AN INTERPLANETARY COMMUNICATION SYSTEM

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Summary

Exploring of space by means of space probes poses some challenging problems if all useful data acquired at the probe's location is to be made available on earth. There exists a monotonic relationship for every communication system between the received energy required per unit of received information The quantity of received data can be increased by an increase in the received energy or more subtly by varying this monotonic relationship through the choice of a more efficient communication system. Proper screening and processing of data before their transmission can increase the amount of useful information received at the expense of other data not so valuable and can ease ground data handling problems. A telemetry system, entitled Telebit, which makes use of some of these principles, and which is a forerunner to the application of others, is described.

Introduction

The purpose of this paper is to discuss a communication system suitable for transmitting information over interplanetary distances. The particular system described is applicable to very long ranges, it minimizes the airborne power and weight required, and utilizes the effective channel capacity efficiently. These objectives are dictated by the inherent limitations of the vehicles available for deep space probes.

The central consideration in all communication systems is the kind and amount of information to be transmitted. The kind of information depends in large measure upon the source and, as the following examples indicate, it is possible by selection to control, to some extent, the form of the information of the messages to be transmitted from satellites and space probes. The amount of information must be tailored to the channel capacity of the communications system and, for many scientific purposes, may be varied without much loss in the utility of the experiment. For instance, the size of the diaphragm on an impact sensing micrometeorite detector may be reduced until the actual number of impulses per second is adjusted to the available bandwidth. Or, in the case of a scintillation or Geiger counter, appropriate scalers may be inserted so that the final output counting rate is a small, but known, fraction of the input rate. This type of system has, in addition, the possibility of easily varying the output rate by switching the number of divider stages. In case there is a requirement for transmitting pictures, the effective bandwidth and information rate may be reduced by sampling techniques.[1]

Another kind of information is obtained from the various monitors of the performance of the equipment in the vehicle. In this case, the information rate is usually very low, and it is possible, by subcommutating, to transmit a very large number of measurements over a very narrow bandwidth. Thus, it is possible by relatively simple means to adjust the information rate for physical measurements to the available channel capacity of a space communication system. On the other hand, there is only a limited possibility of reducing the bandwidth of real time voice channels even though the information rate for this service is small, since here there is a real limitation on the efficiency of encoding represented by our vocal cords. Since voice or video transmission characteristics are not easily modified, and since the weight limitation on equipment is likely to persist for some time to come in space vehicles, the probability of achieving real time voice or video communications at interplanetary distances is rather low.

Basically, interplanetary communications suffers from trying to achieve two mutually incompatible objectives. On the one hand, there is the desire to transmit as much information as possible. On the other hand, there is the necessity to conserve weight with the resultant fundamental limitation on transmission time and information rate. As may be seen from Figure 1, the bandwidth is extremely limited even at fairly short interplanetary distances and for very large antennas. This limitation upon bandwidth sets the channel capacity and thus the information rate which can be transmitted. This figure also demonstrates that an essential characteristic of an interplanetary communication system should be flexibility in bandwidth, so that when the vehicle is at close ranges, its bandwidth can be large while at long ranges its bandwidth may be narrowed. Figure 2 is an alternative presentation which shows signal-to-noise ratio as a function of range for three different antenna sizes and illustrates the very low signal-to-noise ratios which exist even for very narrow bandwidths and relatively high transmitted powers in the vehicle.

Figure 3 shows the required diameter of a ground antenna as a function of range for various effective output powers in the satellite. As may be seen, even if very large effective airborne powers are assumed, extremely large ground antennas are required. Because weight and size are extremely limited in space vehicles, it is both desirable and necessary that the power supply be kept to an absolute minimum. The weight of the airborne power supply can be minimized not only by increasing the gain of the ground and the airborne antennas but by limiting the duty cycle of the transmitter. If during the off-time of the duty cycle batteryies may be charged, relatively high peak output powers may be achieved.

As is also shown in Figure 3, better signal-to-noise ratios may be achieved for a given ground antenna size by use of a maser or parametric amplifier in the ground receiver. The amount of improvement, however, is more limited than is generally realized, and these devices will probably not result in appreciable increases in the maximum information rate or distance for satellite communication (see Figure 4). A more direct improvement is the use of variable receiver polarization. This is dependent on a knowledge or measurement of the plane of polarization of the received signal, but with relatively simple equipment, it will produce a 3 db increase in signal-to-noise ratio.

In the Pioneer series of lunar satellites, an FM/PM analog telemetry system developed by Jet Propulsion Laboratories was used. This "Microlock" system uses a phase-locked receiver to achieve a lock-on sensitivity of -150 dbm with a 10-cycle locked-loop bandwidth. There are six subcarriers with a theoretical modulation bandwidth of 0.8 cps, although in practice, because of subcarrier drift and the dynamic characteristics of the subcarrier discriminators, there have a realizable information bandwidth of only about 1/100 cps. As was demonstrated, this system has the necessary sensitivity to operate to lunar distances with a transmitted power of about 100 mw. The combined total information rate for the six channels is about the equivalent of 0.5 bits per second. The disadvantages of this system are:

1. The information bandwidth is fixed.
2. The practically achievable channel efficiency is low.
3. Since the system is not quantized, it suffers degradation on retransmission or rerecording.
4. The information must be transmitted in real time.

In an attempt to overcome these disadvantages, a digital telemetry system called "Telebit" has been developed which will, for lunar distances and the same 100-mw power, permit the transmission of 8 bits of information per second, or, on command and for transmission at greater or lesser distances, to change power and to transmit either 1 bit or 64 bits per second. In addition, with airborne analog-to-digital converters, the information is quantized and digitalized, so that once a message is received, it will not be degraded by retransmission over communication links to the central station. The Telebit system provides, in addition, a transistor memory for storing the output of the experiments, so that intermittent transmission of the data is possible.

A quantitative comparison of the Pioneer I and II "Microlock" and the "Telebit" system with the ideal communications system described by Shannon leads to the following expressions.*

$$\beta = \left(\frac{S}{N}\right)\frac{B}{H}$$

where β is a figure of merit[2] based on Shannon's theorem

$$H = B \log\left(1 + \frac{S}{N}\right)$$

where H is the information rate in bits/second, B is the channel bandwidth, and (S/N) is the signal-to-noise ratio.

