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THE ABLE-3 PAYLOAD INSTRUMENTATION

Explorer

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1. INTRODUCTION

By the time this paper appears in print, the Able-3 launch will have taken place, and other related vehicles will follow shortly. At the date of writing the payload has been sufficiently well defined to warrant its description nearly two months before scheduled launch.

The Able-3 payload, an earth satellite in a highly elliptical orbit, has two purposes--that of studying the space environment about the earth, and that of providing a test vehicle to evaluate components and techniques developed for use in subsequent interplanetary space probes. The four-stage Able-3 vehicle consists of a Thor first stage, an Aerojet 10-101 second stage, STL mod an ABL 248 solid propellant spin-stabilized third stage, and a spin-stabilized fourth stage or payload weighing about 140 pounds. The first three stages are used to place the payload in a large geocentric orbit whose apogee is about 20,000 nautical miles and whose perigee is about 150 nautical miles. A five-pound solid-propellant injection rocket in the payload can be used, if necessary, to increase perigee and thereby increase the payload's lifetime.

Had the design of a Thor-Able launched payload been concerned solely with studying the space environment about the earth, it could have proceeded in a rather straightforward manner and, with the exception of the number and complexity of the experiments carried, would have incorporated many features found in payloads already orbiting the earth. An already developed FM-PM telemetry system would have been used, power supply design would have been conventional, and heat control could have been handled by proven techniques. The additional requirement that the payload serve as a "flying laboratory" for the evaluation of components and techniques useful in interplanetary space probes, however, has supplemented the usual design requirements with a new and unusual group of problems. Most of the new problems which arise can be associated either directly or indirectly with the need to transmit intelligence over multi-million miles or with the severity and duration of both changing and static environmental conditions.

The range equation,

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi R)^2 L} \qquad (1)$$

expresses the functional relationship between the power received on the ground and the power transmitted in the payload, the payload and ground antenna gains, the wavelengths used, range, and losses due to polarization, diplexers, and cables. A second equation,

$$P_N = k \left[T_s + T_o (1 + n)\right] B \qquad (2)$$

expresses the noise that will be superimposed upon the received signal as a function of Boltzmann's constant, the temperature of outer space and at the receiver, the receiver's noise figure, and the bandwidth of the receiving system. The final relationships which complete the specification of the communication problem are the required signal-to-noise ratio at the receiving site as determined by the quality of data desired and the bandwidth needed as a function of the desired rate of information transmission. Moreover, this latter functional relationship varies with the degree of sophistication employed in choosing a modulation method.

definition

Any attempt to substitute realistic values of the parameters into this system of equations quickly demonstrates that a conflict of interests exists. For instance, by choosing the largest ground antennas available (i.e., the 250-foot radio telescope of the University of Manchester), the most sensitive receivers in existence today, a payload antenna gain consistent with the present state of the art, and a frequency which minimizes extraneous losses, it is apparent that only a few bits of information per second can be conveyed over interplanetary distances using a payload transmitter whose output power is as small as 100 watts. From this example two things become clear: first, the system designer must accept the need for a payload transmitter of relatively large power, together with its attendant power supply problems, and, second, any improvement in the modulation efficiency or in elimination of pre-transmission redundancy will provide a better utilization of the limited transmission rate capability.

values in equation

The high transmitted powers required, coupled with the duration o interplanetary flights, precludes the development of a payload whose power is derived solely from conventional batteries. Since the state o the development of atomic power supplies does not permit their seriou consideration at this time, the payload designer must turn to solar cell as a necessary choice for the source of primary power. The solar cel configuration, discussed later in this paper, approaches the greatest solar cell surface area which could be accommodated. It is capable of delivering between 15 and 20 watts continuously to the payload.

Early in the initial system design, a value of 150 watts of payload transmitter power was specified for use in interplanetary probes because on the one hand it appeared to be using the largest transmitter ar power supply which could be carried and, at the same time, using exis techniques and components it was sufficient to provide reliable commun tions over distances up to 55 million miles. After taking into account t efficiency of the power amplifier and of the static converters needed to develop the high voltages required, it was found that a primary power supply capable of delivering peak powers of 500 watts would be require

It is thus immediately clear that the transmitter must operate at a reduced duty cycle. This in turn implies that a power storage system capable of accumulating power over extended periods of time and discharging it at very high rates must be carried. The payload weight whi is available for a storage battery determines the maximum storage cap city and therefore the maximum "ON" time for a transmitter.

