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DIGITAL SYSTEMS IN SPACE COMMUNICATIONS

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ABSTRACT

Digital techniques play an ever-increasing role in the modernization of space communication systems. Their greatest influence has been observed on data transmission and command-control systems. This paper presents a brief description of modern telemetry systems employing digital techniques and of typical space-borne command programmers for satellite function control.

Future space exploration will place new demands and will require further development of communications techniques, bandwidth compression schemes, and data-handling methods. A specific approach to data bandwidth compression, described in this paper, will yield adequate bandwidth reduction to permit transmission of significant information from outer space without excessive use of power.

INTRODUCTION

Space communications systems incorporate basically three functions: transmission of data between a space vehicle and a ground station, transmission of command-control signals from a ground station to the space vehicle, and tracking of the vehicle flight path. Historically, the three functions have been developed separately and for the most part represent separate subsystems in present-day technology. In each of these subsystems, digital techniques have come to play an important part, indicating that the future in space communications will be based predominantly on applications of digital methods.

DATA TRANSMISSION

Commensurate with the progress of missile and space programs, the demands on data transmission systems have been increasing steadily. Of the parameters that influence telemetry system design, the most important are the following:

Number and bandwidth of data channels. In the early 1950s a relatively modest number of 50 to 100 data points was characteristic of missile instrumentation. Today, missiles and space vehicles require the capability for transmitting 300 or more data points. The total bandwidth of information to be transmitted varies from a few hundred cycles per second to several hundred kilocycles or even megacycles in some applications. It is significant to note that, while the great majority (90 percent or more) of all measurements individually require rather low-frequency response (less than 100 cps), the largest portion of the total bandwidth (70 to 90 percent) is occupied by the few high-frequency channels.

Range of transmission. With the advent of satellites and space vehicles, the transmission range requirements have increased from a few hundred miles to several thousand miles with new requirements arising for millions of miles for deep-space probes.

Power consumption. The minimization of power consumption is, of course, of primary interest in long-life satellite applications. With the steady increase in satellite payload complexity, the requirements on electrical energy will continue to demand minimization of power consumption.

Reliability and life. High equipment reliability was always a mandatory requirement on telemetry systems. The significant change is associated presently with extending the operational life of the equipment by several orders of magnitude, from minutes to years. Requirements for one year of unattended, reliable operation in a space vehicle have become common; and mean time to failure for complete systems is currently specified at 30,000 hr and up.

Data accuracy. These requirements have not changed much since the early missile programs. The majority of data transmitted (85 percent or more) is considered satisfactory when total errors range from 2 to 5 percent. Only a small fraction of all transmitted data (less than 15 percent) requires accuracies of the order of 0.1 to 0.5 percent.

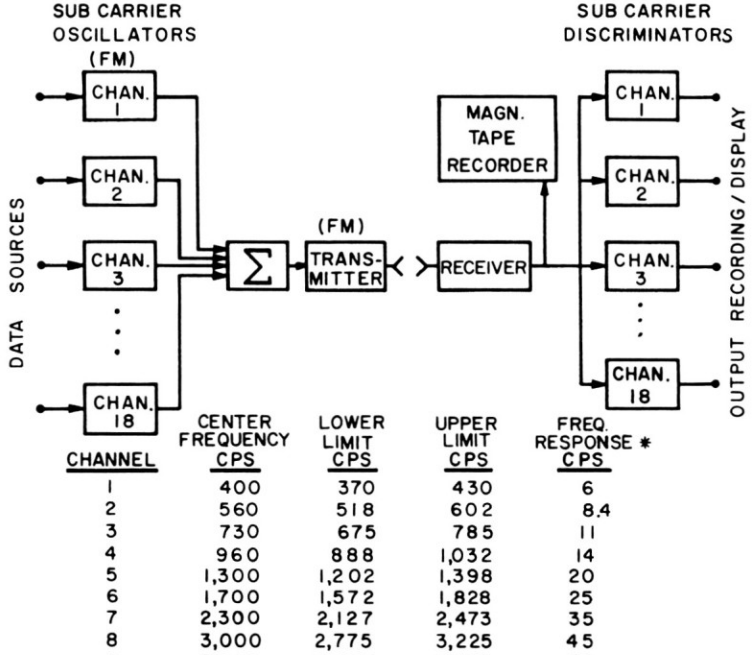
Consistent with these requirements, the implementation of telemetry systems is changing from the FM-FM technique, which was used almost exclusively a decade ago, to the digital sampled-data techniques.