For an ideal system where the transmission channel bandwidth is infinite, the figure of merit

$$\beta_o = 0.693 \ .$$

For the case of the "Microlock" system used in Pioneer I and II

$$\beta = 43.5$$

or

$$\beta/\beta_o = 18 \text{ db}$$

while for the Telebit system

$$\beta = 4.5$$

or

$$\beta/\beta_o = 8 \text{ db}$$

It is interesting to note that this latter figure is as good as the best quantized system described by Saunders in his study and appears to approach the best physically realizable modulation system.

The following paragraphs describe the Telebit system and detail its operating characteristics.

Telebit System

General

Basically, Telebit is a digital telemetry system which provides for transmission of information from space probes to the ground and presents the information in a partially processed form. The payload portion of the Telebit system accepts information from both analog and digital experiments and processes this information until it is in a form suitable for transmission. The

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* See Appendix A.

ground portion of the Telebit system consists of several stations located throughout the world where payload transmissions are received and easily relayed to a central processing station for rapid processing and presentation. The payload portion of the Telebit system permits accumulation of information during long periods when nothing is being transmitted. It also cummutates several types of input information so as to produce a time multiplexed train of pulses containing information about a variety of experiments.

The Telebit system accepts inputs from a variety of experiments measuring such quantities as micrometeorite impacts, magnetic field strength and direction, quantity and energy levels of radiation particles and such environmental parameters as temperatures and supply voltages. These experiments can be divided into two classes. The first class consists of information in the form of the occurrence of an event or events. Typical of this class are micrometeorites and radiation particles. The second class consists of analog inputs where the variable to be measured has a continuous function of time and can take on a value anywhere between two prescribed limits. Information from the digital type of experiment enters the Telebit system as a pulse whenever an event detected by the experiment occurs. Analog information, on the other hand, enters the Telebit equipment as a voltage which can vary between specified limits and which bears a direct relationship to the quantity being measured.

Power considerations have set bounds on the time during which information can be transmitted to the ground and upon the period between such transmissions during which batteries are recharged. Sufficient time exists during each allowable transmission period to permit a read-out of each primary experiment two or three times. The Telebit system has been designed with the intent of optimizing information accumulated during transmitter "off" times while permitting maximum information transmission during the brief "on" times. A careful review of the high energy particle experiments indicated that 10 primary digits would adequately accumulate the number of events during the transmitter "on" time.

The micrometeorite experiment is an example of the use of a word which has been broken into two subwords. This experiment detects the number of micrometeorites striking an aluminum diaphragm at two momentum levels. The expected frequency of impingement of the high momentum micrometeorites is less frequent than the frequency of impingement of low momentum micrometeorites. Thus, three pulses of a 10-bit word are used to convey the number of high level hits and the remaining seven pulses convey the number of low momentum hits.

Analog information does not directly lend itself to any simple means of accumulation. The experimenter must thus be content with obtaining analog information only during transmitter "on" periods. Provision has been made, however, within some of the experiments to provide for changes of scale as a function of the quantity being measured. An analysis of the accuracy with which analog information is obtained indicated that most primary experiments could be adequately described by six bits while some secondary experiments can be characterized by four bits. By grouping a six-bit experiment with a four-bit experiment, a word of 10 bits is derived. Conversion of the analog data to digital form is accomplished in an analog to digital converter which makes use of a 64 level digital ramp.

In addition to its function of accumulation and analog to digital conversion, the Telebit system commutates the successive experiments and thus derives a sequence of pulses which in groups characterize these experiments. The information conveyed during each commutated segment is called a "word" and the sequence of all words is called a "frame." While the number of pulses which comprise a word could take any value, a Telebit word is composed of 10 information pulses. Similarly, the number of words which compose a frame is determined by the number of experiments. The Telebit system includes 10 information words.

In addition to the information pulses of each word and the information words of each frame, synchronizing symbols are inserted to ease the decommutation problem on the ground. Two synchronizing pulses always having the same form are added to each word and one synchronizing word is added to the set of each frame. Thus, an entire word consists of 12 pulses and an entire frame of 11 words.

Inasmuch as it is desirable to vary the information transmission rate as the range to the payload changes, three pulse rates were provided, one, eight, or 64 per second. For these rates it takes approximately two seconds, 17 seconds, or 132 seconds to transmit one frame.

A number of experiments which measure the payload environment and condition such as temperatures and voltages are very slowly varying and thus a measurement every 16 frames is all that is necessary to characterize them to the accuracy required. Therefore, one of the analog words has a 16 element subcommutator associated with it. This subcommutator has the capability of selecting in sequence any one of 16 slowly varying quantities. Thus, at the three transmission rates it will take approximately 1/2, 4-1/2, or 35 minutes to complete an entire subcommutator cycle.

In investigating possible methods of transmitting a sequence of binary digits to the ground, many possible approaches were considered. The system finally adopted was chosen for its simplicity, its reliability, and for its proven performance. The telemetry information is biphase modulated on a subcarrier which is used to phase modulate the radio frequency carrier. This technique has the advantages of providing a continuous carrier for acquisition and tracking from the ground and an unambiguous resolution of the pulse data through the use of an adjacent pulse comparison biphase demodulator without a ground coherent oscillator. A disadvantage of this technique is an approximately 6-db loss in signal-to-noise ratio because of the limited subcarrier modulation power.

Telebit Components

Shifting Accumulator. The principal component of Telebit is the shifting accumulator. There is a shifting accumulator for each of the 10 information words in each frame. Each shifting accumulator serves a dual purpose; that of storing as a binary number the input data from the experiments and then, by using the binary scaler as a shift register, delivering the stored binary data in sequence to the biphase modulator to be transmitted to the ground. Each shifting accumulator consists of 12 binary scalers with associated gating circuits and blocking oscillators which function as pulse generators. Ten of the binary scalers, corresponding to the 10 bits of information associated with each word, are connected in three groups having four, three, and three scalers in each group. Each shifting accumulator can accept inputs from one, two, or three experiments. A blocking oscillator is used to drive each of the three groups of binary scalers. The first group of four binary scalers, together with its program gating and associated blocking oscillator, produces one output pulse for every 16 input pulses and each group of three produces one output pulse for every eight input pulses. The printed circuit board which collects the binary scalers and gating circuits are designed to connect by appropriate jumpers the output of the first group of four binary scalers either to the input of the second group of scalers or directly to its own input. Similarly, if desired, the output of the second group of scalers can be connected to the input of the third group of scalers. Connected in the former manner, the entire shifting accumulator would function as a unit and have a discrete state for any number of pulses from zero to 1023. If two subwords are desired instead of a single word, rearrangement of the jumpers mentioned previously permits a second experiment to be entered into the shifting accumulator at the start of the second or the third group of scalers. Thus a 4/6 or a 7/3 split in the word can be obtained. Similarly it is possible to divide or split a word into three subwords. The remaining two binary scalers contain word synchronizing information and do not connect in the binary scaling chain. Reset pulses are delivered to these scalers during each word interval.