The problem of how to obtain maximum information from the scientific experiments is a consideration which arises from the transmitter duty cycle limitations. Fortunately, many of the data obtained are most meaningful in the form of events per unit time. Micrometeorite impacts and radiation particle impingements are of this type. While it is desirable to keep the unit of time at some reasonably small value, information is obtained, though with greater smoothing, even when the unit of time is the several hours between successive transmissions. Hence there is a need for accumulating the number of events as they occur and later transmitting the total to the earth.

The information content explicit in analog data, however, is so great as to preclude its storage in the payload for later transmission. The experimenter must therefore content himself with periodic spot checks of such quantities as magnetic field strength and direction and payload temperature.

Another factor implicit in the use of a low duty cycle transmitter is the need for an automatic controller or a command system capable of turning the transmitter on and off. Inasmuch as a doppler transponder was to be carried aboard the payload for tracking purposes, it was logical to decide to use the greater flexibility inherent in a command system. The command system is also used to fire the injection rocket, to change the rate of transmission of telemetered information, to turn on a simplified television system, and other functions.

Using the vehicle capabilities existing today it can be anticipated that interplanetary distances will require months to traverse. Thus, equipment designed for interplanetary space probes must have the reliability to endure unattended through the launching and for several months or even years in an airless environment while maintaining reasonable equilibrium temperature.

The Able-3 payload incorporates in its design what are felt to be adequate solutions to all of these problems. While these solutions will

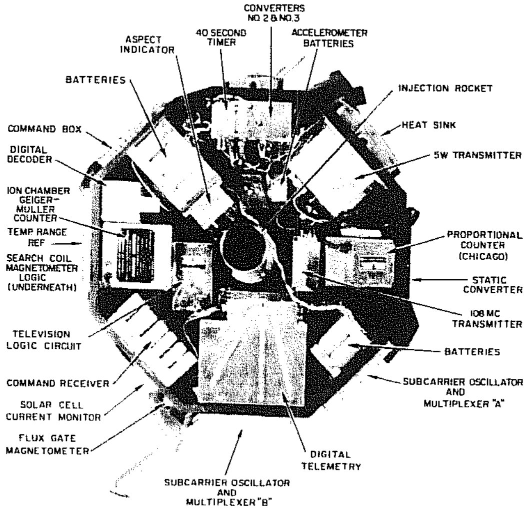
not be evaluated under actual interplanetary travel conditions, it is believed that sufficient information will be obtained to greatly increase our confidence in the success of later launching of truly interplanetary probes. Two photographs of the interior of the payload are given in Figure 1.

2. COMMUNICATIONS AND TRACKING

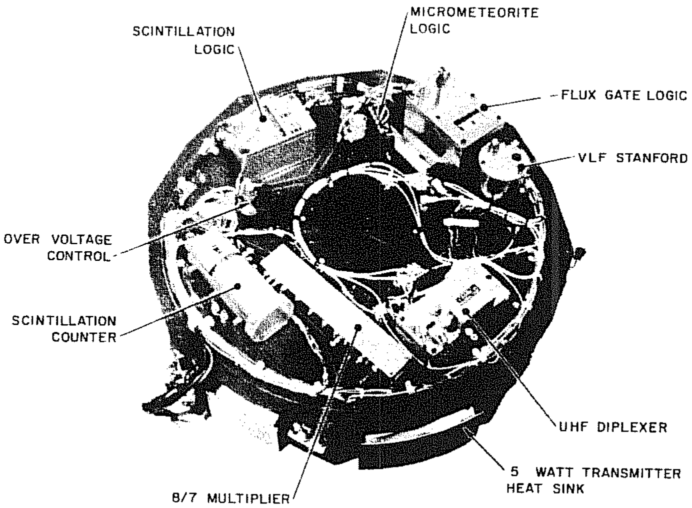
Transmitting and receiving equipment within the payload permits two-way communication. Payload transmitters convey telemetry information to the earth and a payload receiver permits the reception of earth transmitted commands. When interconnected coherently, the payload receiver and one of the transmitters form a transponder capable of providing both range and range rate information as an aid in tracking the payload.

