

Telemetry systems in widest use are the FM-FM frequency-division, and the PAM, PDM, and PCM time-division systems. A new hybrid system, PACM, could be used to combine the advantages of both PAM and PCM. In the future there will be marked improvement in speed, accuracy, and reliability of telemetry systems, along with reductions in size, weight, and cost.

# New Trends in Telemetry

The rapid growth of our missile and space technology has created many challenging new goals in the field of radio telemetry. Both missiles and satellites are becoming larger and more complex; this means that the telemetry systems used to recover in-flight information from these vehicles must be capable of handling an increasing quantity of test data and scientific information.

The role played by the telemetry transmitting and receiving systems used for this purpose is an important one. A single missile firing or satellite launching may cost millions of dollars, and the main purpose of that expenditure is to gain scientific information. The information may be concerned with the performance of the vehicle itself, or the environment through which it passes. Whatever the purpose of the information, most of it must be transmitted from the vehicle to a ground receiving station *via* radio telemetry since the vehicle itself is rarely recovered. Consequently, the only tangible result of a multi-million-dollar firing is frequently a collection of magnetic tape recordings of telemetry signals.

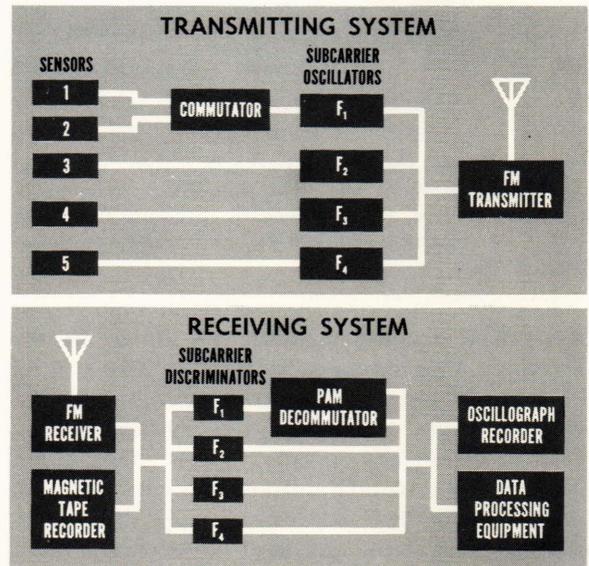
The purpose of this paper is to describe briefly the four major telemetry systems in use today, and to discuss some of the new trends in the field of telemetry.

## Telemetry Systems

The word "telemeter" is defined in *Webster's New Collegiate Dictionary* as "an electrical instrument for measuring a quantity, transmitting the result to a distant station, and there indicating or recording the quantity measured." Although the field of telemetry is quite broad, the telemetry systems discussed in this paper are restricted to those used in transmitting information from guided missiles or space vehicles.

