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TELEMETRY SYSTEM FOR SATURN S-I STAGE DEVELOPMENT

By

James E. Rorex



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GEORGE C. MARSHALL SPACE FLIGHT CENTER

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ABSTRACT

The telemetry system used on the Saturn S-I stage for the transmission of vehicle test data is described. Multiplex and modulation techniques such as PAM/FM/FM, SS/FM and PCM are used in the system. The diverse data requirements for developing the eight-engine liquid-fueled stage necessitated the use of a combination of several modulation techniques to efficiently handle the data. A cursory comparison is made of the merits of each technique. Physical and electrical requirements and characteristics of the system are outlined.

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ASTRIONICS DIVISION

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SUMMARY

The telemetry system used on the Saturn S-I stage for the transmission of vehicle test data is described. Multiplex and modulation techniques such as PAM/FM/FM, SS/FM and PCM are used in the system. The diverse data requirements for developing the eight-engine liquid-fueled stage necessitated the use of a combination of several modulation techniques to efficiently handle the data. A cursory comparison is made of the merits of each technique. Physical and electrical requirements and characteristics of the system are outlined.

INTRODUCTION

Much of the telemetry system developed for the S-I stage evolved from the Redstone and Jupiter missiles which used PAM/FM/FM systems that were updated and improved in the past decade as the state of telemetry art rapidly advanced. These telemetry sets had developed into reliable, flexible and relatively accurate systems that were considered very good for handling the data requirements of these missiles.

The Saturn S-I stage, with its cluster of eight liquid-fueled engines, compounded the data transmission problems. The magnitude of the Saturn as compared to the Jupiter increased the requirements for telemetry channels by a comparable magnitude; for example, the average measuring program for a Jupiter missile contained about 150 measurements, 9 of which were wideband (vibration 30 to 3000 cps). The Saturn S-I measuring program contains about 550 measurements, about 50 of which are wideband data.

An analysis of the requirements indicated that the traditional FM/FM system used on previous missiles developed at Redstone Arsenal would not be adequate to handle the volume of wideband data required for the development of the Saturn space vehicle. Since a preliminary study

indicated that several transmission links would be required to handle this data within IRIG bandwidth limitations, it was decided to take advantage of a combination of modulation techniques that best fitted the particular data requirements. Previous designs of the FM/FM systems had set standards of reliability, flexibility and accuracy that could not be compromised on most of the data, but the measuring requirements indicated that, in general, the wideband data did not require the amplitude accuracy obtainable with the FM/FM system and some of the very low frequency data required higher accuracies. The FM/FM system appeared to be the best method for transmitting data below 1000 cps, which did not require accuracies better than 1 percent.

After an extensive study of practical modulation techniques and an investigation of state of the art hardware developments, it was decided to:

1. Redesign the FM/FM system using solid-state components, where practical.
2. Develop a single-sideband AM/FM system, designated SS/FM, for more efficient transmission of vibration data.
3. Develop a PCM (pulse code modulation) system to be used for data with high accuracy requirements as well as digital automatic checkout systems.
4. Develop a solid-state, high-capacity, time-division multiplexer, capable of being used with both PAM and PCM systems, as well as operating synchronously with other multiplexers for serializing checkout data.
5. Develop demultiplexing equipment to operate with the on-vehicle counterpart for "real time" display and data reduction.

FM/FM SYSTEM

Predecessors to the Saturn, e. g. , the Redstone, Jupiter and Juno missiles, used PAM/FM/FM telemetry systems for transmitting data from developmental test flights. These systems went through several years of design evolution and have proven to be reliable data systems. The set used on the first Redstone weighed 130 pounds, whereas a set used on the Jupiter weighed 37 pounds. The volume was reduced proportionally.

These sets all used vacuum tubes because, at the time they were designed, transistorized components were hand selected and not readily

reproducible in the quantities desired. The savings in weight, space and heat dissipation did not offset the increased cost; however, since the Saturn is a multistage space vehicle, the design criteria for telemetry is somewhat different from that of weapon systems. The operating time, cooling and pressurization philosophies, and other environmental factors that influence physical characteristics were changed. It was necessary to redesign the FM/FM system to further reduce the size, weight and power consumption. Transistorized components were now reproduced in such quantities that a design replacing all vacuum tube components with transistorized components would save enough in total weight and, consequently, increase payload weight enough to offset the additional unit cost. The new design is electrically similar to previously designed FM/FM sets, but is smaller and more efficient. FIGURE 1 is a view of the set which was designated model XO-5. This nomenclature was used because previously designed Army models still in use carried the designation XO-1 through XO-4. The system utilized 17 of the 18 IRIG subcarrier bands.

The 400-cycle band is not used because this frequency coincides with the frequency of the power source for the guidance platform. The 30 kc subcarrier is modulated by a 30 x 10 PAM multiplexer (commutator). If needed, additional multiplexers can be added external to the package. To increase system accuracy and for convenience in data reduction, pre-flight and inflight calibration is provided. This calibration consists of five precision voltage steps injected into the input of the system at programmed intervals. Channel inputs are all 100 k ohms, 0-5 volts full scale, permitting convenient changes in the measuring program with no redesign in the system.

Packaging is designed for easy accessibility and service. Modular construction allows rapid exchange of components. The layout provides easy on-board preflight adjustments. Serviceability and ready access to adjustments enhance both reliability and accuracy.

The XO-5 weighs 13 pounds, is 320 cubic inches in volume, and consumes 24 watts of power. The system has a data bandwidth of 4 kc, ranging from two cps for the commutated channels to 1050 cps on the 70 kc SCO. Using an SCO modulation index of five, the accuracy of the continuous channels is 1 percent, while the commutated channel accuracy is 3 percent. The data bandwidth can be increased, at a cost in accuracy, by reducing the modulation index. The system is versatile in that it has channels with a variety of data bandwidths, lending itself readily to the average measuring

program. Unlike the time division multiplex and the data sample systems such as PAM, PCM and PDM, this system has the advantage of not requiring the use of low-pass filters between the measuring transducer and the SCO. There is no "fold over" effect, as with time division systems; therefore, no loss of data or ambiguity exists. If the data frequency is above that anticipated, some reduction in amplitude and phase accuracy will result. This distortion is a function of the modulation index and, to some degree, can be compensated for in the process of data reduction. The system does not have the bandwidth efficiency of SS/FM nor the accuracy of PCM, but it is applied very favorable to the transmission of a portion of the Saturn data.

The model XO-6 telemetry set is a PAM/FM/FM system utilizing IRIG channels 2 through 14 plus one special wideband SCO, 70 kc \pm 30 percent (FIGURE 2). The wideband SCO is modulated by the output from a special 3600 pps PAM multiplexer that will be described later. In other respects this set is similar to the XO-5.

Occasionally, one or more of the high frequency SCO's may be modulated by a bank of low frequency SCO's, leading to FM/FM/FM. Although this technique is very inefficient and generally not recommended, sometimes it is an expeditious means to increase the number of low-response channels at the cost of total data response.