The FM-FM system (shown in Fig. 1) is representative of a frequency-division multiplex technique. The vehicle portion of the system consists of a group of subcarrier oscillators, each of which is frequency-modulated by the input signal. The composite output of all subcarriers, in turn, frequency modulates a radio carrier (hence the term FM-FM) which transmits the data to a ground station. Here a complementary process takes place, i.e., the radio carrier is detected and the subcarrier signals distributed to a bank of discriminators, tuned to the frequencies of the vehicle-borne oscillators. In cases where a large number of slowly varying inputs is present, selected subcarrier channels may be commutated, provided the commutation speeds are compatible with the channel bandwidth capabilities.

The standard FM-FM system appears to be inadequate for the demands of modern-day space technology, primarily because of its total bandwidth limitation and lack of flexibility. In contrast, a sampled-data system with time-division multiplex permits a better utilization of the link bandwidth, provides the flexibility to greatly vary the number of data points and their bandwidth distribution, and permits better tailoring of the system accuracy to a given data requirement. There are three preferred modes of modulation selected for the sampled-data systems used at the present time; these are the PAM-FM, PCM-FM, and the PACM-FM.

In the PAM-FM system, amplitude samples of the input data, time multiplexed, are applied to a modulator-transmitter resulting in frequency modulation of the radio carrier in proportion to the amplitude of the sample. This system offers the most effective use of power and spectrum for medium accuracy transmission where errors of 1 percent or greater are acceptable.

In a PCM-FM system, all samples of the input data are converted to binary words. The resultant digital signal modulates the frequency of a radio carrier. The PCM-FM system is superior in performance for high-accuracy data transmission, where errors of 1 percent or less are desirable.



CHANNEL	CENTER FREQUENCY CPS	LOWER LIMIT CPS	UPPER LIMIT CPS	FREQ. RESPONSE * CPS
1	400	370	430	6
2	560	518	602	8.4
3	730	675	785	11
4	960	888	1,032	14
5	1,300	1,202	1,398	20
6	1,700	1,572	1,828	25
7	2,300	2,127	2,473	35
8	3,000	2,775	3,225	45
9	3,900	3,607	4,193	59
10	5,400	4,995	5,805	81
11	7,350	6,799	7,901	110
12	10,500	9,712	11,288	160
13	14,500	13,412	15,588	220
14	22,000	20,350	23,650	330
15	30,000	27,750	32,250	450
16	40,000	37,000	43,000	600
17	52,500	48,562	56,438	790
18	70,000	64,750	75,250	1,050

* FREQ. RESPONSE IS BASED ON DEVIATION RATIO OF 5

Fig. 1. FM-FM telemetry system.

The PACM-FM system is a combination of the two modes of operation, where a selected number of data points (those that require high accuracy) may be transmitted in the PCM mode while the others proceed with a direct pulse-amplitude modulation.

Figure 2 depicts a sampled-data system in which any of the three modes are accommodated. The vehicle portion of the system consists of a multiplexing device, an analog-digital converter, a programmer, and a transmitter. The multiplexing device may be a single multiplexer or a group of multiplexers tied together to permit subcommutation and super-commutation as required to meet the instrumentation demands. Typically, a multiplexer (see Fig. 3) comprises a set of analog sampling gates which are triggered in sequence by pulses generated in the sequencer. The sequencer generally consists of binary logic elements (such as bistable multivibrators and gates) connected in accordance to the desired timing function.