Program gating at the input to each binary scaler includes an "or" gate, such that pulses arriving at one input cause it to function as a binary scaler, while pulses at the other input cause it to function as a shift register. Thus it can receive either binary scaling pulses or shifting pulses. When binary scaling pulses are received, the unit performs as a binary scaler whose state represents the number of input pulses received, while if shift pulses are received, the unit performs as a shift register. A pair of reciprocal gates in the binary scaling line and in the shifting line insure that the unit cannot both shift and scale simultaneously.

For those shifting accumulators whose input information content is the occurrence of an event and whose output consists of a binary sequence characterizing the total number of such events, it is desirable to make the shift register mode of operation recirculating. In this case the shift output pulses, in addition to being delivered to the modulator, are returned to the first stage of the shift register. Thus after 12 shift pulses have been applied, the state of the shifting accumulator is exactly the same as before the shifting began and the succeeding scaling pulses will add to the previous total.

Eleven-Place Commutator. The purpose of the 11-Place Commutator is to readout the shifting accumulators sequentially. The 11-Place Commutator consists of 11 flip-flops, their associated gating circuits and blocking oscillators. Flip-flops are interconnected with gating modules so as to form a pseudo shift register. Gating circuits are designed so that a "1" occurs at only one spot in the 11-Place Shift Register and such that a "1" is inserted in the leading element when and only when all other elements contain zeros. The output of the normally zero side of each flip-flop is connected to the gate in the corresponding shifting accumulator which admits shift pulses. The normally "1" side of each shifting accumulator which admits pulses to be accumulated. Thus, only one shifting accumulator at any time is in its shifting phase while all other shifting accumulators are in the accumulation phase. The pulses which drive the 11-Place Commutator are a biproduct of the stair-step generator which is discussed in a later section.

Master Timer. The pulses which control the operation of the 11-Place Commutator and the shifting and reset functions of the shifting accumulator, originate in a programmer which is in turn controlled by pulses generated in the master timer. The heart of the master timer is a tuning-fork resonator which in conjunction with a transistor amplifier forms an oscillator which produces a 1024 cps square wave. This square wave is differentiated and applied to a blocking oscillator whose output consists of a train of pulses occurring at 1024 pps. Also contained in the master timer is a second amplifier containing a bandpass filter whose output is a 1024 cps sine wave. This sine wave, after passage through the biphase modulator, becomes the telemetry subcarrier.

Programmer. The Programmer accepts the 1024 pps train of pulses from the biphase modulator and delivers it to the input of a sequence of binary scalers. These are grouped to produce trains of pulses at repetition rates of 128 and 16 pps. These two pulse trains together with the original 1024 pps are delivered to three gates whose outputs are common. By selecting one of these three gates, the speed of the system can be programmed to yield output rates of one, eight, or 64 bits per second. The output of the triple gate after regeneration of blocking oscillator is delivered to a circuit which divides the pulse repetition rate by 16 to become the shift pulses for the 10 shifting accumulators and to a circuit which divides it by three to provide the drive for the stair-step generator.

Stair-Step Generator. The Stair-Step Generator serves two purposes; that of generating the 64-element digital ramp for use in the analog-to-digital converters and the division of the incoming pulse repetition rate by 64 for delivery to the 11-Place Commutator. It should be noted that the ratio of the total frequency division in the divide by "3" circuit and the stair-step circuit and the divide by "16" circuit is precisely 12. Thus, the requirement that each state of the ring of the 11-Place Commutator admits precisely 12 pulses to the appropriate shifting accumulator is fulfilled.

Each of the six flip-flops associated with the divide by "64" circuits is associated with a gate which applies a uniform amplitude square wave of voltage to one of six inputs to a resistive summing network. The waiting factors for each input of the summing network differ in factors of two. Thus the output of the summing network is at a voltage whose magnitude is proportional to the binary number characterized by the state of the divide by "64" circuit and, as pulses are applied and the divide by "64" circuit goes through its binary scaling operation, a 64-element stair-step function is generated at the output of the summing network. After passage through a gain stabilized emitter follower circuit, the digital ramp is delivered to the comparator circuits. In addition, the train of pulses entering the divide by "64" circuit are delivered to the comparator so that one pulse exists for each step of the ramp.

Comparator. The purpose of the Comparator unit is to accept each of several input voltages from analog experiments and to deliver a number of pulses proportional to each analog voltage.

The conversion is accomplished by applying the input voltage whose value can lie between zero and three volts and the output of the stair-step generator, which passes through all voltages in the same range, to a circuit which emits a gating signal as long as the voltage of the experiment exceeds the voltage of the ramp. This gating signal is used to open a gate between the pulses emerging from the stair-step generator and the shifting accumulator. Thus in the case of the 64-pulse-per-ramp output of the stair-step generator, one pulse will pass into the shifting accumulator for every step of the ramp lying below the input signal. The "ring of 11" commutator provides an input to the controlled gate so that analog-to-digital conversion is accomplished only once each frame and this during the word just preceding its own transmission. The shifting accumulators associated with analog experiments do not recirculate during readout, but rather dump their information so that the shifting accumulator starts from zero at the beginning of each conversion. Four shifting accumulators are used to store analog information. Thus four 6-bit analog words and four 4-bit analog words are available. The digital noise generated in the 64-pulse comparison is less than two per cent of band edge to band edge, while the digital noise generated in the "16" pulse comparison is less than seven per cent and is adequate for some less critical experiments.

Subcommutator. The input to one of the 6-bit analog-to-digital converters comes from a 16-place subcommutator. The purpose of the subcommutator is to sample many slowly varying quantities largely having to do with performance of the payload, such as temperatures and voltages. The subcommutator is constructed from 16 flip-flops using the same logic as is contained in the "ring of 11" commutator. As the subcommutator goes through its 16 steps, one of a series of 16 gates is opened to allow the signal from its associated sensor to enter the analog-to-digital converter. The subcommutator is stepped once each frame so that 16 frames are required before the subcommutator cycle is complete. A secondary function performed by the subcommutator is the generation of a 16-step digital ramp, which is applied to the 4-bit portion of the word associated with the subcommutator to identify the segment of the commutator being sampled.