For communication to the earth, three transmitters are employed. One transmitter accepts an r-f signal from the payload receiver, multiplies it eight times in frequency, and amplifies it to a 5-watt level. In the process the resultant signal, whose frequency is 378 mc, has been modulated with a 1024-cps subcarrier containing the time-multiplexed pulse-code-modulated output of a digital telemetry system. Biphase modulation is employed to impress the telemetry output on the subcarrier. This system when supplemented with a 150-watt power amplifier, whose development was not included for the Able-3 program, forms the basic vehicle-to-earth portion of the interplanetary communication system. The transmitter, about 3 by 6 by 1.6 inches, weighs about a pound, and has an efficiency of about 15 per cent.

Each of two transmitters conveys analog data by means of a six-subcarrier FM-PM telemetry system operating at a carrier power of 100 milliwatts and a frequency near 108 mc. The transmitters together weigh one pound and consume about 1.5 watts of power.



(Top View)



(Bottom View)

Figure 1. Internal Views of the Able-3 Payload.

Except for some vehicle performance inputs, both telemeters convey the same information, and thus the older and more proven FM-PM system can be used to monitor the performance of the new digital telemetry system.

The payload command receiver is a transistorized double-conversion, phase-lock-loop receiver which produces a coherent output at 2/17 of the received frequency. It can be operated with either a 250-cps or a 40-cps bandwidth. The receiver operates continuously and, since its bandwidth is considerably less than the frequency uncertainty of the received signal, it repeatedly sweeps over a range of 30 kc searching for a carrier. The sweep period is 10 seconds for the wide band and three minutes for the narrow band. When the receiver acquires and locks on a signal from the earth, the sweeping stops and the receiver can then accept any of 30 possible commands. A list of the 14 commands employed in the Able-3 payload is given in Table 1.

Table 1. Commands to Payload.

Commands	
1. Digital Telemetry, 64 pps	8. 108-mc Transmitter On
2. Digital Telemetry, 8 pps	9. Over-voltage
3. Television On	10. Receiver Wide Band
4. 378-mc Transmitter Off	11. Receiver Narrow Band
5. 5-watt Transmitter On	12. Clear Rocket
6. Accelerometer On	13. Arm Injection Rocket
7. 108-mc Transmitter Off	14. Fire Rocket

Note: When command 4 is given command 6 is negated and the digital telemetry is restored to 1 pps.

The digital command demodulator was developed after an extensive examination of various time and frequency multiplexed command systems. Investigation indicated that excessive weight and/or unreliability characterized each of the multiple-tone command systems capable of meeting the required bandwidth and frequency stability. The development of the digital decoder, however, required only one narrow band filter and made use of many of the components already existing in the digital telemetry system.

In the narrow band position, the receiver exhibits a sensitivity (based on a 12-db noise figure) of -140 dbm. At the present state of development, commands can be given only down to a sensitivity of -133 dbm.

Signals from the earth to the payload are transmitted by using a high-power carrier, phase-modulated with a 512-cps subcarrier. Amplitude modulation of the subcarrier using a train of 13 pulses permits the transmission of a synchronizing pulse, a simple address code, and a 5-bit command together with its complement.

The receiver weighs four pounds, occupies 1300 cubic inches, and draws 1.5 watts at 16 volts. The command decoder used with the doppler-command receiver is shown in Figure 2.

In its role as a transponder, the payload receiver accepts a CW signal from the ground and after suitable processing delivers it to the 5-watt transmitter for retransmission to the ground at 16/17 of the received frequency.

Range rate is measured on the ground to accuracies of 1 ft/sec by extracting the doppler frequency shift between the transmitted and received signal after correcting for the frequency offset introduced by the vehicle transponder. Range is measured by frequency modulating the ground transmitter by low-frequency sinusoids. A modulating frequency of 2 cps provides a range solution of better than 100 miles when adequate smoothing exists. A second modulating frequency of 0.25 cps is used to