TIME DIVISION MULTIPLEXER

Most of the data channel requirements for Saturn are for data of low-frequency response; the majority of these measurements are the type that has a maximum dynamic range which is low and predictable. Certain temperature measurements typically fall in this category. Such measurements are readily adaptable to time division multiplexing without the need for presampling filters. FIGURE 3 shows a multiplexer that was developed for use with both PAM and PCM systems. The unit is a 300 x 12 transistorized multiplexer with 216 data channels and 84 sync channels. The number of sync channels was chosen so existing decommutation equipment could be used for demodulation and at the same time achieve a "quick look" feature for comparing the performance of the eight engines. The system, although in one package, is essentially a 30 x 120 master multiplexer with 27 submultiplexers, each 10 x 12. Two channels of each submultiplexer are used for subframe sync and for zero and full scale calibration; thus leaving eight data channels for each submultiplexer. This fits the eight engine vehicle, since each of the submultiplexers will

sequentially sample identical measurements for each of the eight engines. FIGURE 4 is a block diagram of a PAM/FM/FM system with the 216 channel multiplexer which is a high level (0-5 volts) system.

The multiplexer is presently being redesigned. The new design will be similar in format but will have 270 data channels by eliminating the subframe sync pulses. Subframe sync will be accomplished by changing the level of the zero servo pulse once each ten frames. Full scale servo is referenced to the master frame sync pulse. If higher sampling rates are required, 120 samples-per-second rate may be acquired by eliminating the submultiplexer. Programing the gating logic can give other sample speeds. The master multiplexer and the submultiplexers are housed in remote measuring areas. This will reduce the amount of wiring required and, as a result, reduce weight and noise pickup. The inputs may be either high level, low level or mixed. One or more of the remote submultiplexers may have low level gates and feed a common amplifier. Several of the main multiplexers can be synchronized, allowing all data to be serialized for preflight measurement calibration and automatic checkout. The multiplexer is used with both PAM and PCM systems.

SS/FM

The vast increase in requirements for vibration data from the Saturn made the consideration of more efficient modulation techniques necessary. On-board spectrum analysis of vibration data had been experimented with to some degree of success on the Jupiter missile. This technique would only be considered as a last resort on Saturn, since it is a statistical tool that reveals only certain predetermined statistical data. Since the burning time is less than three minutes and the number of tests are very limited because of cost and time considerations, it is deemed essential to get the complete data spectrum if possible. Another view is that the purpose of a development test flight is to determine the unpredictable; therefore, all data that can be intelligently analyzed within practical limits should be recovered.

A single sideband AM/FM telemetry system has been developed that can, within the standard telemetry carrier bandwidth specifications, transmit 15 channels of full spectrum (30 to 3000 cps) vibration data. The system, similar to that used for telephone voice transmission, was made practical for vehicle-borne applications by the development of the small mechanical bandpass filter.

FIGURE 5 shows a block diagram of the SS/FM system. The data input of each channel is fed to a balanced modulator and is heterodyned with a 455 kc carrier. Neither of the inputs appears at the output of the modulator, only the sum and difference. The output of the modulator is fed to a mechanical bandpass filter which passes only the upper sideband (455-458 kc). This frequency was chosen to utilize standard tooling in the manufacture of the filters.

The second modulator translates the data to an assigned baseband frequency. The baseband position is determined by the tone supplied from the frequency synthesizer. The channel units are identical, consequently enhancing serviceability. The output of the channel units is mixed, amplified and fed to an FM transmitter. State of the art in transmitter linearity is provided to minimize crosstalk.

The frequency synthesizer generates 15 carriers for the second modulator and a synchronizing tone for the ground equipment. To accommodate a 3 kc information bandwidth and to allow sufficient guardband, a channel spacing of 4.74 kc was chosen. This spacing was convenient to generate in the synthesizer and it allows an adequate guardband of 1.74 kc. To facilitate slaving ground demodulators and to simplify the on-vehicle equipment, all reference signals are derived from a crystal-controlled 910 kc oscillator. A 75.83 kc synchronizing tone for the ground equipment was selected since this frequency falls above the highest baseband frequency and is available in the divider chain from the master oscillator. A view of the vehicle-borne equipment can be seen in FIGURE 6.

FIGURE 7 is a view of the demodulation equipment. This equipment essentially accomplishes the reverse frequency transpositions from those in the vehicle. The 75.83 kc tone is used for AGC compensation as well as a frequency reference to the synthesizer. A special service channel has been added to allow other modulation techniques to be applied directly to the carrier. An example of this would be a low bit rate PCM system combined with a few SS/FM channels. Standard telemetry receiving and recording equipment is used to record the data. The demodulator is required only in data reduction stations.

Although this system is very efficient as compared with other telemetry systems with respect to bandwidth utilization, it has poor phase response and amplitude accuracy. Using preflight calibration, i. e., a constant amplitude sweep generator (30 to 3000 cps) fed to each channel,

the system is good for amplitude accuracies of 5 percent. This limits the present use of the system to such data as vibration or voice. Developments now in progress will improve the system but substantial improvement will require advances in the state of the art as well as redesign. The system can eventually be used for data other than vibration but the inaccuracies in phase and amplitude will limit its use for some time.

The on-vehicle portion of the system weighs about 18 pounds, is 750 cubic inches in volume and consumes 23 watts of power. The total data bandwidth is 45 kc and the overall accuracy is 5 percent.

PCM SYSTEM

The vehicle-borne PCM system will consist of one or more of the previously described multiplexers, an analog-to-digital converter, a programmer, and an FM transmitter. The A to D converter is designed for a high degree of flexibility. A maximum accuracy of 0.1 percent may be obtained by a ten-bit word. If this accuracy is not required, the word length can be shortened as desired by the proper programming.

The format is non-return-to-zero with frame sync provided by three coded words at the beginning of each frame. The frame code may be programmed as desired to insure maximum sync probability. Bit sync is provided by phase-lock techniques. Bit rate depends upon the number of words programmed into the system with a maximum of 200 k bits/sec. Data originating in digital form can be programmed into the format. The size of the converter and programmer is approximately the size of one multiplexer. The total size depends upon the number of multiplexers used.

The main advantage of the PCM system is the high accuracy that can be obtained. Since it is a time division multiplex system, it has the same "fold over" or "aliasing" problem previously mentioned and requires presampling filters if used efficiently. If data filters are used, one questions the overall accuracy because of the characteristics of the filters; however, it is definitely advantageous for certain data, especially that originating in digital form such as in a digital guidance computer. Certain other data adapts readily to digital techniques and, as a result, one digital link will be employed on the Saturn S-I stage.

PRELAUNCH CALIBRATION AND CHECKOUT CONSIDERATIONS

For the eventual firing rate of vehicles, necessary to achieve rendezvous for lunar exploration, it was evident that a means of automatic calibration and checkout would be required. An analysis of the problem revealed that a large portion of checkout data could be handled by the equipment existing on the vehicle.

A block diagram of a typical system is shown in FIGURE 8. In the calibration and checkout mode, most of the measurements are in a quasi-static condition; therefore, a high dynamic response is not necessary for calibration. Some 85 percent of the measurements are time division multiplexed in the existing telemetry system. With little additional cost and negligible weight and space, the other 15 percent can be time division multiplexed in the preflight mode. All data can be serialized and digitized by operating the multiplexers synchronously and alternately switching the output to the A to D converter. The PCM wave train is fed to the computer in the checkout stations.