The analog-to-digital converter may use whatever technique is best suited to convert analog voltages to digital words in the environment of its mission. The word structure (i.e., number of bits, pulse format, serial or parallel output)

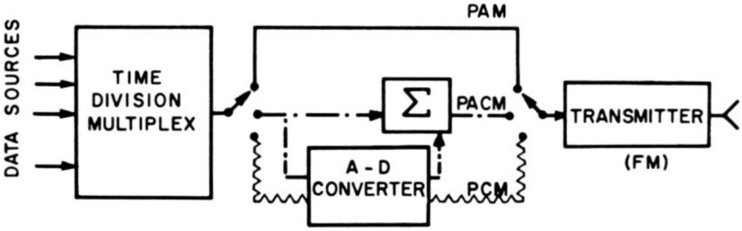


Fig. 2. Sampled data system (vehicle equipment).

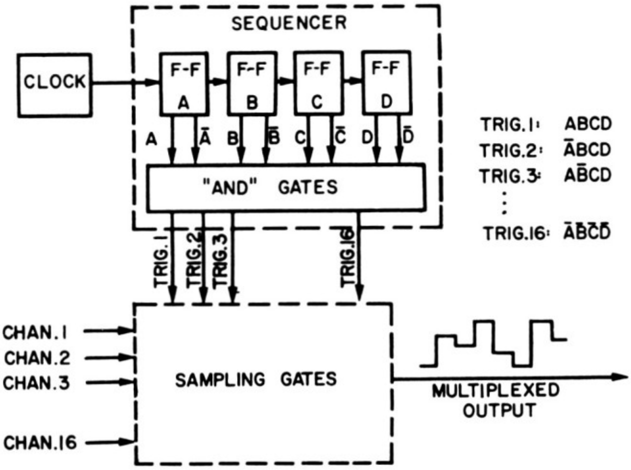


Fig. 3. Sixteen-channel multiplexer.

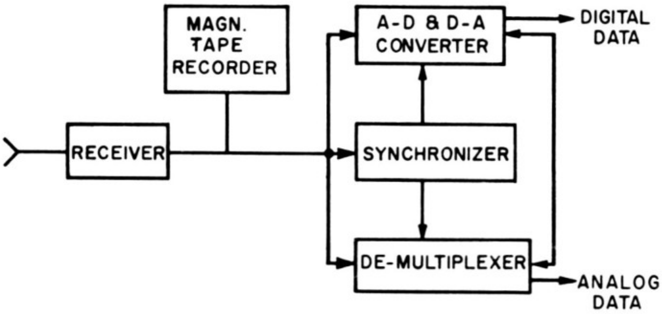


Fig. 4. Sampled data system (ground station).

depends on the requirement of the system at hand. In general, word lengths of ten bits with a serial nonreturn-to-zero format (NRZ) are preferred.

The ground station of such a system is shown in Fig. 4. The basic function is to record the composite signal and demodulate as many channels in real time as necessary for real-time data analysis and/or display.

COMMAND-CONTROL SYSTEMS

The purpose of a command-control system is to provide a means for remote control of various equipments aboard a satellite or space vehicle from a ground control center. When the space vehicle is in direct radio contact with the ground control center, the most likely mode of operation is that of real-time control. In many cases, however, the time at which certain functions in the vehicle are to be performed may coincide with a vehicle location which does not permit radio contact with the ground station. Under these conditions, a stored-program mode of operation is employed.

The vehicle-borne device associated with the command-control subsystem is referred to as a command programmer. Its function is to receive command messages from the ground station and, depending on their designation as "real-time" or "stored-program" commands, execute the command immediately or transfer it to a storage device for further reference, respectively. A typical command programmer is a digital computer, the major elements of which are shown in Fig. 5. The receiver and input logic circuits process the incoming signals to differentiate between real-time and stored-program commands. A real-time command signal is passed directly to the output stage where it causes an execution of the command; whereas a stored-program command proceeds to the memory for further processing. Typically, a stored-program message consists of two words—a time word and a command word. The time word specifies vehicle time, generated by the vehicle clock, at which the command is to be executed. Every time interval, the contents of the memory are scanned in search for a time word equal to the time reference which the clock applies to the comparator. When a coincidence occurs, the command word is passed to the output stage for execution.