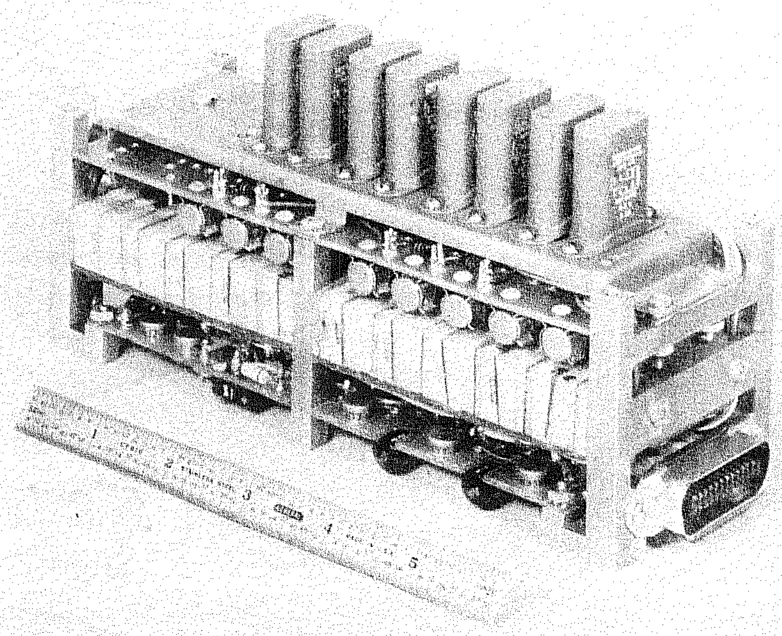


Figure 2. Digital Command Decoder

resolve the phase ambiguities in the 2-cps signal. Further ambiguities are resolved by measuring the time delay between the start of modulation on the ground and the beginning of modulation in the return signal. Tracking in angle is performed by nodding the ground antenna alternately in elevation and azimuth. Angular accuracies of about 0.2 degree are possible.

3. TELEMETRY

The analog telemetry system carried aboard the Able-3 payload is essentially a double-scale version of the system carried aboard the Pioneer I and II payloads. Eleven input signals are applied to two groups of subcarrier oscillators occupying the lowest five and the lowest six IRIG channels, respectively. A twelveth signal, a VLF propagation experiment occurs directly as a subcarrier. Two multiplexers sum the two groups of subcarrier oscillator outputs and the VLF experiment and deliver the resultant composite signals to two low-power VHF transmitters. One transmitter delivers a signal whose frequency is 108.06 mc, while the other delivers a signal whose frequency is 108.09 mc.

The digital telemetry system is carried aboard the Able-3 payload principally to evaluate its usefulness in interplanetary probes. However, the automatic data handling techniques which are available for digital information give it a definite purpose for use in an earth satellite. It is anticipated that digital techniques will prove to be better suited to the transmission of information over interplanetary distances than are analog techniques because of the nature of the thresholding characteristics of the analog system.

The digital telemetry unit developed by STL, the Telebit system, is shown in block diagram in Figure 3. A photograph of the unit is shown in Figure 4. This system accepts both analog and digital inputs from various experiments. The converted information at its output appears as a binary coded subcarrier (1024 cps), which then phase modulates the signal of the 5-watt transmitter.