Packaging. The philosophy of packaging adopted for the system was based on making foam potted rectangular modules of all basic circuit elements. Two basic sizes were chosen for all modules as shown in Figure 5. The leads of each module were passed through holes in a printed-circuit collector board to form subassemblies such as shifting accumulators, programmers, stair-step generators, and comparators. Magnesium blocks were used to clamp the modules together and to interconnect the subassemblies to form an entire digital telemetry unit as shown in Figure 6a and 6b. The Telebit system installed in its shielding container is shown in Figure 7.

The Future of Telebit

The present Telebit system is the first step towards the full utilization of digital techniques in the development of fully automated communications systems for deep space probes.

Two promising avenues for further investigation are the use of biphase modulation of the carrier with a resultant signal-to-noise improvement of approximately 6 db and the use of multiple bit encoding techniques which should further improve the modulation efficiency. In addition to these fundamental changes, it is possible, by changing the logical design of the system, to decrease the weight and power requirements. Such changes in logical design become more desirable as the quantity of information to be transmitted from future payloads increases. By these means it appears possible to more closely approach the theoretical limits on channel capacity.

Another general area of improvement in the Telebit system involves expanding analysis or processing of the experimental data before transmission. For example, in the present Telebit system, the micrometeorite count is stored for a period of 6 to 10 hours and thus the resulting transmission from the satellite to the ground provides an average rate for a six-hour period and then, as the experiment is read out again, the average rate for a 2-1/2-minute interval. A relatively simple change in the digital circuit logic would permit one to record during the six-hour period the maximum counting rate that occurred in any one of the 2-1/2-minute intervals, the minimum counting rate that occurred in any of the 2-1/2-minute intervals, the time at which these maximum and minimum rates occurred, in addition to the average count for the entire six-hour period. By the skillful application of such satellite data processing, considerable increases in the amount of information obtained from the experiments can be achieved without appreciably increasing the requirements on the total information channel capacity.

Finally, as data is accumulated, the experimenter will be better able to define the steps required for the analysis of the data. At this point it will be possible to program the central computer to accomplish the mechanical part of the data analysis in addition to its normal task of data reduction. This ability to approach the ideal of real time analysis of experimental data is perhaps the most important single characteristic of the digital telemetry system.

Conclusion

The utilization of digital techniques in the Telebit system provides five present and potential advances in the art of scientific space communication. These are increased:

Efficiency. Digital encoding techniques provide a nearly ideal modulation technique. Telebit itself is less than 10 db above the Shannon limit on the required energy per bit of information.

Accuracy. Digital encoding at the source is the first great step towards improving transmission accuracy. Optimum redundant encoding will make possible virtually error free transmission where channel bandwidth is available. Finally, data reduction and analysis by direct reading into and use of the digital computer will minimize human errors in the final processing of data.

Flexibility. Data processing before transmission, changes of scale and accuracy of readout, addition, subtraction, or rearrangement of experiments are all facilitated or made feasible by the digital system.

Speed. The time required for data gathering and data reduction are greatly reduced in the Telebit system. Ultimately, it is possible to provide a continuous and automatic flow of data from the experiment through the entire communication network to the computer which collates, selects, and analyzes the experimental and position data and presents the results in graphical or tabular form.

Economy. The elimination of human intervention in the flow of information from experiment to its ultimate presentation with the attendant increase in data handling capability is a most important step on the way to the economic utilization of the experimental data garnered from our unmanned space laboratories.

Acknowledgement

The Telebit system would not have been possible without the creative efforts of our colleagues and particularly the work of R. E. Gottfried. The paper itself is due in large measure to the unstinting effort of R.A. Park.

Appendix A

The following section derives relationships showing the communication efficiency of a single channel FM system using a phase-lock discriminator and a single channel Telebit system. To arrive at these expressions, certain assumptions are required which may not necessarily be equivalent in the two cases. However, the form of the resulting expressions is correct even though the values of certain constants may vary with the assumptions. Both the systems can be described by the same block diagram as shown in Figure 8. To make the systems equivalent, information is considered to pass through a low pass filter which limits its maximum frequency to a value ω_i. In the case of the frequency modulated subcarrier, the encoder consists of a voltage-controlled oscillator which translates the varying input voltage to a varying output frequency. In the case of the Telebit system, the encoder consists of an analog-to-digital converter followed by a biphase modulator. The channel bandwidth is defined as the minimum-width bandpass filter which can be inserted between the encoder and the decoder without loss of information. Noise of uniform-spectral-density is assumed to be added to the signal in the channel. The decoder for each of the two systems inverts the process carried out in the encoder. Furthermore, to make the two systems equivalent, it is assumed that N + 1 distinguishable levels of information are to be transmitted. That is, with a reasonable possibility of success, the data user should be able to tell which one of the N + 1 possible levels was transmitted.

FM Telemetry System

To avoid duplication in the derivation of certain equations, this section follows the notation and uses several results derived by Jet Propulsion Laboratories.[3] For ease in reference, the equations which are used are summarized here:

$$\Phi = \frac{\Phi_c}{S} \qquad (1)$$

$$\epsilon_m = \frac{\Delta\omega \cdot \omega_i}{2 B_o^2} = 0.35 \text{ radian} \qquad (2)$$

$$\begin{aligned} 1.06\, B_o &= 2\, B_{1o} \\ &= \text{Loop Noise Bandwidth} \qquad (3) \end{aligned}$$

$$\begin{aligned} 2\, B_{1o}\, \Phi &= \left(\frac{N}{S}\right) 2\, B_{1o} \\ &= \text{Loop Noise-to-Signal Ratio} \\ &= 0.4 \qquad (4) \end{aligned}$$

$$\sigma_f^2 = \frac{\Phi B_o^3}{2\sqrt{2}} \qquad (5)$$

Equation (1) expresses the phase-noise spectral density (Φ) as a function of the channel-noise spectral density (Φ_c) and the signal power (S). Equation (2) expresses the relationship between the maximum loop resonant phase error (ϵ_m) and the maximum peak-to-peak excursion of a sine wave ($\Delta\omega$) having a frequency ω_i and the loop resonant frequency B_o. The above-mentioned report also states that a 2σ confidence level is obtained if the maximum transient error is set equal to 0.35 radian and the loop signal-to-noise ratio expressed in equation (4) is set equal to 4 db. Equation (3) states the relationship between the loop resonant frequency and the loop noise bandwidth. Equation (4) is self-explanatory and equation (5) expresses the relationship between the mean square output noise, the input noise spectral density, and the loop resonant frequency. It should be noted that the dimension of σ_f is radians/second which corresponds dimensionally with the peak signal excursion $\Delta\omega$.