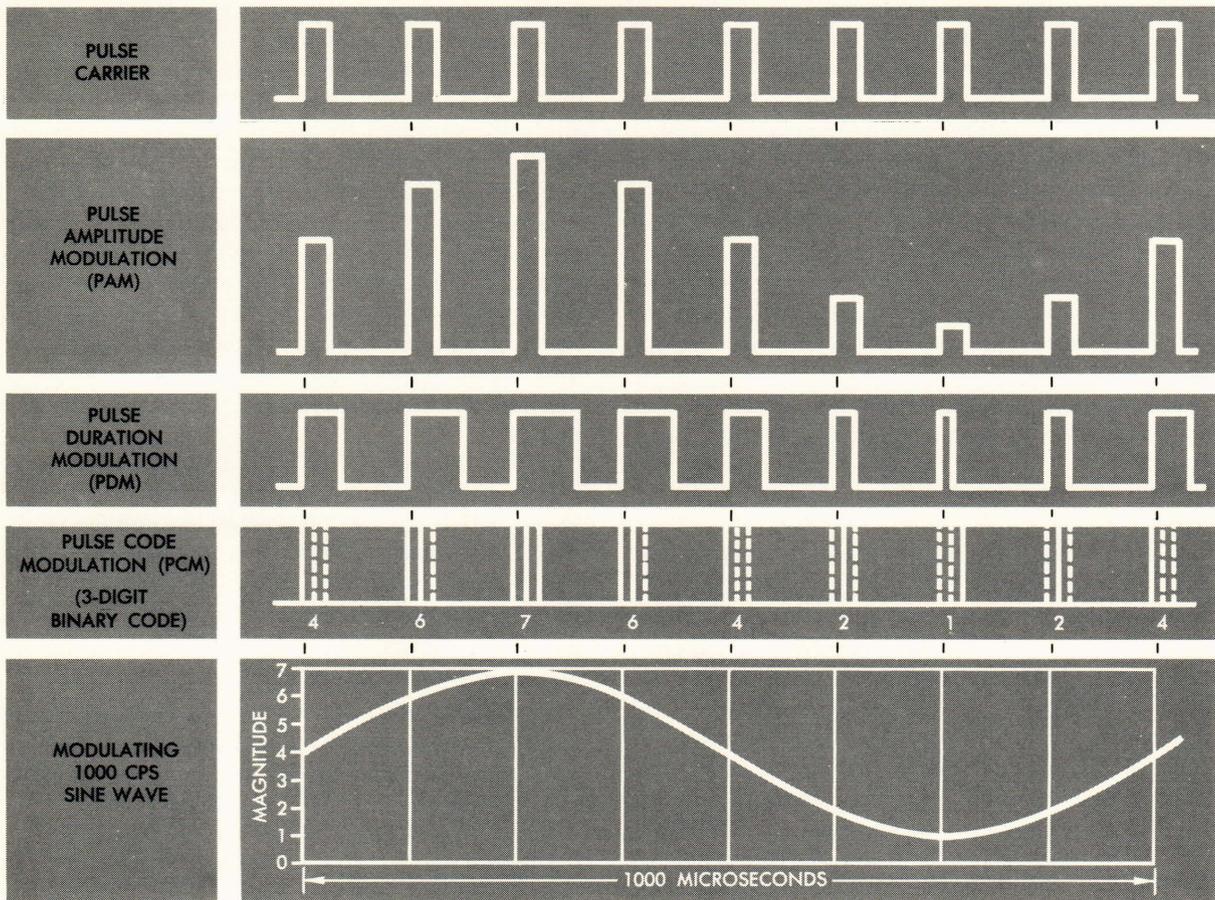
These systems utilize a radio-frequency transmission link, and the data are normally recorded in analog or digital form on magnetic tape.

The many types of radio telemetry systems in use today may best be characterized by the modulation system and multiplexing scheme used. Since nearly all missile and satellite telemetry systems must handle a number of information channels on each RF link, some means of multiplexing must be employed. Telemetry systems may use either frequency-division or time-division multiplexing or a combination of both.



A simple FM-FM four-band telemetering system providing three continuous and two commutated channels.

**Frequency-Division**—One of the oldest and most widely used telemetry systems is the FM-FM frequency-division system. Much of the early work on this system was done at Princeton Uni-



Three examples of pulse modulation used in time-division telemetry systems.

versity and at APL. It was first adopted as the standard by the Research and Development Board in 1948. Since the termination of the RDB, the task of promulgating new or revised telemetry standards has been assigned to the IRIG (Inter-Range Instrumentation Group) which represents the major Department of Defense missile test ranges. The IRIG has extended the FM-FM standards and added standards for other telemetry systems.

The FM-FM telemetry system illustrated is an example of a simple four-band system providing three continuous and two commutated channels. Each function to be telemetered is sensed by an end instrument or sensor which produces a voltage analog of the physical quantity involved. The voltage thus produced frequency-modulates a turn-gate-controlled subcarrier oscillator which in turn frequency-modulates an RF transmitter.

There are 18 standard subcarrier bands specified by the IRIG; these range from 400 cps up to 70 kc and provide intelligence frequencies ranging from 6 cps to 2100 cps.

At the receiving station the composite signal containing all of the modulated subcarrier frequencies is recovered at the receiver output and is usually recorded on a single track of an analog tape recorder. This signal may also be fed simultaneously, or later by tape playback, to a bank of subcarrier discriminators. Each discriminator is equipped with a bandpass filter which selects the particular subcarrier frequency to which the discriminator is tuned. The voltage analog of each original function is recovered at the appropriate discriminator output and fed to a separate galvanometer element in a recording oscillograph which produces a time history plot of each function telemetered.