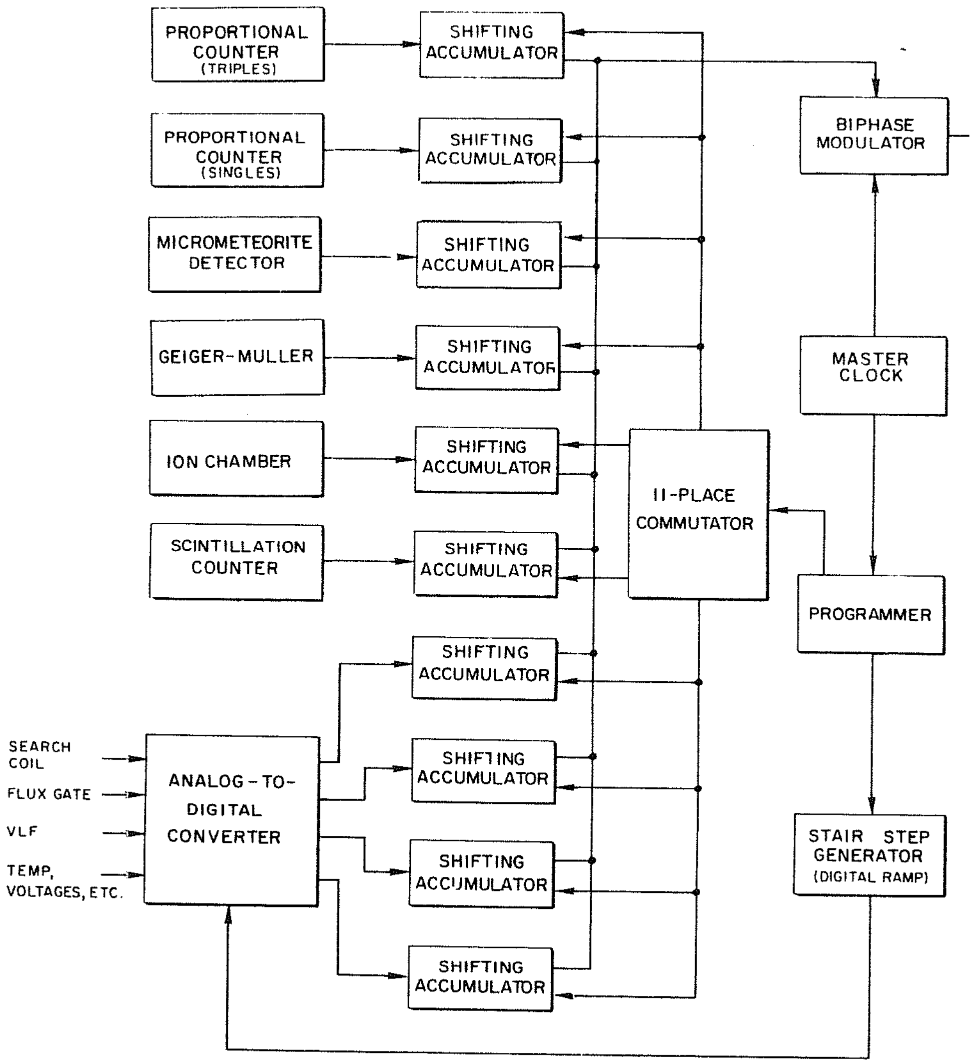


Figure 3. Block Diagram of Telebit System.

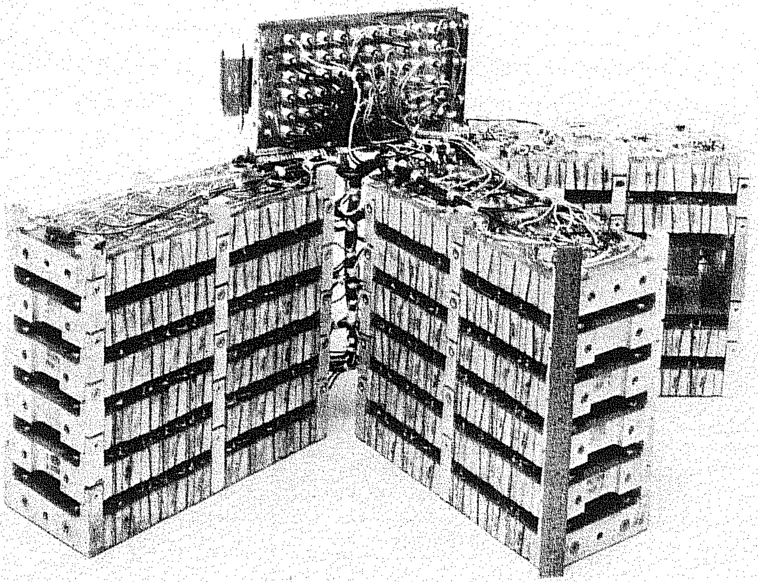


Figure 4. Telebit System.

The binary output of the Telebit system occurs at a synchronous rate and is composed of repeating sets of frames of words. For Able-3, 11 words per frame are used. One word of each frame is used as a frar sync and is read out as all zeros, while the balance of the words are coc with the digital representation of the input information. Each word contains 12 pulses. The first two pulses (for information words) are alway coded the same (zero, one) and define the start of a word; that is, these two pulses provide a word sync. The other 10 pulses may take on any combination of binary values to represent a number from 0 to 1023.

Another advantage of the digital telemetry system over the analog system is that the rate of transmission of information can be adjusted as a function of range. Provision is made for the transmission of information at the rate of one, eight, or 64 pulses per second. This flexibility of information rate will find its greatest usefulness during the transit of interplanetary distances, where large changes in range are encountered. At 55 million miles, using 150 watts of power, informatio can be conveyed only at one pulse per second, while at less than 500,000 miles five watts are sufficient to transmit at 64 pulses per second.