FIGURE 9 shows a block diagram of the data acquisition system. In the computer room, a PCM ground station will separate and parallel the data into buffer memory storage. The data will be updated four times per second, and upon command the computer can have access to all data within 1/4 second. The response is more than adequate for this type of checkout.

The complete telemetry system is designed for long operating times and may be used as a utility link. The few measurements that require higher dynamic response during prelaunch procedures can be fed through the normal telemetry system, digitized and fed to the computer. A similar procedure will be used by the computer when calibrating the telemetry system by comparing the analog output to the digital output.

DATA SYSTEM

Saturn test number 5 (SA-5) is an example of the typical system. FIGURES 10 and 11 are block diagrams of the S-I stage and instrument unit, respectively. The instrument unit is the compartment that carries the guidance and control equipment for the total multistage vehicle. This unit contains one SS/FM link, one PCM link and two FM/FM links. The S-I stage contains two SS/FM links and four PAM/FM/FM links.

The 27 x 120 multiplexers are required to facilitate a large number of strain measurements on the fins. A frequency response of 25 cps is adequate for this data but higher frequencies may be encountered. As a result, presample filters are necessary. The vibration multiplexer is an electronic switch used to switch measuring points alternately in three second intervals; this technique allows twice the number of observations for half the time. There is no gain in data bandwidth but more areas are observed in this manner; consequently, more data is obtained.

The ten telemetry links required on this particular test weigh about 300 pounds, have a volume of about 6 cubic feet and consume about 1,800 watts. The total data bandwidth of the ten links is approximately 160,000 cps. Most of the power is consumed by 35 watt RF power amplifiers for each link. Since the flight duration is short and the data is of extreme importance, a considerable RF power safety margin has been allowed. If a single telemetry technique were used, such as FM/FM or PCM/FM, about four times as much vehicle-borne equipment would be required.

CONCLUSIONS

The quantity of data required in the development of a space vehicle as massive and complex as the S-I stage of the Saturn vehicle dictated that a data systems approach be taken to obtain the merits of various modulation techniques. To conclude that one modulation technique is best for all data is like a doctor prescribing a pill to cure all diseases. Development time and costs can be reduced by retrieving as much data from a development flight as can be intelligently digested. A systems approach to telemetry has been taken to facilitate a more efficient data system.

As the upper stage development progresses, a telemetry system design philosophy will be applied to the total vehicle. Each stage will have problems peculiar to the location in the vehicle system. For example, weight, power and space will be much more critical for the stage going into orbit for rendezvous operation than for the S-I stage. This is one of several factors that influence the determination of the modulation techniques used on a particular stage.