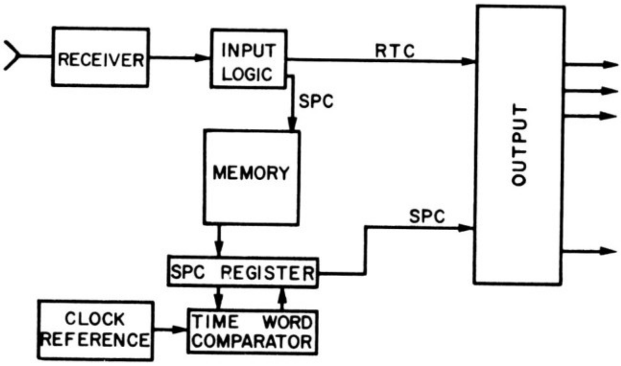


Fig. 5. Command programmer block diagram.

The clock stability depends entirely upon the system considerations, i.e., the maximum length of time between radio contacts from the ground control station and the smallest time interval which separates execution of distinct commands. Long-term stability of one part in 10^6 for 24 hr is a common requirement.

TRACKING

The application of digital techniques to tracking systems has not been as pronounced as in the other two subsystems. Most often, tracking systems are based on phase- or frequency-shift measurements (using techniques such as interferometers, multiple range tones, and Doppler shifts) except for radar tracking in which time displacement between transmitted and received pulses provides the measure of distance.

FUTURE DEVELOPMENTS—BANDWIDTH COMPRESSION

As the objectives of our space programs expand to include exploration of other planets, space communications systems may develop to be the key to our ability to meet such objectives. Once beyond the gravitational field of the earth, a space vehicle may proceed to great distances with a relatively minor expenditure of propulsive power. However, its ability to communicate with an earthbound station decreases proportionately with the square of the distance, thus imposing a severe requirement on the vehicle electrical power plant and on the radio transmitter.

As an example, Table 1 illustrates the radio power demand on a space-borne communications system typical of those presently employed in earth satellites, assuming that the same amount of data is to be transmitted from the moon, Mars, or the edge of the solar system. Although these exceptional power requirements are to be expected from the astronomical distances involved, they are somewhat startling and demonstrate clearly that communication between far-flung locations in our solar system will require high order-of-magnitude improve-

Table 1. ILLUSTRATIVE LINK CALCULATIONS

Link parameter	Earth satellite	Moon	Mars	Edge of solar system
Range, NM	4,500	0.25×10^6	200×10^6	$3{,}200 \times 10^6$
Frequency, mc	2,300	2,300	2,300	2,300
Propagation, db	−178	−213	−271	−295
Transmitter antenna gain, db	12	12	12	12
Receiver antenna gain, db	50	50	50	50
Miscellaneous feed losses, db	−6	−6	−6	−6
Receiver noise, dbw $B_{IF} = 600$ Kc, $NF = 4$ db	−142	−142	−142	−142
Required received signal, dbw	−130	−130	−130	−130
Total link gain, db	−122	−157	−215	−239
Required transmitter power, dbw	−8 (160 m watts)	+27 (500 watts)	+85 (3×10^8 watts)	+109 (8×10^{10} watts)

ments in our system capabilities. The necessary improvements concern an increase in antenna gains, reduction of receiver noise figure, reduction of the receiver threshold, and a marked reduction in bandwidth requirements for deep-space missions.