If subcommutation is used, a decommutator must be employed to separate and reconstruct the individual functions prior to recording. The voltage outputs of the discriminators may also be fed to other data processing equipment. For example, they may be fed to an analog computer or digitized for entry into a digital computer.

**Time-Division**—Time-division telemetry systems utilize some form of pulse modulation, of which three types are illustrated. The top waveform represents the signal which is to be telemetered. The modulating signal is sampled periodically, and the voltage level at the instant of sampling is used to modulate the pulse coinciding with that sample. The modulation systems shown are described in order as follows:

1. *Pulse-Amplitude Modulation (PAM)* — In pulse-amplitude modulation, the amplitude of the pulse varies in accordance with the amplitude of the modulating signal.

2. *Pulse-Duration Modulation (PDM)* — In pulse-duration modulation, the pulse amplitude remains constant but the pulse duration is controlled by the amplitude of the modulating signal.

3. *Pulse-Code Modulation (PCM)* — In pulse-code modulation, all pulses are of uniform shape and are periodic; the information is contained in the code formed by the presence or absence of certain pulses in each code group. In the bottom waveform is shown a 3-bit binary code. The pulses have the value, reading from left to right, of  $2^2$ ,  $2^1$ , and  $2^0$ . The presence of a pulse is indicated by a solid line, and the absence of a pulse is indicated by a dashed line. The decimal value of each binary code group is equal to the sum of the values of the pulses present in that group. The decimal value of each code group is indicated below that group.

In the simplified block diagram of a PCM telemetry system, the airborne telemeter accepts both

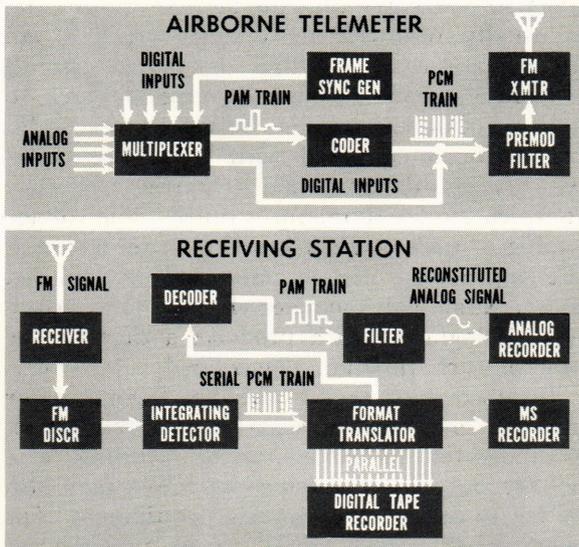
analog and digital inputs; these inputs are fed to a multiplexer (electronic commutator) which permits time sharing of a single coder. In the multiplexer, continuous analog signals are periodically sampled to produce a PAM pulse train representing the signal. The PAM samples are fed to the coder where each pulse is digitized as a coded pulse group. The serial train of code groups resulting from a single sample of all inputs (in the simplest case) constitutes a frame of data which is identified by a unique digital word produced by the frame sync generator. The serial pulse train is filtered and fed to a transmitter where it frequency-modulates the RF carrier.

At the receiving station the output of the receiver discriminator is fed to an integrating detector which recovers the serial PCM pulse train. This pulse train is fed to a format translator which reassembles the data by channels into serial or parallel format as required. From this point the data may be recorded in any or all of the following three ways:

a. *Analog Recorder*—The reassembled pulse train representing each channel may be fed to a decoder which converts the PCM signal back to a PAM pulse train. The PAM train is then passed through a filter to reconstitute the original analog signal which may then be fed to an analog recorder.

b. *Multistylus Recorder*—The reassembled PCM words may be fed to a multistylus recorder for direct recording as an analog presentation.

c. *Digital Tape Recorder*—The serial PCM words may be converted to parallel format and recorded on a multitrack digital tape recorder.



Simplified block diagram of a pulse-code modulation telemetry system.

## Future Telemetry Requirements

**Data Requirements**—The multiplicity of telemetry systems and the many variations within each system have caused considerable chaos at test ranges and data-processing facilities serving a number of different programs. In an effort to determine what type of standardized telemetry system should be developed to meet the needs of the majority of telemetry users for the next ten years, the three armed services sponsored a three-year study program conducted by the Aeronutronic Division of Ford Motor Company.