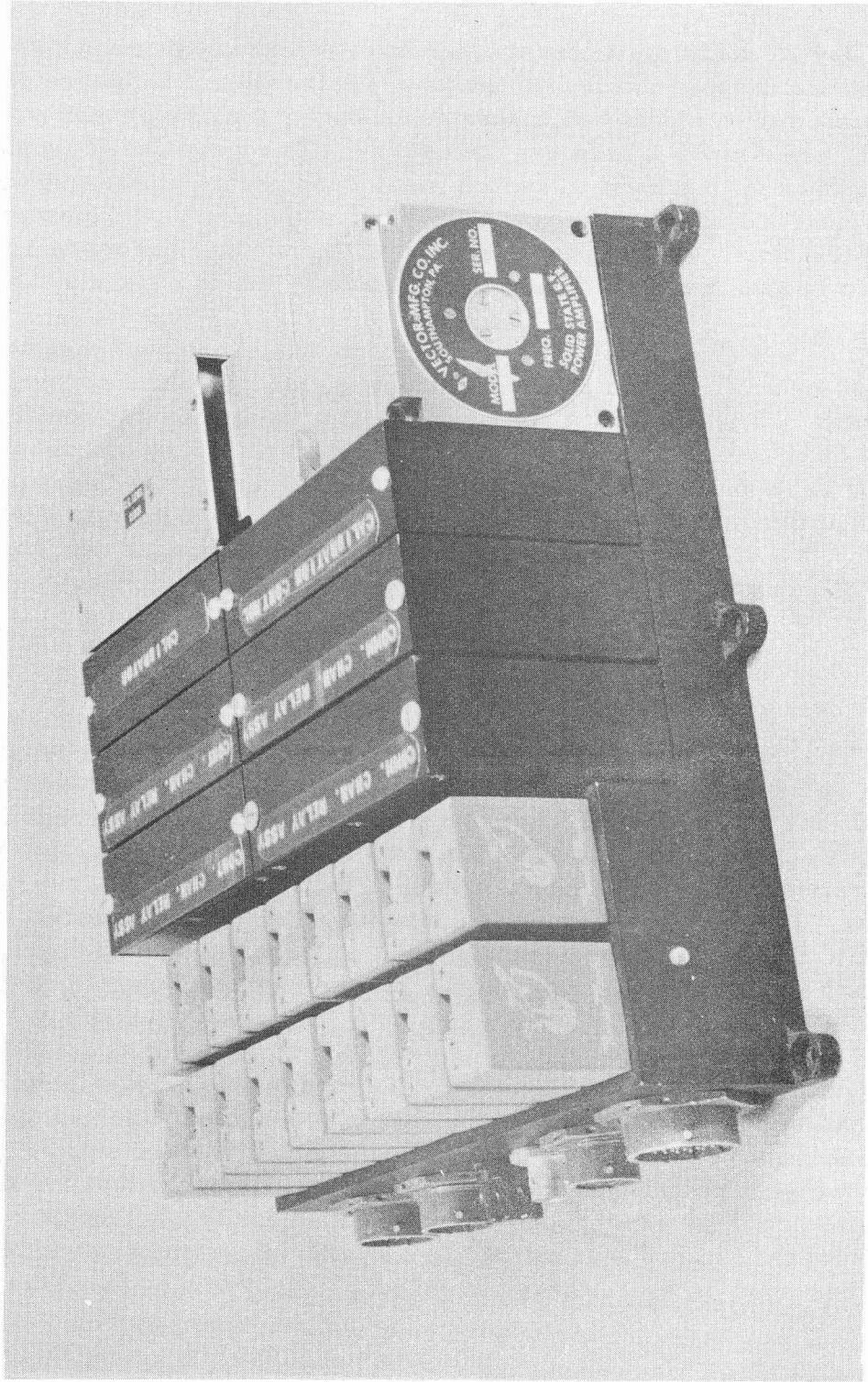


FIGURE 1. PAM/FM/FM TELEMETRY SET, MODEL XO-5

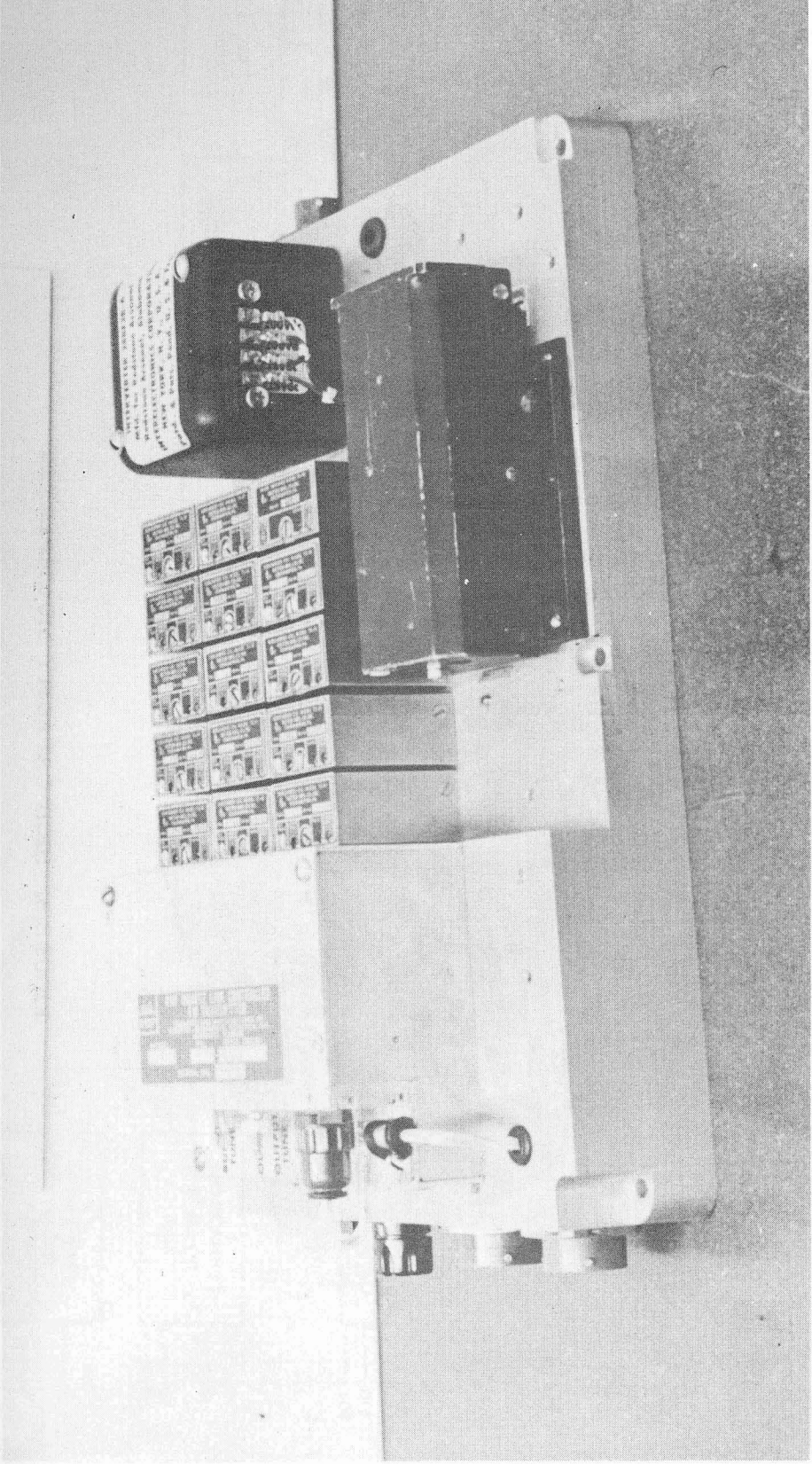


FIGURE 2. PAM/FM/FM TELEMETRY SET, MODEL XO-6

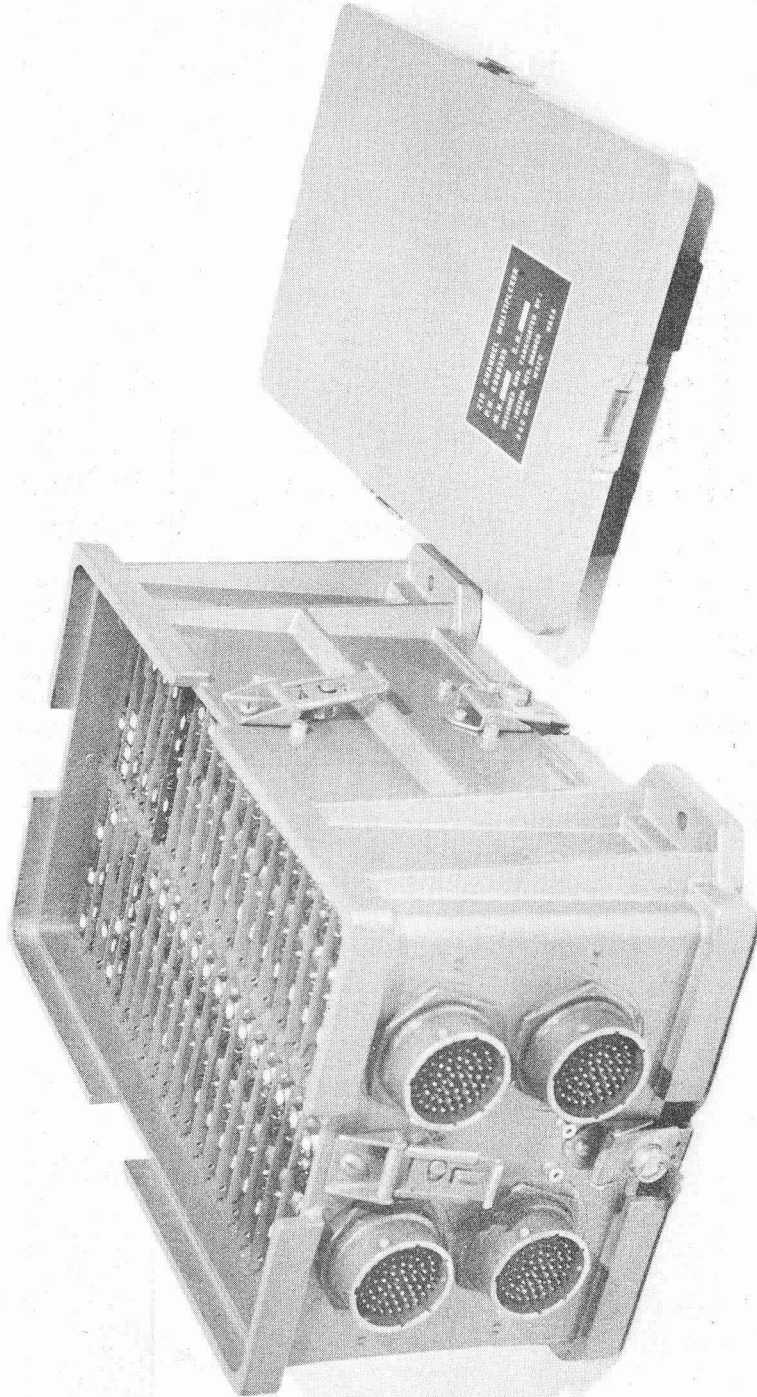


FIGURE 3. HIGH CAPACITY MULTIPLEXER