While the efforts spent in developing techniques for constructing large aperture ground-based antennas and reducing receiver noise figures lead to important improvement in the overall system design, one must consider the technical difficulties attending the construction of large antennas and the problems involved in reducing the noise figures from, say, 4 db to 0.5 db as they relate to the eventual gain of 6 db from doubling the antenna size and 3.5 db from noise figure reduction. It is recognized that the largest payoff lies in vehicle antenna improvements and in the reduction of receiver bandwidth. Since the latter is dictated by the bandwidth of the modulation signal applied to the transmitter, the major potential improvement of our present system lies in the reduction of the modulation bandwidth itself. The following will present a digital system approach to data bandwidth compression.

Signal Compressibility. The first step in the design of a space-to-ground data transmission system employing time-division multiplex techniques, normally consists of generating an instrumentation table. This table lists, among others, items such as identification of the data source, characteristics of the transducer, expected range of signal values, the maximum frequency component of the data input, and the accuracy required for the particular data channel. The latter two characteristics, i.e., the maximum frequency component and the accuracy, determine the minimum sampling rate for each channel that will be required to faithfully reproduce the signals. The minimum sampling rate for the system is then the sum of the sampling rates required by each individual channel. In practice, however, because of equipment design considerations, the total sampling rate must turn out to be slightly higher than the minimum required. The modulation bandwidth of the composite signal which is applied to the transmitter is proportionally related to the total sampling rate, depending on the particular mode of coding and modulation employed by the system.

The procedure described above is essentially correct and is used by most system designers. The selection of the sampling rate must be based on the value of the highest frequency component and the accuracy requirement. Thus, as long as the highest frequency component of the input remains constant, the sampling rate for a channel in which band-limited white noise is to be transmitted is the same as in the case where the spectrum of the input signal has predominately low-frequency data with the high-frequency component occurring only a small percentage of the time. The shortcoming of this system is that no advantage is taken from "a priori" knowledge of the fact that the probability of occurrence of high-frequency components is rather small compared with that of the low-frequency components. Consequently, a significant amount of redundancy is being transmitted through the communication link. The objective of data compression is the removal of such redundancy.

To evaluate the bandwidth compressibility of sampled-data signals, the following assumptions are made:

(*a*) The spectrum of the signal is known to be different than band-limited white noise.

(*b*) The amplitude distribution of the signal follows a truncated gaussian probability curve with the full-scale range corresponding to $\pm 5\sigma$ of the distribution.

(*c*) The sampling rate is larger than twice the highest frequency component of the input spectrum.

A typical waveform of such a signal is shown in Fig. 6. Since the interest of the data analyst is primarily concerned with the variations of data describing a particular experiment rather than a continuing display of constant values, it is possible to define a minimum significant data change below which no need for new inputs exists. This "significant change" can be defined, for example, as a fraction of the full scale of the data range for each individual channel. Thus, a tolerance band can be assigned to data variations in each channel. Changes in data will be considered insignificant as long as they stay within the tolerance band, but become of interest as soon as they exceed the limits of the tolerance band.

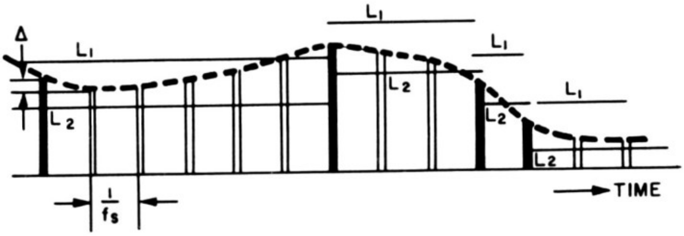


Fig. 6. Sampled data waveform.

As shown in Fig. 6, the sample-to-sample amplitude variations within a given tolerance band may exhibit random characteristics, i.e., the sample amplitude may increase or decrease as compared with the previous value. The problem is analogous to the "random walk with absorbing barriers" where the length of the step is the variable sample-to-sample amplitude change, Δ. The solution shows that the average number of steps taken (i.e., input data samples) before the barrier is reached (i.e., before transmission of a new sample is required) is

$$\bar{N} = \frac{L_1L_2}{\sigma_\Delta{}^2} = \frac{L_1L_2}{2\sigma^2(1-\rho)}$$

where L_1, L_2 = limits of the tolerance band
σ = standard deviation of the input signal
σ_Δ = standard deviation of the sample-to-sample variations
ρ = correlation coefficient of the input samples

$\bar{N}$ is the expected data compression ratio defined as the total number of samples taken to the average number of samples which will require transmission.