A 12-bit combination binary counter and shift register, referred to as a shifting accumulator, is provided for each word. Pulses from a digital-type experiment are applied directly to the counting input of a shifting accumulator, while an analog input is applied to an analog-to-digital converter whose output is then applied to a shifting accumulator. An electronic commutator running synchronously at the word rate, gate 12 shift pulses to each shifting accumulator during one word interval each frame.

These shift pulses cause the information in the shifting accumulator to be delivered to the biphase modulator, and at the same time the outpu of the digital shifting accumulators is returned to the input so that after 12 shift pulses the state of the shifting accumulators is exactly as it beg

The outputs of all of the shifting accumulators are connected together but since only one is shifting at a time no interference results.

The conversion of analog to digital information is accomplished with the aid of a digital ramp and a voltage comparison circuit. In essence, conversion results from counting the number of steps in the ramp below the level of the analog input. The counting is actually done in a shifting accumulator, just as for digital experiments. The Able-3 payload has six digital and four analog shifting accumulators.

The biphase modulator accepts the pulses emerging sequentially from the shifting accumulators and produces a subcarrier whose phase shifts by 180 degrees each time there is a "one" to be transmitted and retains its phase each time a zero is to be transmitted. This biphase modulated subcarrier is then delivered to the transmitter for phase modulation upon the carrier.

The pulses which cause the electronic commutator to step and the shift registers to shift originate in the programmer, and the programmer in turn receives its excitation from the master clock. The programmer is equipped such that application of an outside signal derived from the digital command decoder causes the pulse rate of the digital telemetry system to change.

4. ANTENNAS

The Able-3 payload uses both VHF and UHF for data transmission and UHF for guidance functions. The VHF transmission circuit from the two transmitters consists of a coaxial ring hybrid for coupling both transmitters to the single antenna system, a shunt tuning stub to match the antenna system to the hybrid, a diplexer for diverting signals for the VLF whistler mode experiment, and two monopole antennas.

The VHF diplexer consists of a resonant circuit tuned to 15 kc for the whistler experiment and is shunted by a bandpass filter employing a helical transmission line. The VHF monopole antennas are conventional in design and operate against the payload shell as the ground plane. Although the resultant radiation pattern is perturbed by the nonplanar ground plane and the solar cell paddles, pattern coverage and gain are adequate for the mission requirements. The UHF antennas, similar in design to the VHF radiators but appropriately scaled in length, are two monopoles operating against the payload shell, located on the opposite end of the payload from the VHF antennas. Both the antenna systems are symmetrically located with respect to the spin axis of the payload.

5. POWER SUPPLY

Placing solar cells directly on the surface of the payload presented two difficulties: (1) the surface area of the payload was too small to permit adequate solar energy interception; (2) inasmuch as the solar cells also absorb large quantities of heat, the payload temperature would be intolerably high. An early decision was made to locate the solar cells on paddles extending essentially radially from the payload. These paddles fold within the nose fairing during launch, but when the fairing is jettisoned they spring out and latch into place. The paddles extend radially 22.5 degrees from the payload equatorial plane, as shown in Figure 5. Approximately 8000 silicon solar cells are carried on the Able-3 satellite. Because of attitude and spin considerations, however, only about 1000 of the solar cells are receiving solar energy at one time. A prototype paddle with solar cells mounted on it is shown in Figure 6.

The payload storage battery consists of a 50-watt-hour capacity at 16.8 volts. A type of battery which would have been lighter for the same capacity, such as silver zinc, was not chosen because of doubtful reliabilit Part of the power developed in the solar cells is immediately consumed in experiments and the receiver, and the charging rate of the battery is thus lessened by this amount. It is anticipated that between 6 and 10 hours wil be required to completely recharge the battery.