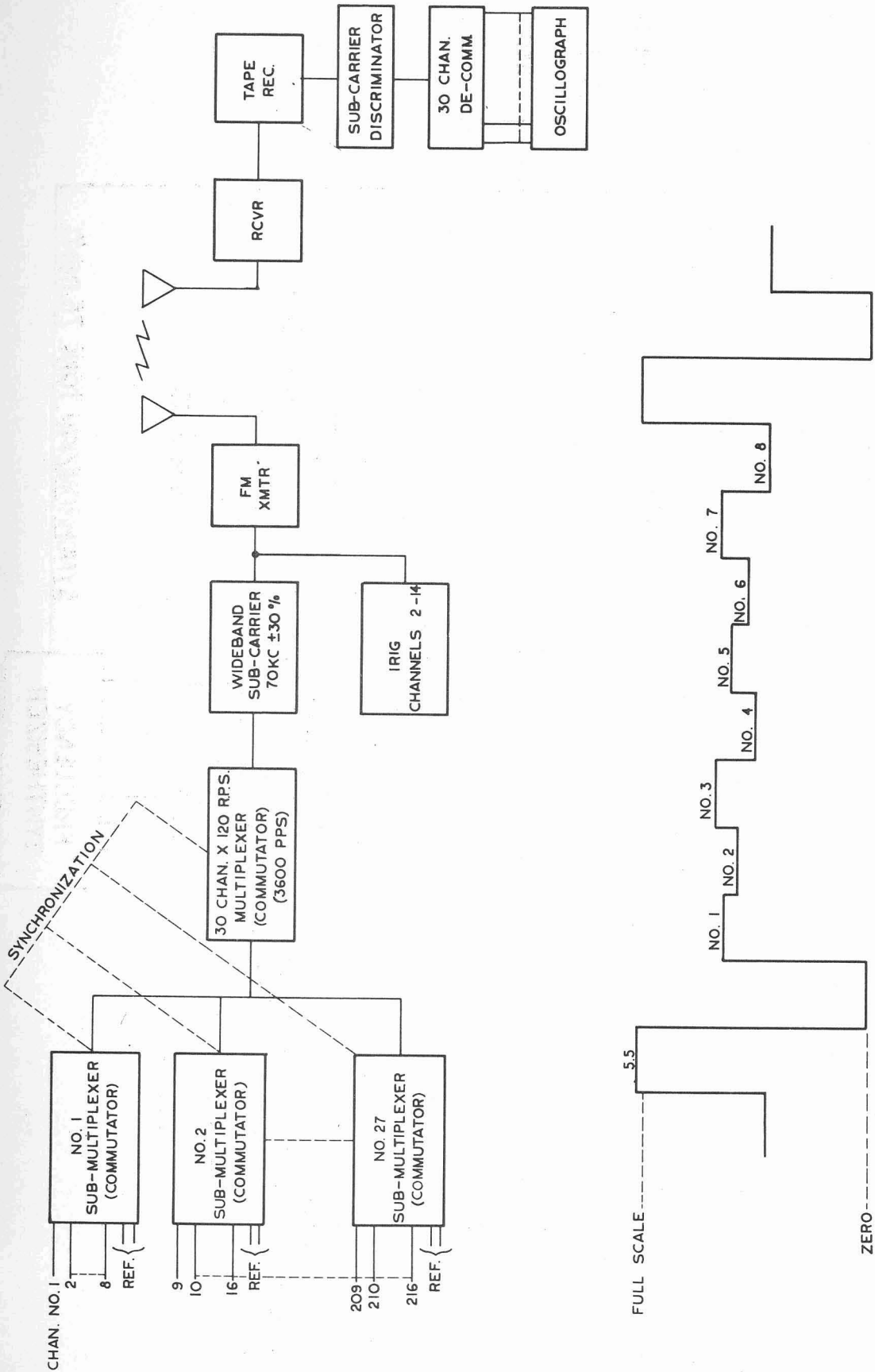


FIGURE 4. BLOCK DIAGRAM OF PAM/FM/FM SYSTEM

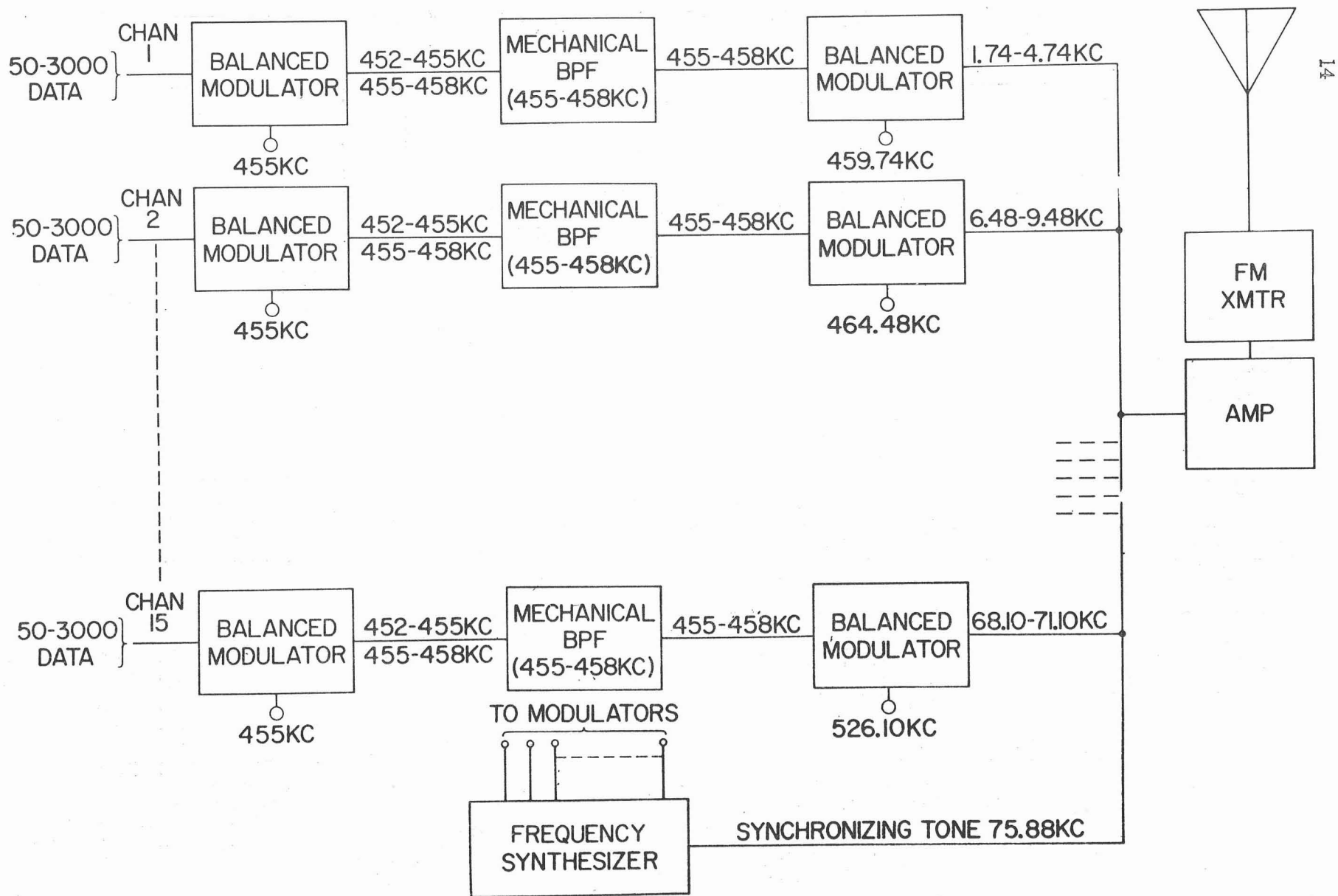


FIGURE 5. BLOCK DIAGRAM OF SS/FM SYSTEM

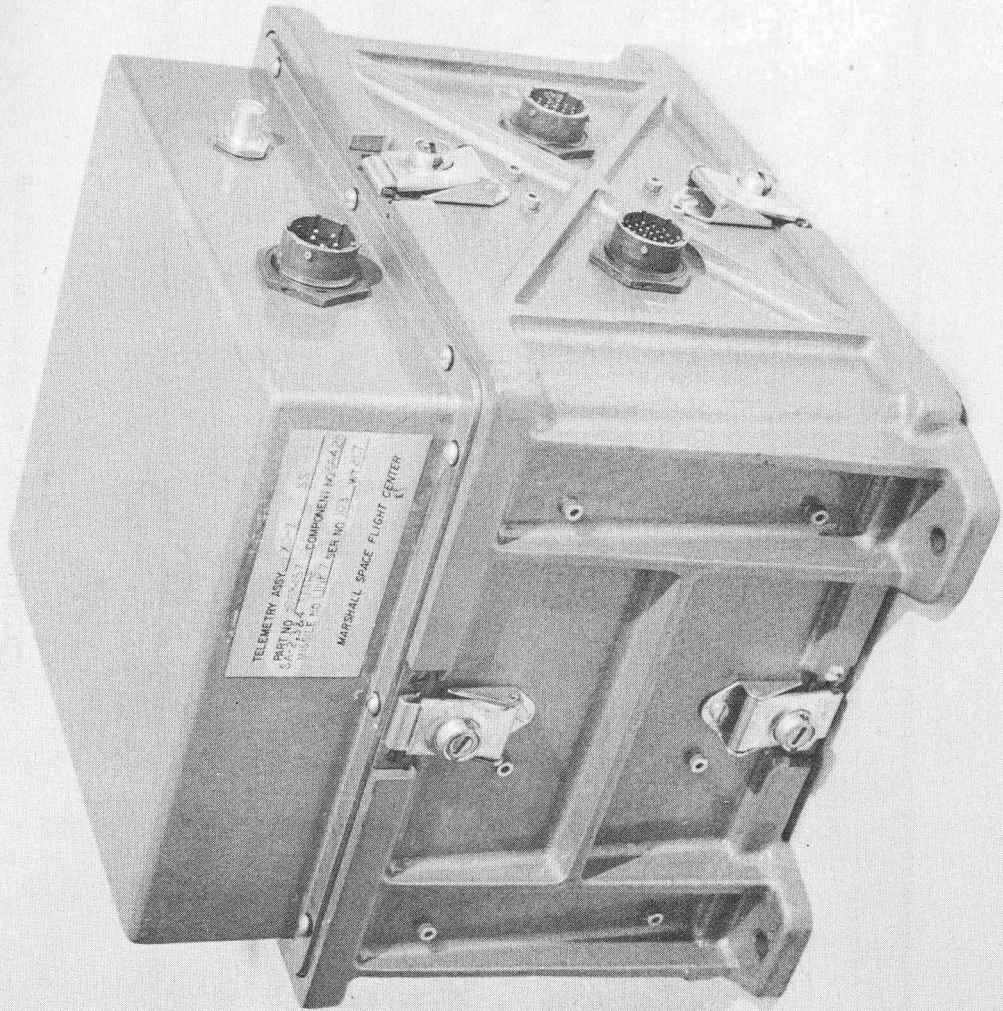


FIGURE 6. VEHICLE-BORNE SS/FM TELEMETRY