If it is assumed that $N+1$ levels are just distinguishable if each level is separated from the next adjacent level by one standard deviation of σ_f, a relationship between $\Delta\omega$ and σ_f will be established. This relationship is

$$\Delta\omega = N \sigma_f \qquad (6)$$

Now by combining equations (3), (4), and (5), the following relationship is derived:

$$\sigma_f = 0.365\, B_o \qquad (7)$$

Here use has been made of the fact that for a 2σ confidence level, the loop signal-to-noise ratio is 4 db.

Now equations (6) and (7) can be combined to give

$$\Delta\omega = 0.365\, N B_o \qquad (8)$$

Equation (2) can be rewritten to yield

$$B_o^2 = 1.43\, \Delta\omega \cdot \omega_i \qquad (9)$$

Now solve the system of equations (8) and (9) to give B_o and $\Delta\omega$ as functions of N and ω_i

$$B_o = 0.52\, N\omega_i \qquad (10)$$

$$\Delta\omega = 0.19\, N^2 \omega_i \qquad (11)$$

Thus if the number of levels of the highest information frequency are specified, the frequency deviation $\Delta\omega$ which should be used for minimum signal power when a 2σ confidence level has been specified, is given by equation (11). Similarly the loop resonant frequency of the phase-lock-loop discriminator used to demodulate this signal is given by equation (10).

Now, to define a figure of merit for the system, we must define the information rate H. It is clear by the use of the sampling theorem that the maximum information rate for this system is twice the highest frequency in cycles/second multiplied by the number of bits represented by the distinguishable levels. Under the assumptions made,

$$H = \frac{\omega_i}{\pi} \log_2 (N+1) \qquad (12)$$

The signal power required to convey this amount of information can be determined by the use of equations (1), (3), (4), and (10).

$$S = 1.38\, \Phi_c N \omega_i \qquad (13)$$

R. W. Sanders has chosen a figure of merit β which characterizes the system efficiency and represents the signal energy required per bit, normalized for noise spectral density. For this system

$$\beta = \frac{S}{\Phi_c H} = \frac{4.33\, N}{\log_2 (N+1)} \qquad (14)$$

By way of example, β has been computed for a system requiring 64 levels, that is $N = 63$, and for a binary system, that is $N = 1$. For these cases $\beta = 45.5$ and 4.33, respectively. Thus a system requiring 64 levels is 18.2 db poorer than the ideal and the two-level system is 8 db poorer than the ideal. It should be noted that the form of β for the FM system follows closely that of a multilevel AM system.

Telebit System

The signal power required for the Telebit system can be derived as follows: Using a PCM system, $\log_2 (N+1)$ binary pulses are required to convey $N+1$ levels of information. And by the sampling theorem, we must sample the incoming information at a rate equal to ω_i/π. Thus $(\omega_i/\pi) \log_2 (N+1)$ pulses/second must be transmitted through the channel. This requires a channel bandwidth $\Delta\omega$ as follows:

$$\Delta\omega = 2\,\omega_i \log_2 (N + 1) \qquad (15)$$

The noise in this bandwidth is

$$\frac{\omega_i}{\pi} \Phi_c \log_2 (N + 1)$$

The required signal is derived from the above and the required signal-to-noise ratio

$$S = \frac{\omega_i}{\pi} \Phi \frac{S}{N} \log_2 (N + 1) \qquad (16)$$

Now the signal-to-noise ratio that is required depends on the quality that is desired. If a 3σ confidence level is desired for each pulse, then for a biphase system $S/N = 4.5$. Putting this value of S/N into equation (16) shows that

$$S = 4.5 \frac{\omega_i}{\pi} \Phi_c \log_2 (N + 1) \qquad (17)$$

Thus, the figure of merit β for the Telebit system is found to be

$$\beta = \frac{S}{\pi_c H} = 4.5 \qquad (18)$$

This is 8-db poorer than the limit. This equation indicates that β is independent of N which is not completely true. For a more rigorous comparison, the 3σ confidence level should be imposed on each group of pulses characterizing one N bit sample taken as a whole. This imposes the requirement that the probability of success for each individual pulse must be greater than that for the group and therefore greater signal power is required. However, since this increase is based on an inverse error function, it is much smaller than the increase encountered in the FM system.

References

1. Baker, Stuart C. and John M. Kelso, "Miniature Movies of the Planets," Astronautics, May, 1959.

2. Saunders, R. W., "Communication Efficiency of Space Telemetry System," Space Electronics Corporation, Glendale, California.

3. "A Coherent Minimum Power Lunar Probe Telemetry System," Jet Propulsion Laboratories' external publication No. 610.

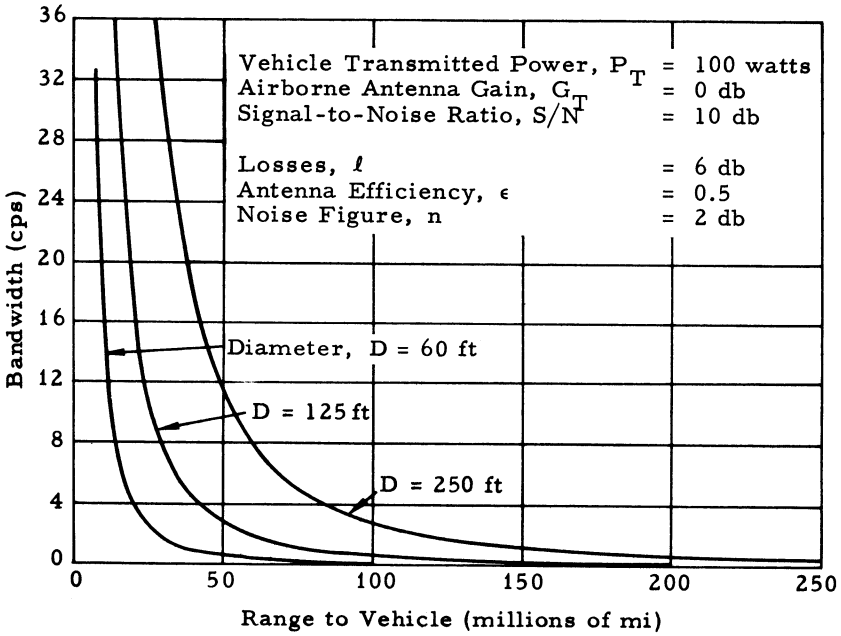


Figure 1. Bandwidth as a Function of Range for Three Ground Antenna Sizes.

