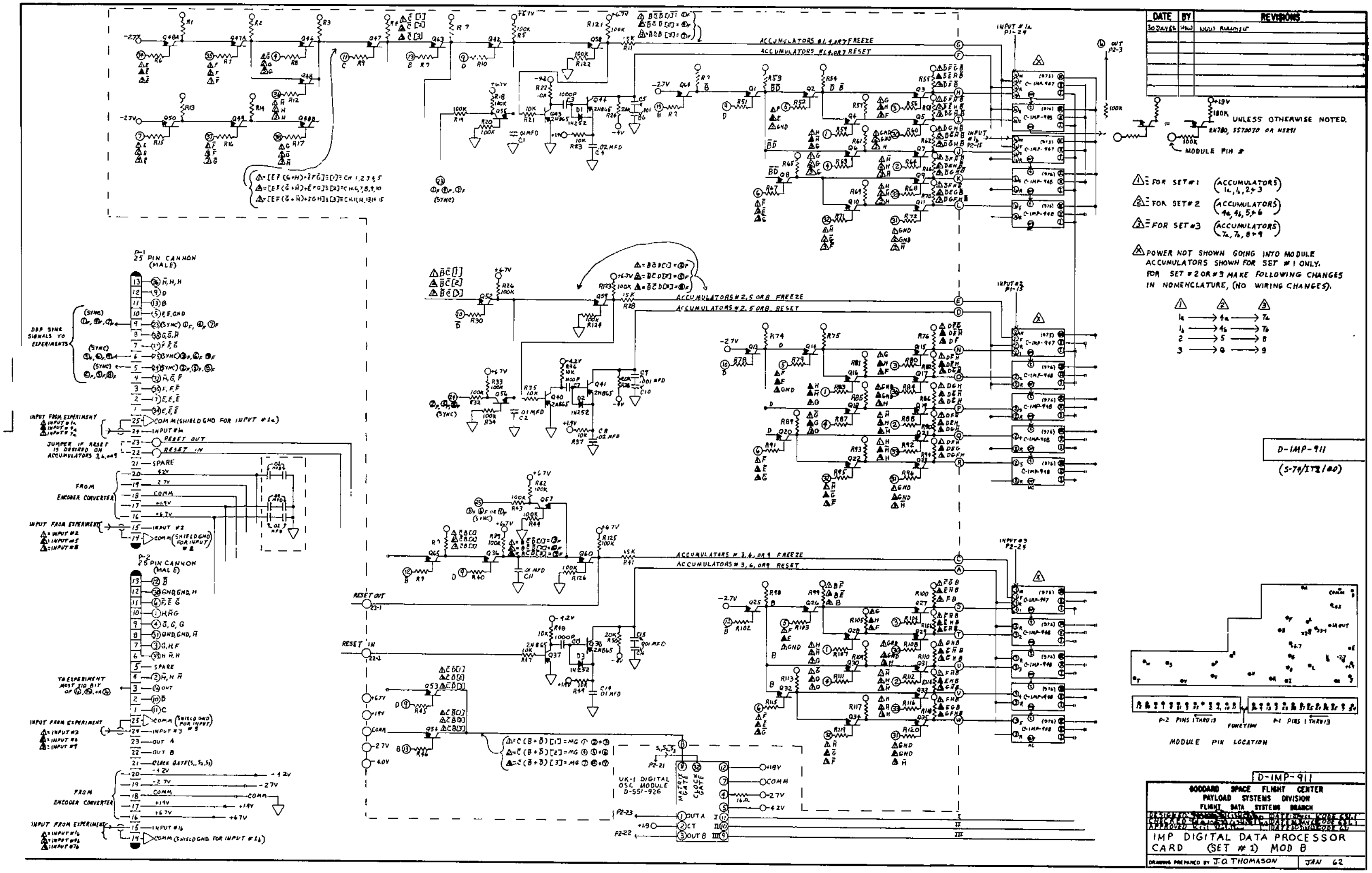

Figure 15—IMP digital data processor, mod B

CONCLUDING REMARKS

PFM telemetry lends itself to relatively simple encoding techniques. The development of these techniques has been directed toward making PFM encoders more easily used by satellite experimenters. It has been demonstrated that the basic PFM format can be readily changed to adapt PFM telemetry to varying space applications.

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