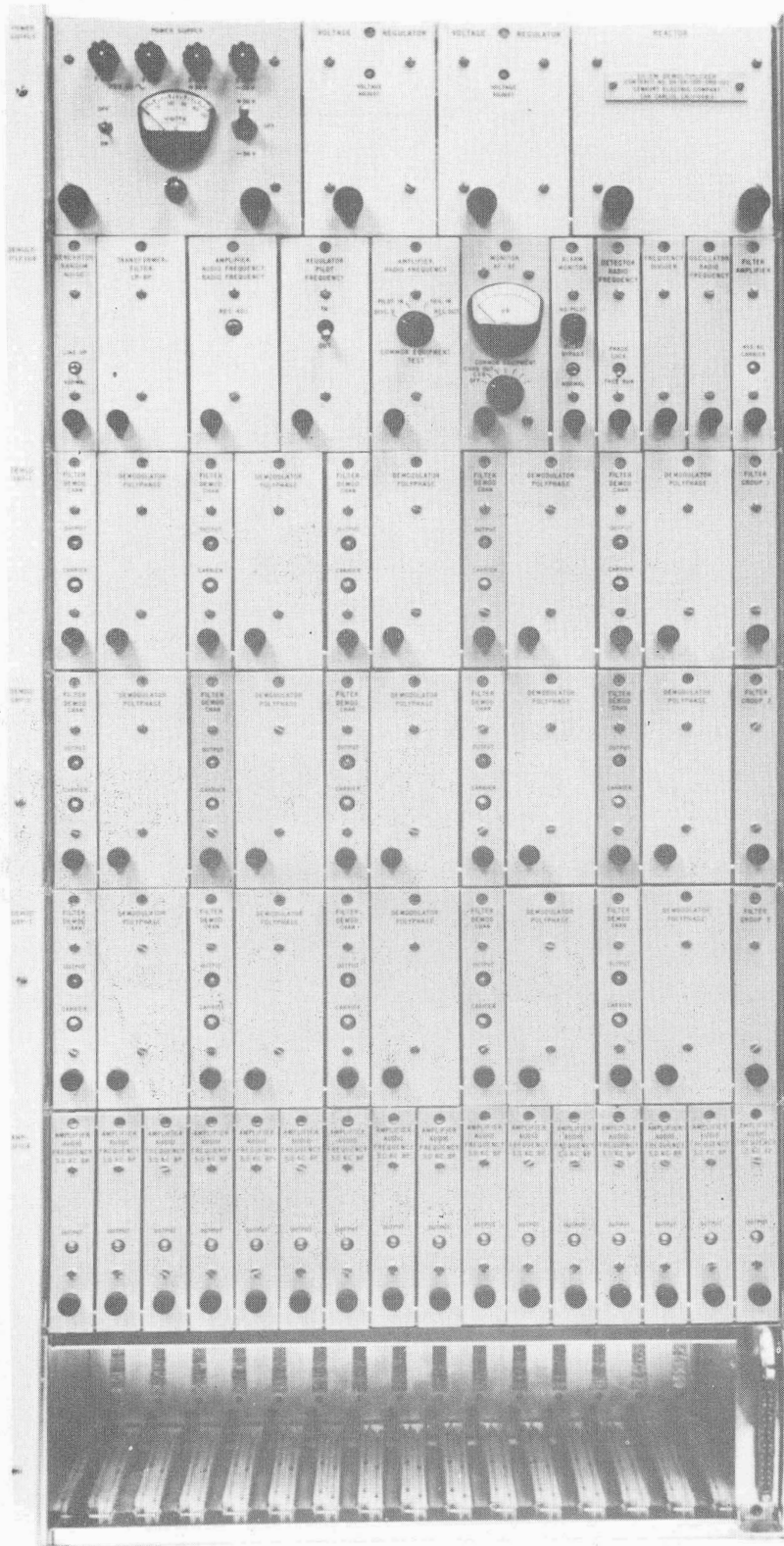


FIGURE 7. SS/FM DEMODULATOR

FIGURE 3. VEHICLE SYSTEM ARRANGEMENT FOR AUTOMATIC CHECKOUT

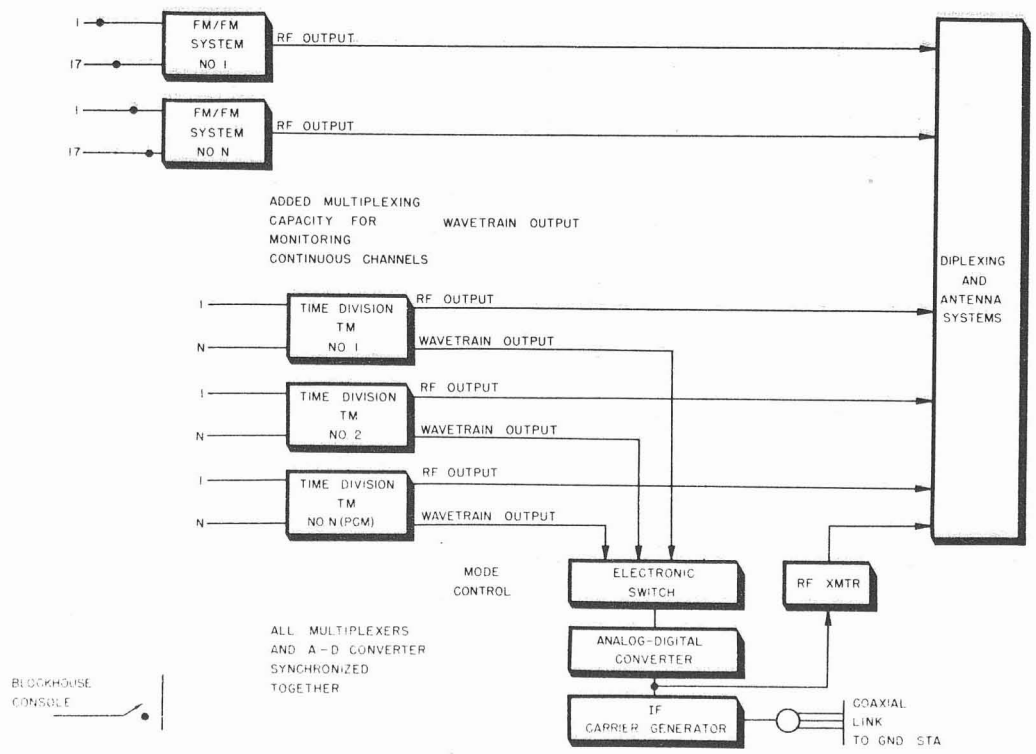


FIGURE 3. VEHICLE SYSTEM ARRANGEMENT FOR AUTOMATIC CHECKOUT

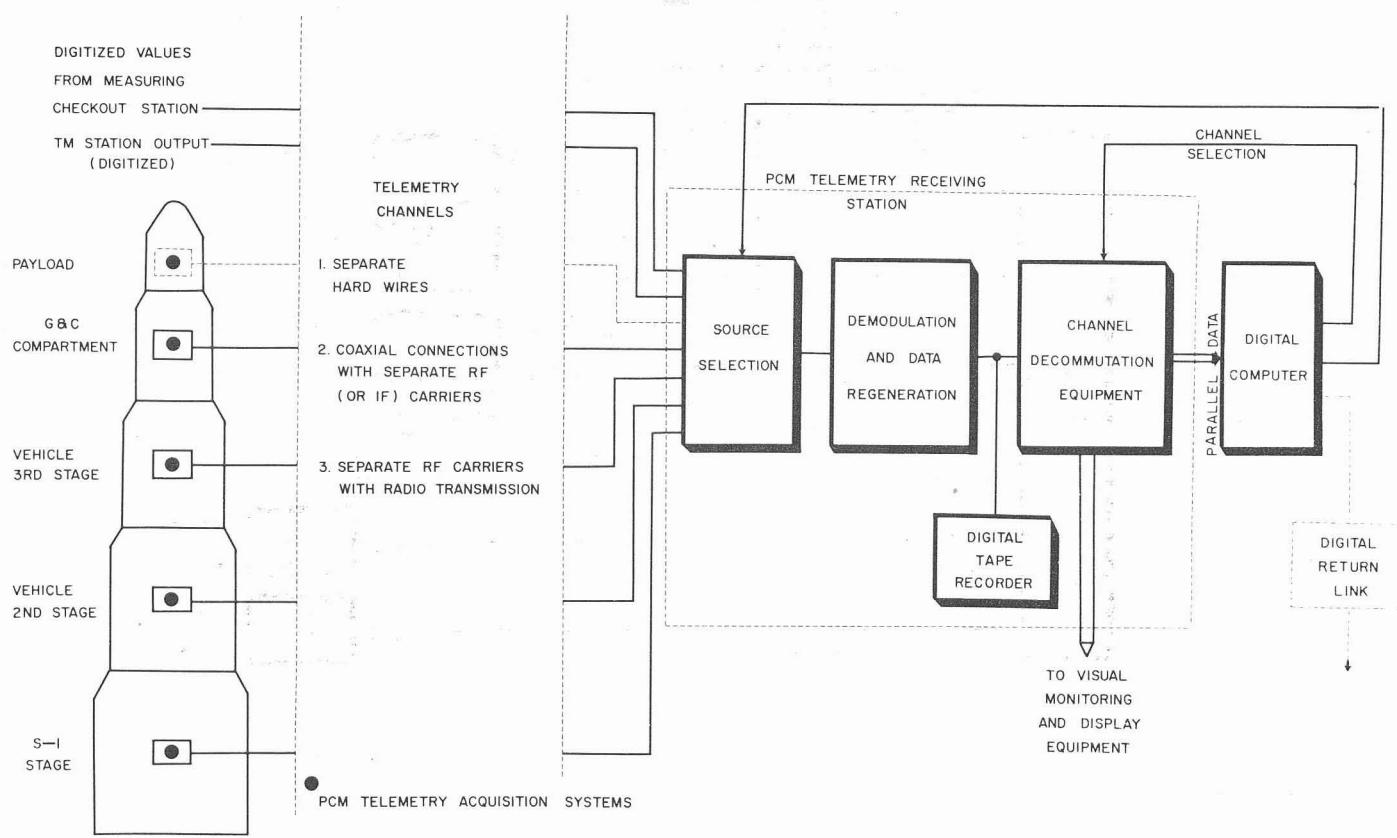