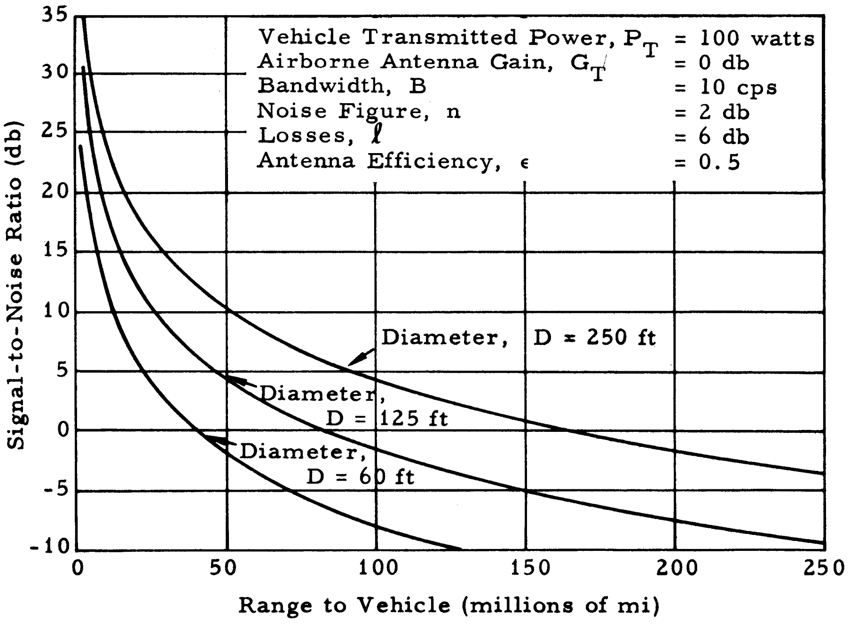
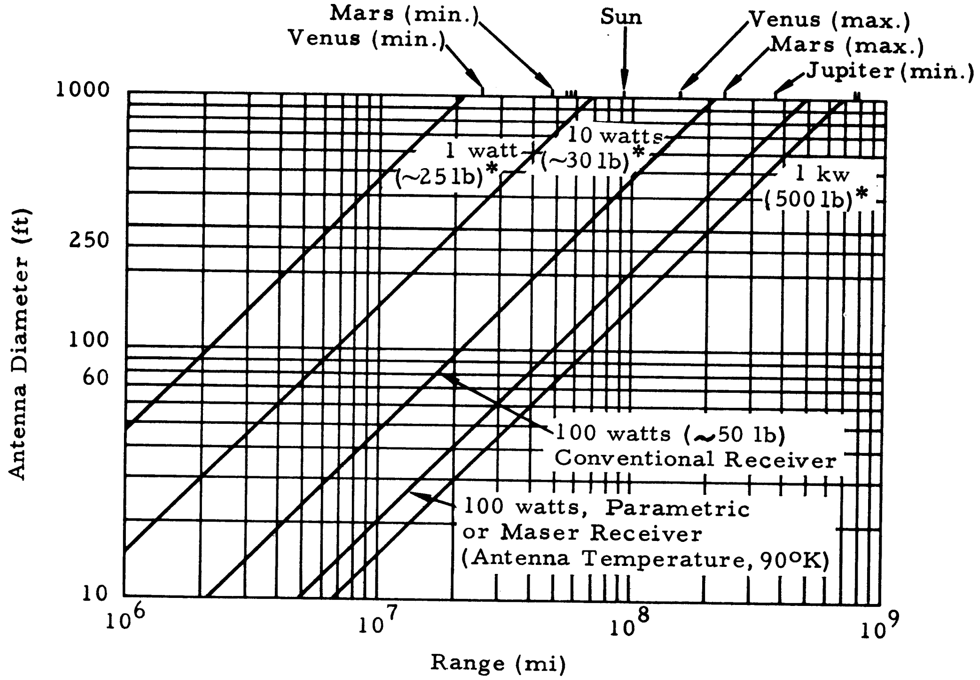


Figure 2. Signal-to-Noise Ratio as a Function of Range for Three Ground Antenna Sizes.

$kT = 4 \times 10^{-21}$ joules ($T = 300^{o}K$)
Noise Figure, $n = 2$ db
Signal-to-Noise Ratio, $S/N = 10$ db
Airborne Antenna Gain, $G_T = 0$ db

Antenna Efficiency, $\epsilon = 0.5$
Bandwidth, $B = 10$ cps
Losses, $\ell = 6$ db



*Transmitter weights include power supply

Figure 3. Antenna Diameter as a Function of Range for a Number of Transmitters.

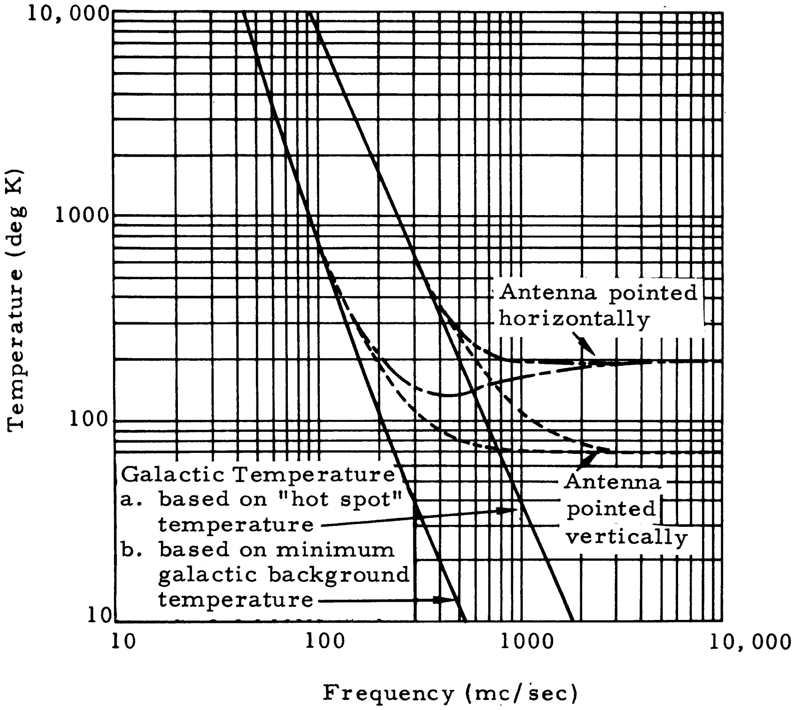


Figure 4. Equivalent Antenna Temperature Including Galactic Background, Atmospheric Attenuation, and Antenna Sidelobes. (Assumes an aperture efficiency of 0.5, that half the sidelobe energy is received from the ground, which is assumed to be a blackbody at 280°K.)