Aeronutronic first conducted an extensive survey of test ranges, government agencies, and manufacturers to determine the future telemetry requirements. The results of the survey

indicated the following:

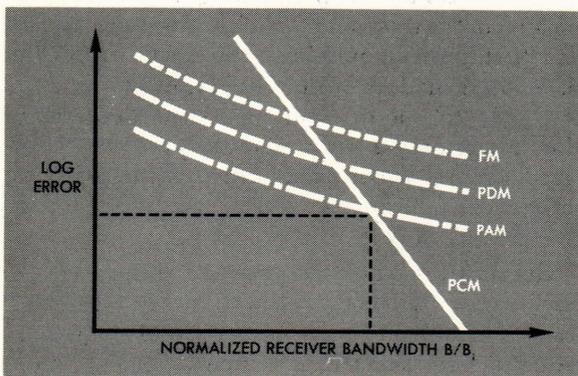
1. The average requirement is for a system having 75 sensors, an average data accuracy of 2.5%, and a total data rate equivalent to 75,000 bits per second.

2. The maximum requirements include systems having up to 400 sensors and accuracies to 0.1%. Nearly 10% of the users required data rates in excess of 1,000,000 bits per second.

3. A standard system should provide data rates of 200,000 to 400,000 bits per second and a range of accuracies varying with channel requirements. It should be an extremely flexible system, compatible with existing equipment where possible, highly reliable, and small in size.

**Modulation Systems**—In comparing existing systems, Aeronutronic considered only FM-FM, PAM-FM, PDM-FM, and PCM-FM. They compared the systems both analytically and experimentally from the standpoint of accuracy and bandwidth utilization.

The accompanying figure contains a plot for each of the four systems showing normalized receiver bandwidth *vs* logarithmic error. The



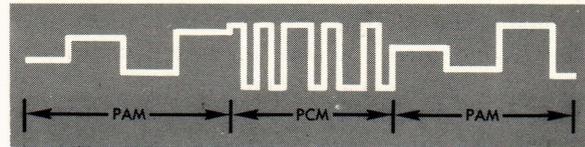
Plotted comparison of FM-FM, PAM-FM, PDM-FM, and PCM-FM telemetering systems, showing normalized receiver bandwidth *vs* logarithmic error.

normalization is accomplished by dividing receiver bandwidth by information bandwidth. This comparison shows that for accuracies better than 2%, PCM is clearly the best, while for lower accuracies, PAM provides the best bandwidth utilization. Their results also agreed with the earlier work of Nichols and Rauch in showing that the FM-FM system has the lowest information efficiency of any of the four systems considered. It should be noted parenthetically here that FM-FM is still an attractive system for use in small vehicles having a limited number of channels including some high intelligence frequencies. It is flexible, compact,

and reliable; standard FM-FM components are available from many sources, and all major test ranges are equipped to receive the FM-FM signals.

In view of the conclusions reached, Aeronutronic recommended the development of a hybrid telemetry system to be called PACM. This system would transmit high accuracy data as PCM and at the same time transmit low accuracy data as PAM, thereby combining the advantages of both systems.

A typical PACM waveform is shown. The PAM and PCM pulse groups are intermixed. Both pulse types are transmitted as 100% duty cycle non-return-to-zero pulses. The PAM pulses have a duration of four times the PCM bit period.



A typical PACM waveform, showing intermixing of PAM and PCM groups.

While such a system seems appealing from a purely theoretical standpoint, there appears to be some question as to whether or not the system complexity is warranted by the advantages gained. It would seem preferable to utilize one system or the other in a given application; if the accuracy requirement should make some PCM mandatory, then a pure PCM system could provide both high- and low-accuracy channels through the use of variable word lengths. The Aeronutronic report includes a design example of a PACM system to meet a typical set of future requirements. For that particular set of requirements, the use of variable word length PCM would increase the required signal-to-noise ratio by only 1 or 2 db as compared to the PACM system; this seems a small price to pay to avoid the complexity of the hybrid system.

**Frequency Allocations**—Whatever modulation systems are used in the future, a number of new goals common to all telemetry systems must be met. One of these is the inevitable shift to the UHF bands. The present telemetry frequency allocations are shown.