FIGURE 9. DATA ACQUISITION SYSTEM FOR AUTOMATIC CHECKOUT

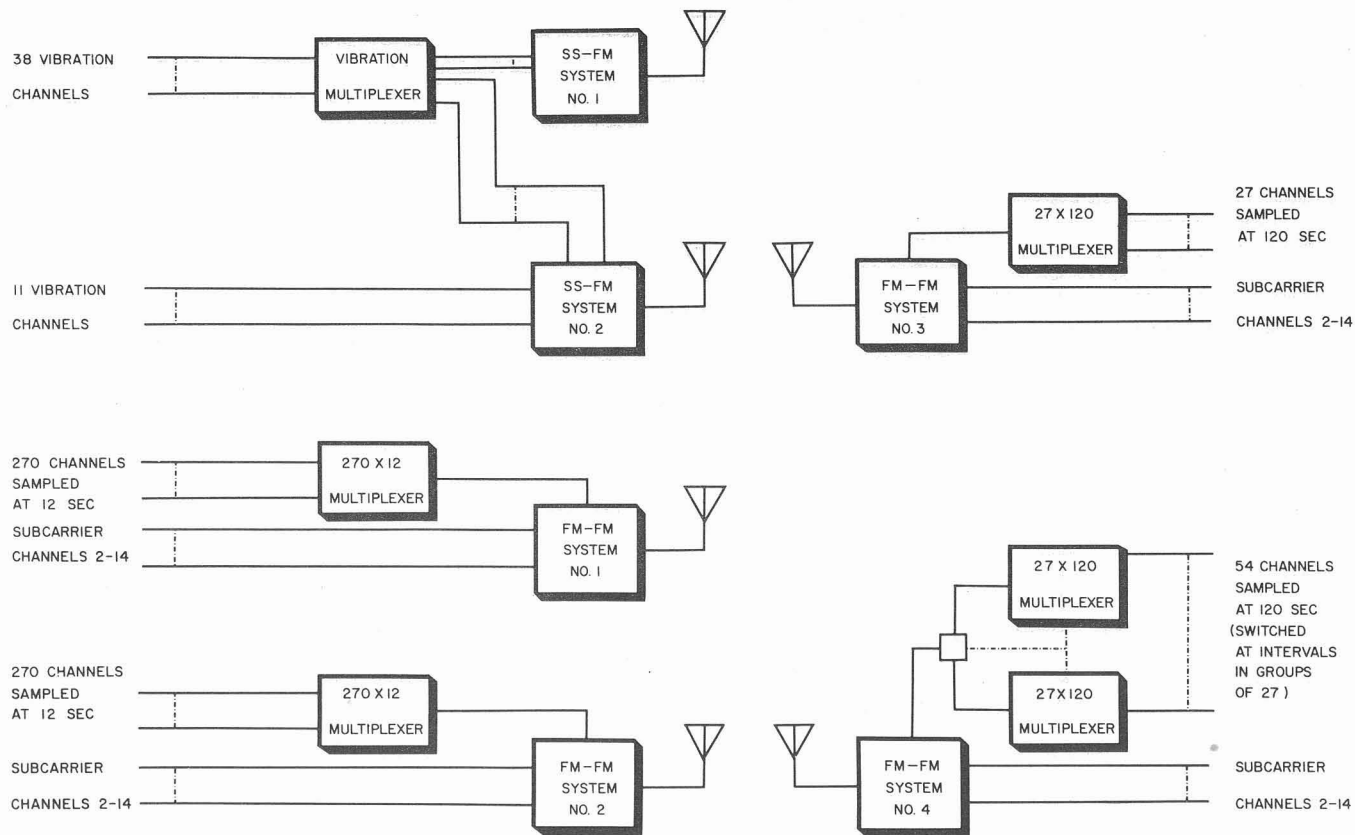


FIGURE 10. S-I STAGE TELEMETRY FOR VEHICLE SA-5

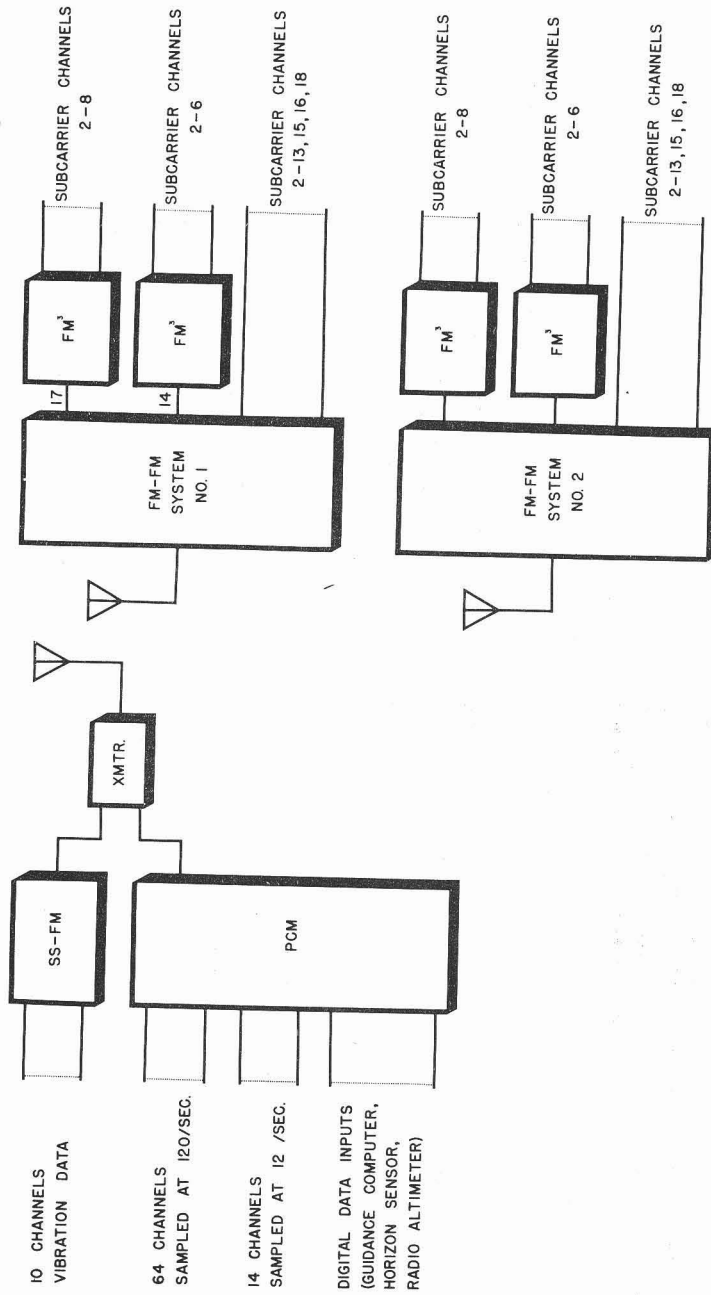


FIGURE 11. INSTRUMENT UNIT TELEMETRY FOR VEHICLE SA-5

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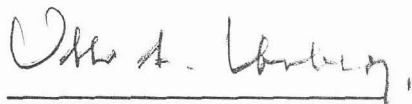
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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.



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