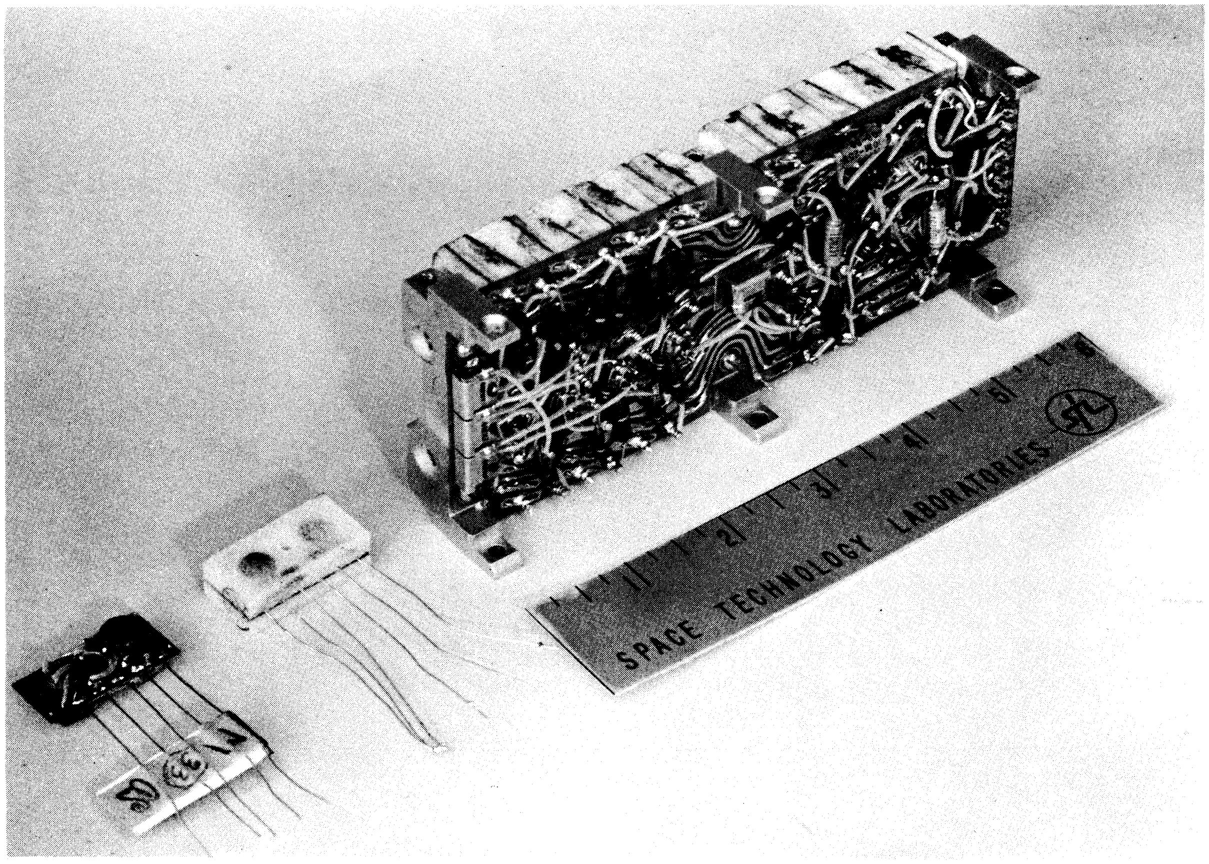


Figure 5. Modules and Breadboard.