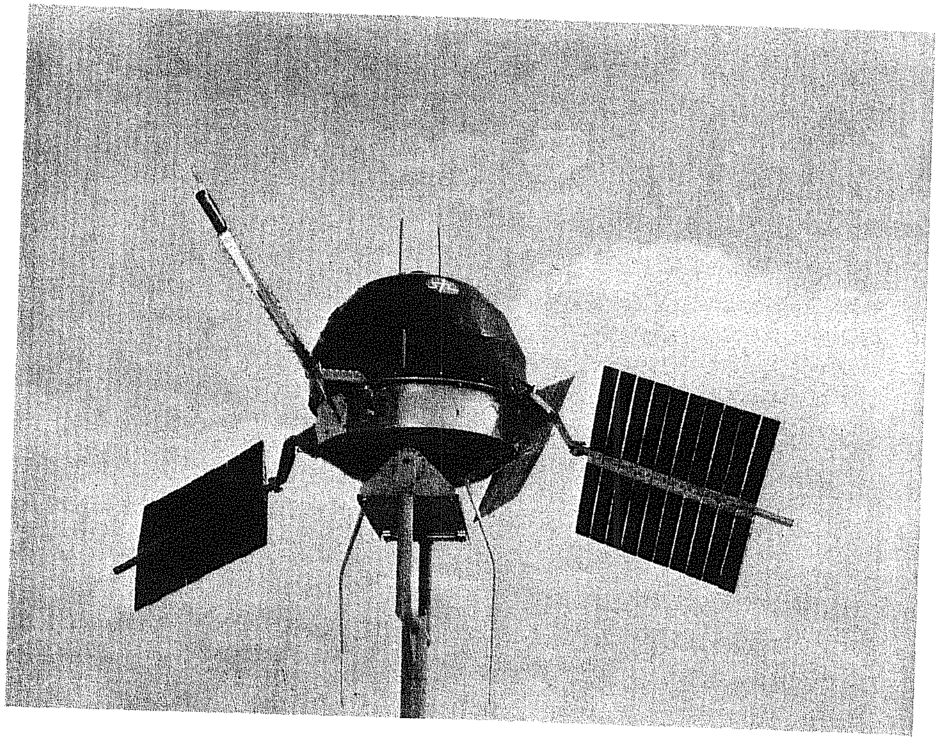


Figure 5. Able-3 Payload

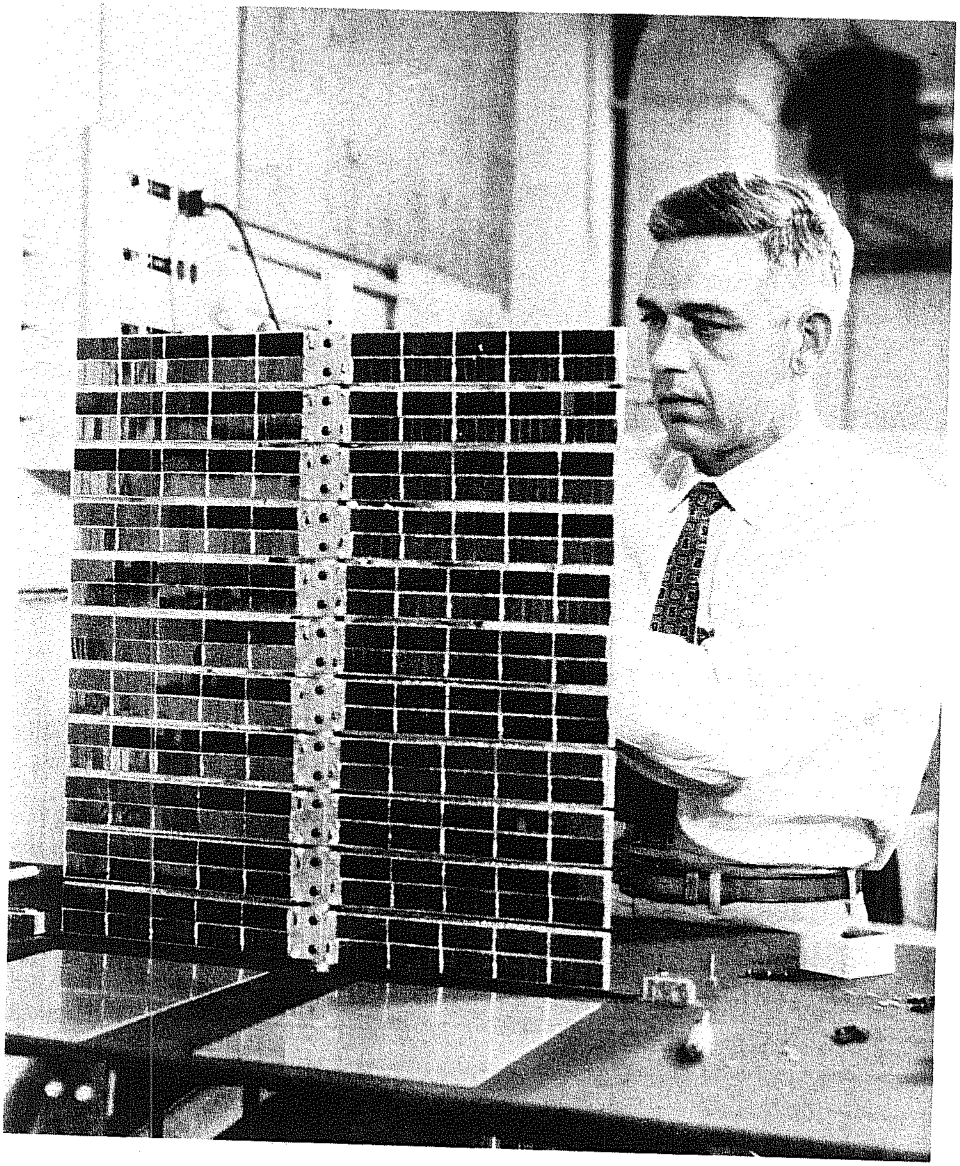


Figure 6. Model of Paddle with Solar Cells.

An over-voltage control operated on command from the ground can be used to reduce the charging rate if it appears that the battery is being consistently overcharged. An under-voltage control is provided which automatically removes the 5-watt transmitter from the load on the batteries in case battery discharge goes so far as to disable the receiver and thus prevent its being commanded off from the ground.

The batteries operate at 16.8 volts. Since this voltage is inadequate for all of the electronics, a series of static converters is employed to provide a variety of voltage levels.

6. TEMPERATURE CONTROL

Temperature control of the payload is achieved by arranging the thermal balance between input solar radiation and infrared emission so that it occurs at a temperature within the desired operating range. This is done by selecting a surface coating that will give a value of the ratio of solar absorptivity to long wavelength emissivity (α/ϵ) in the range of about 1.0 to 1.3.

A similar problem exists in the solar cell paddles but there is less freedom of solution. Furthermore, the solar cells are quite temperature-sensitive and their conversion efficiency drops off about 0.6 per cent per degree centigrade above a nominal value of 25° C.

Because the absorptivity-to-emissivity ratio of a silicon cell is about 3, the cells will run excessively hot unless their surfaces are coated to alter the long wavelength emissivity. Thus glass plates, 0.003-inch thick, cemented individually to each cell, are used to increase the long wavelength emissivity without appreciably altering the cells' conversion efficiency. To protect the cement from