In order to obtain a quantitative measure of the expected compression ratio, calculations were made based on the following assumptions:

(*a*) The zero to full scale range of the input signal extends from -5σ to $+5\sigma$.
(*b*) The input data is random and gaussian distributed.
(*c*) The input spectrum has a maximum frequency component f_m. Six cases have been treated in which

(1) $F(\omega) = k_1 \exp(-5\,f^2/fm)$; for $|f| \leq fm$
$= 0$ otherwise

(2) $F(\omega) = k_2$; for $|f| \leq .1\,fm$
$= .01k_2$; for $0.1\,f_m < |f| \leq fm$
$= 0$ otherwise

(3) $F(\omega) = k_3 \exp(-25\,f^2/fm^2)$; for $|f| \leq fm$
$= 0$ otherwise

(4) $F(\omega) = k_4 \exp(-5\,f/fm)$; for $|f| \leq fm$
$= 0$ otherwise

(5) $F(\omega) = k_5(1 - f/fm)$; for $f \leq fm$
$= 0$ otherwise

(6) $F(\omega) = k_6$; for $|f| \leq fm$
$= 0$ otherwise

(*d*) The sampling rate is 5 times the high-frequency component: $fs = 5\ fm$.

(*e*) The limits of the tolerance band, L_1 and L_2, are respectively K_1 and K_2 times the full scale of the input signal range.

The results of the calculations are shown in Fig. 7.

It appears that in a majority of space experiments in which significant changes are allowed to be 2 to 5 percent of full-scale amplitude, data compression ratios of the order of 20 to 40 can be expected.

Design of the Data Bandwidth Compressor. Figure 8 shows a logic diagram of the data compressor under consideration. The approach is based on comparing the value A_i, which is the current sample of the *i*th data channel, with the last transmitted sample of that channel, B_i, to see if the difference lies within tolerance limits L_1 and L_2. If a significant change has been observed, i.e., if

$$A_i > B_i + L_1 \qquad \text{or} \qquad A_i < B_i - L_2$$

the sample A_i will be transmitted and will be stored for reference for the next comparison. If a significant change has not been observed, A_i is discarded and B_i is used as a reference for the next comparison.

Since the samples to be transmitted now occur at random time intervals, it is necessary to store them temporarily in a buffer prior to transmission. The purpose of the buffer is to convert the random rate of arrival of data to be transmitted to a uniform rate approximately equal to the average of the arrival rate. Thus, bandwidth compression is achieved by temporarily storing samples to be transmitted (which potentially can arrive at a rate equal to the sampling

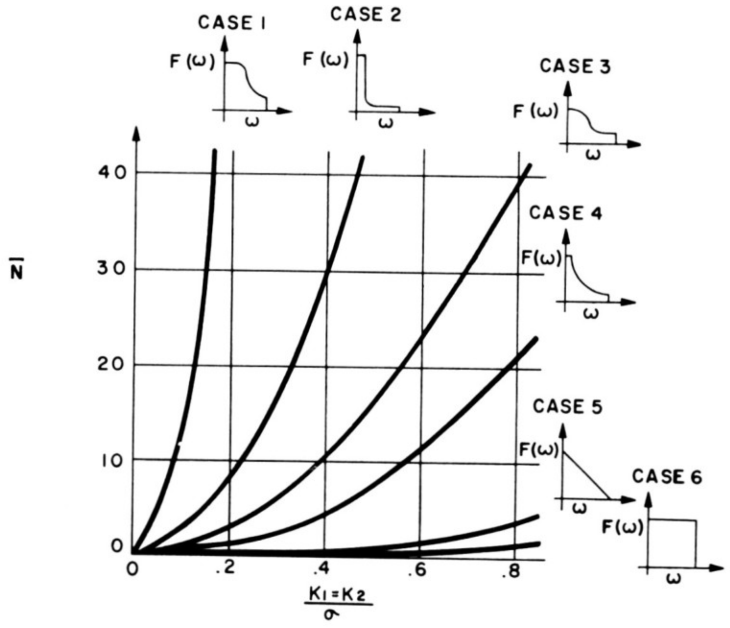


Fig. 7. Compression ratio for several spectral densities.