TELEMETERING FREQUENCIES

| Region | Band         | Bandwidth |
|--------|--------------|-----------|
| UHF    | 2200-2300 mc | 1 mc      |
|        | 1435-1535 mc | 1 mc      |
| VHF    | 225- 260 mc  | 0.5 mc    |
|        | 216- 225 mc  | 0.5 mc    |

A directive issued in 1958, by the Joint Communication Electronics Committee of the Joint Chiefs of Staff established a target date of January 1, 1970 for telemetry users to vacate the 225-260 mc band; protected operation in the 216-225 mc band has already expired as of January 1, 1960. While strong efforts will be made to retain some portion of the VHF spectrum for long range applications, telemetry users should be prepared to transfer at least the bulk of their operations to the 1435-1535 mc and 2200-2300 mc bands by 1970. In spite of the serious congestion in the VHF band, very little use has been made of the UHF allocations, primarily because of the almost complete lack of available components for use at these frequencies. Although some design effort is now under way, the development of UHF telemetry equipment should be intensified if reliable and proven hardware is to be available by 1970. Some of the differences to be encountered in operating in the UHF region, as compared to the VHF region, will be as follows:

1. *Transmitters*—For a given range, transmitters will be larger and heavier and will require higher output power.

2. *Antennas*—The size of transmitting and receiving antennas will be reduced and their efficiency will be increased.

3. *Transmission Losses*—The increased transmission losses may be just about offset by the higher gain in the receiving antennas.

4. *Receivers*—Presently available receivers have noise figures in the order of 10 to 15 db. The development of receivers using traveling wave tube amplifiers or solid state amplifiers, such as tunnel diodes, masers, and parametrics, may reduce the noise figure to 2 db or less.

A survey of many telemetry experts in government and industry was conducted by the Naval Ordnance Laboratory, Corona, California, to determine the design objectives to be met in the development of telemetry transmitters, receivers, and receiving antennas required in Navy missile programs during the period 1960 to 1970. While these objectives are not to be used for procurement, they do give an insight into the thinking of qualified people in the field. Some of the suggested performance requirements for UHF telemetry which have been set forth as a result of the survey are as follows:

1. *Transmitters*—To be smaller than at present—ultimately 25 to 50 cubic inches for a 2- to 3-watt unit. These should be FM transmitters capable of being modulated by FM, PAM, PDM

and PCM with no design modification, and should be capable of deviations up to  $\pm 1$  mc.

2. *Receivers*—To have a noise figure of 2 db or less, a local oscillator stability of  $\pm 0.005\%$  of received frequency, and a preamplifier gain of 25 db. They should be equipped for optional phase lock operation and should have an IF output after the limiters and ahead of the discriminator for predetection recording.

3. *Receiving Antennas*—To have high gain, narrow beam, circular polarization, and full hemispherical coverage. They should provide automatic target acquisition and tracking with switchable beamwidths appropriate to each mode. Gains in the two modes should be 10 and 28 db respectively at 1485 mc, and 12 and 32 db respectively at 2250 mc. Reflector diameters should be limited to 12 feet for a ground-based operation and 4 feet for shipboard operation.

**Size and Weight**—There is a continuing requirement for telemetry equipment of smaller size and weight for missile use. The need is even more urgent for satellite applications; this is immediately obvious when it is realized that every additional pound of weight in a satellite means over 100 pounds of additional takeoff weight for the launching vehicle. Great strides have been made in miniaturization of presently available telemetry components, particularly in the transistorized units, but still greater reductions in size are needed. Microminiaturization techniques now appear to offer drastic reductions in size and weight.

**Reliability**—The necessity for improved reliability in telemetry as well as in all other aspects of missile and space technology is continually increasing. As systems become more complex the mean time to failure tends to become shorter; yet at the same time missile flights are becoming longer, and satellites are required to remain in unattended operation for months and even years.

Some approaches to improved reliability include rigid quality control, severe preflight testing, and the use of self-healing circuitry. The use of redundancy is one obvious approach but is costly in space and weight; it becomes more feasible, however, as components become smaller. One relatively new technique is the use of electrically welded joints to replace solder connections. The welded joints are stronger and the process may be more accurately controlled; damage to components through overheating is practically eliminated, and reliability is improved by an order of magnitude.