ultraviolet radiation and to reduce the cell temperature even more by eliminating a part of the solar spectrum to which the solar cells are functionally insensitive, an ultraviolet reflective coating is applied to the glass before it is cemented to the cell. For the glass plates to reduce the temperature successfully, it is essential that the glass be bonded to the cell over the whole surface, so that there is no gap to cause a greenhouse effect.

The large thermal capacity of the payload prevents large drops in it internal temperature for eclipses expected during the first 1000 days of flight. Temperature drops of 15 to 20° F are the most severe expected during this time. After about 1000 days, however, long eclipses (about 2-1/2-hours duration) will occur; the payload temperature drop by the end of such an eclipse will be of the order of 50° F.

Temperatures of the solar cells, on the other hand, drop rapidly during an eclipse. While there is, of course, no operating requirement for the solar cells during an eclipse, they must be able to survive the low temperatures. For one-half-hour eclipse, the lowest temperature on the solar cell paddle should be about -50° F, and about -175 to -200° for a 2-1/2-hour eclipse.

7. CONCLUSION

Considerable effort has gone into the solutions briefly outlined here. The component and system designs represented by the payload are felt to be sound, and laboratory environmental testing has indicated their reliability. However, long-term operation in space can provide the only adequate test, and the results of this test are bound to indicate areas requiring further development. In any event, future space probe vehicle necessitating considerably more sophisticated instrumentation at considerably further ranges, will be able to profit from this experience.