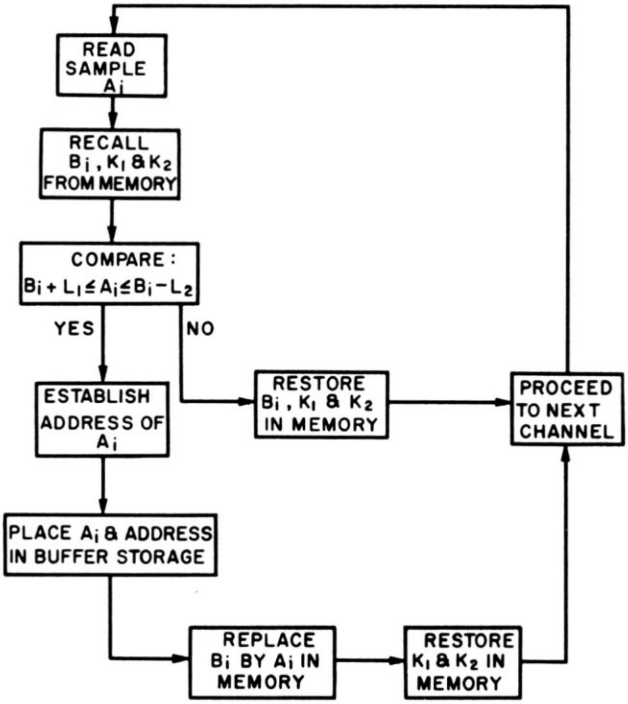


Fig. 8. Data compression logic design.

rate) and transmitting them at a much lower uniform rate. Since the buffer introduces a variable delay prior to data transmission, the identification of the data source has been lost. This necessitates attaching an identifying address to each sample as it is entered into the buffer. The size of the buffer memory can be determined from queueing theory considerations.

A block diagram of the data compressor is shown in Fig. 9. The operation can best be described by following the processing of a particular data point. The analog input is sampled by the multiplexer and applied to the analog-to-digital (A-D) converter, where it is converted to a 10-bit word. The digital word is then transferred in parallel from the A-D converter to the A register. The address counter is also advanced by one count. Simultaneously, the data from memory row "i" is transferred to the B and K registers. This information contains the last "significant" data from channel "i" plus the deviation constants (K_{1i} and K_{21}) corresponding to this data point.

The old data B_i and current measurement A_i are now fed to the comparator where B_i is serially subtracted from A_i and the resulting word scanned under the control of K_{1i} and K_{2i} to determine the magnitude of difference. If the two words are identical prior to subtraction, an all-zero word will occur. Otherwise, a binary word, corresponding to the magnitude of change, will appear. The polarity of change (increase or decrease) is determined from the state of the most significant bit.

Tolerance band constants K_{1i} and K_{21} select, respectively, the positive and negative ranges or octaves of magnitude over which agreement of A_i and B_i must occur for a sample to be considered redundant. These may be assigned as unequal numbers if an asymmetric tolerance band is desired. With a three-bit word to describe each of the K's, tolerance bands from ±0.39 percent to ±50 percent may be selected.

At the end of the check, a decision will have been made as to whether the data being processed is "redundant" or "significant." If the data is redundant, A_i is discarded and B_i is transferred to the write register to be restored to memory. If the data is significant, B_i is discarded and A_i is transferred to the write register to be transferred to memory and also to the buffer (along with the identifying address from the address counter) for subsequent transmission. In either case, the constants are restored to memory.