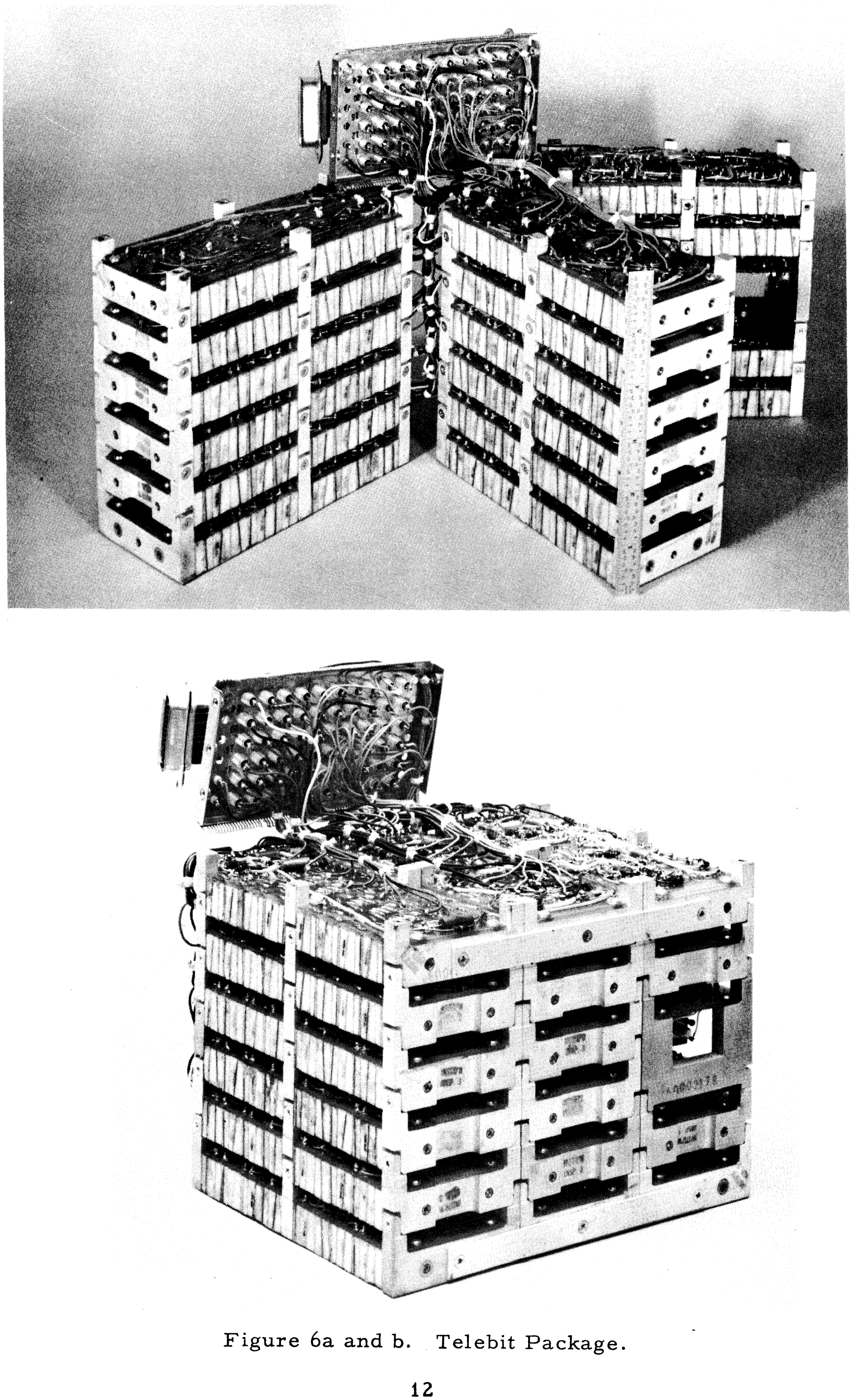


Figure 6a and b. Telebit Package.

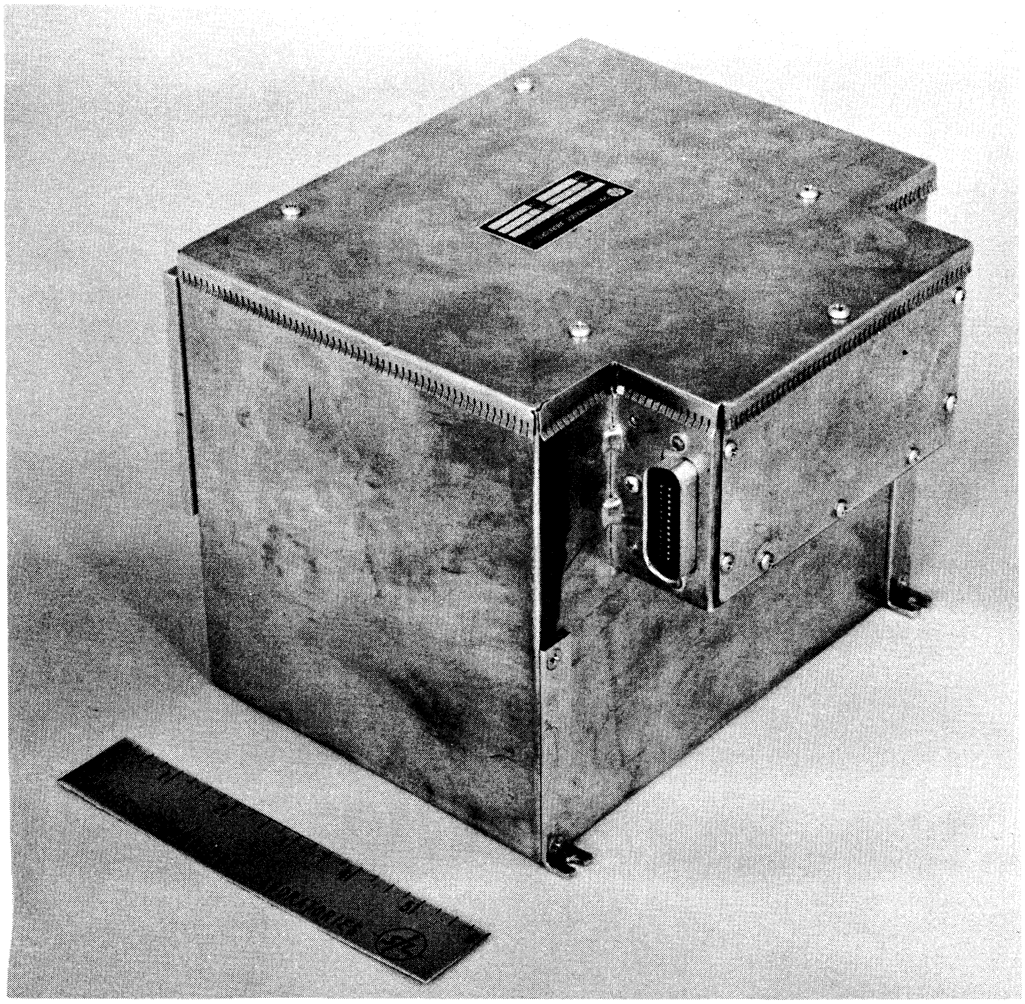


Figure 7. Telebit Flight Package.

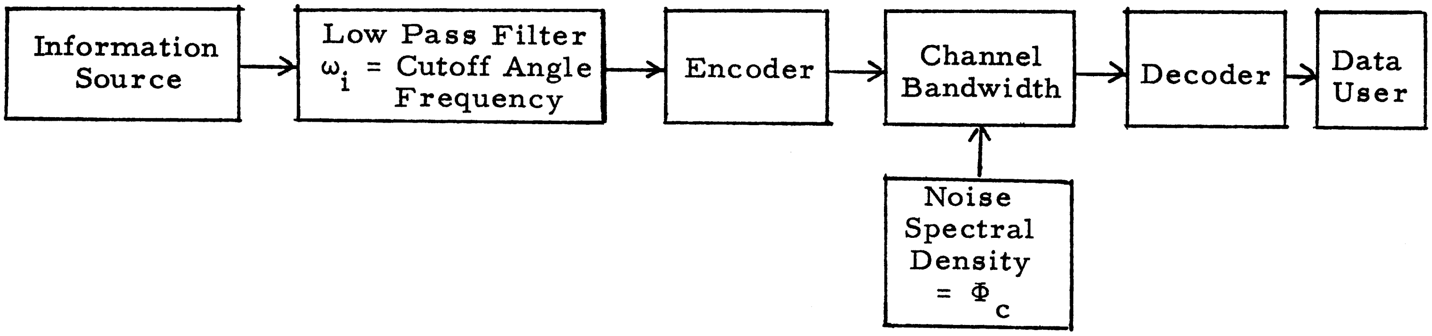


Figure 8. Block Diagram.