This cycle is repeated for each of the data points. The amount of transmission resulting or the actual "redundancy reduction" achieved is a direct function of the constants assigned to the various data points.

A data compressor, by its very nature, must process many more samples than the number requiring transmission. The buffer is designed to handle temporary intense activity; but the average input rate must not exceed the average output rate for a prolonged time, otherwise the buffer will overflow and data will be lost.

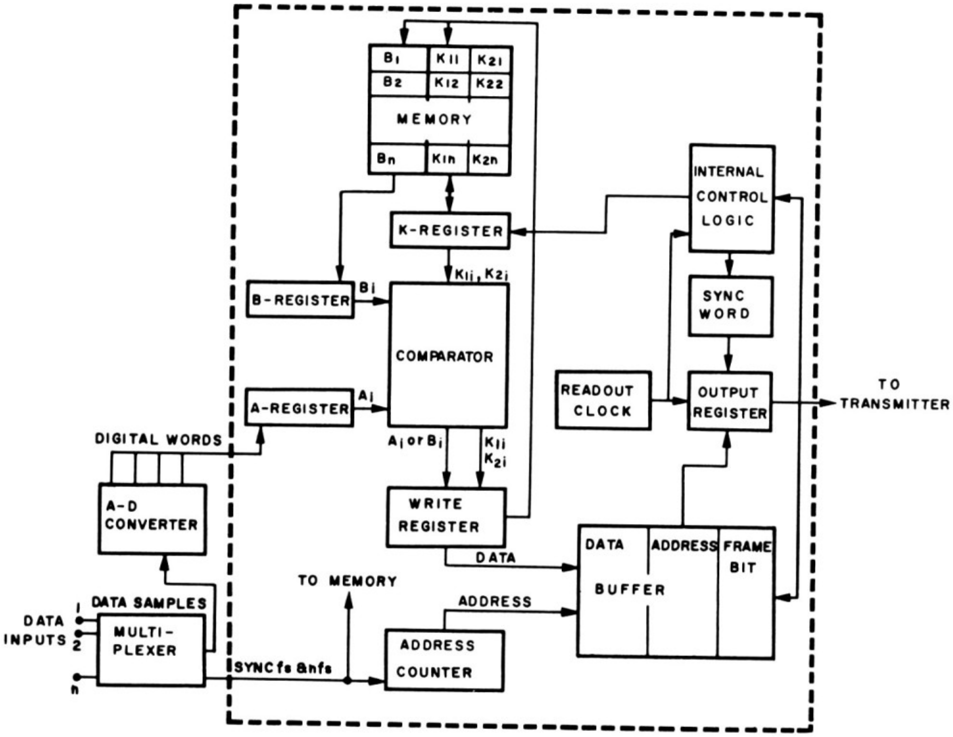


Fig. 9. Block diagram of data compressor.

The buffer size must be selected to match the expected data and system sampling and output rates. Even though the buffer may normally be well selected, unusual sporadic conditions may still cause it to overflow temporarily unless some provision is included to prevent this condition. Imminent overflow is indicated when the buffer write selector begins to overtake the read selector. An overflow "alarm" may be generated by a continuing analysis of the buffer read and write counters. When the alarm occurs, the average buffer input rate may be curtailed or else the output rate increased (assuming the transmission increase requirement can be tolerated).

Input-rate control may be imposed either by temporarily imposing the priority selection feature or by increasing the tolerance limits (K_1 and K_2) on all measurements in the data processor. The latter correction may be achieved by categorically ignoring the least significant bits of K_1 and K_2 during the data processing cycle. Through minor design modifications in the particular logic mechanization, any combination of these control features may be obtained.

CONCLUSIONS

As shown in the preceding discussion, digital techniques found extensive applications in space communications systems. Their use improved the inherent accuracy of data transmission, increased the system flexibility and efficiency, and contributed to the simplification of equipment design.

The importance of communications to the progress of space exploration will require continued efforts toward improvements in communications techniques in which more sophisticated applications of digital methods will arise.