THE ABLE SERIES OF SPACE PROBES

Adolph K. Thiel

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1. Introduction

The United States has launched 21 payloads into space, of which nine are still there, seven in orbit about the earth, two about the sun. Four of the 21 and two of the nine are members of what has come to be called the Able series of space probes. These vehicles are of particular importance in the space program for several reasons. Each payload has been a sophisticated and coordinated space laboratory containing a great deal of sensing equipment integrated such that the scientific measurements made in each provide a highly meaningful context in which the data from individual measurements can assume a larger significance than it would have standing alone. Each has used its predecessor as a developmental stepping stone toward more reliable and more efficient components. Each has been of noteworthy success both in advancing the science of space technology and providing entirely new data applicable in understanding the physics of space. In addition, it is this series that has produced the familiar paddlewheel configuration and the consequent capability for long operational lifetime in a variety of missions.

These Able vehicles, whose characteristics and results are briefly discussed in this paper, are listed in Table 1. The fifth vehicle in this table has not been launched yet, but is presently scheduled for lunar orbit, and since it is the most recent and most advanced of the series, it deserves mention.

The decision to create the first of the Able space probes was not final until very late in 1957. Before the first launch in 1958, a three-part program had to be completed, on a schedule that appears no less incredible now than it did then. First, the entire complex of launch vehicle and ground support had to be designed and brought to operational status. Second, the first payload vehicle had to be designed, constructed, and tested. And third, a global tracking network had to be created. This paper will take up each of these parts, not from a historical so much as a developmental point of view and will necessarily cover only the highlights of this development.

Table 1. The Able Payloads.

Payload	Weight (lb)	Engine	Power Supply	Launch	Result
Pioneer I	84.4	Solid vernier rockets and retrorocket	Mercury batteries	11 Oct 58	113,800 km altitude
Pioneer II	87.3	Solid vernier rockets and retrorocket	Mercury batteries	8 Nov 58	1550 km altitude
Explorer VI	143	Solid orbit adjustment rocket	Four paddles with 8000 solar cells	7 Aug 59	Earth orbit 250 to 42,400 km
Pioneer V	94.8	--	Four paddles with 4800 solar cells	11 Mar 60	Solar orbit inside earth's
Able-5	375	Liquid multi-start vernier and injection	Four paddles with 8800 solar cells	Scheduled	

2. Launch Vehicle

The Able launch vehicle was founded on a two-stage rocket, called the Able, designed by Space Technology Laboratories in 1957 for a U. S. Air Force re-entry test program. These two stages consisted of the Thor IRBM with a slightly modified guidance system and the Aerojet-General Corporation's AJ-101 with a new, highly accurate STL guidance system. Both stages are liquid propelled. To complete the vehicle for space launches a solid propellant rocket, the Allegany Ballistics Laboratory Model 248, was added as a third stage. Calculations showed that if the payload was light enough this three-stage booster was capable of sending space probes into accurately guided geocentric orbits, to the moon, or to the nearer planets.

The payload, as fourth stage, was in each case mounted above the third stage and encased in an aerodynamic fairing which covered both third and fourth stages. Figure 1 shows the vehicle as used for Pioneer I, and Figure 2 shows the launch of Explorer VI. As can be seen, the external appearance of the two is identical.

Although timing differs for each mission the sequence of events in the launch of this vehicle is approximately as follows. Almost immediately after liftoff the Thor autopilot rolls the vehicle, by means of its roll control jets, into the proper attitude for its pitch program. A few seconds later, again initiated by the autopilot, the Thor begins a gradual pitch down maneuver which continues almost throughout its entire burning period. After nearly three minutes of thrust the Thor achieves its programmed velocity and its main engine shuts down. For a second or two the vehicle continues only on small vernier engines, during which time blast doors are blown off the adapter section between the first and second stages. The second stage then is ignited by a timer and the explosive bolts joining the two stages are fired. The empty Thor falls through a carefully precalculated trajectory into the sea, and the second stage continues on course. Soon after first and second stage separation, explosive bolts holding the nose fairing are fired by a timer and the two halves of the fairing, held down under tension by the bolts, spring away. The second stage, under control of both autopilot and radio

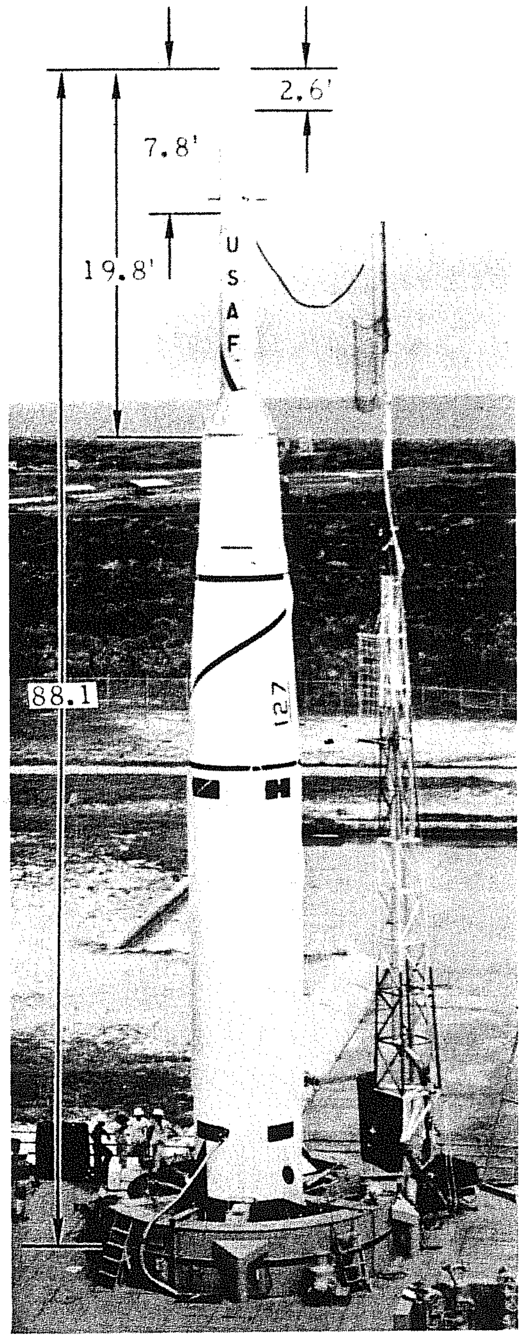

Figure 1. The Pioneer I Launch Vehicle.

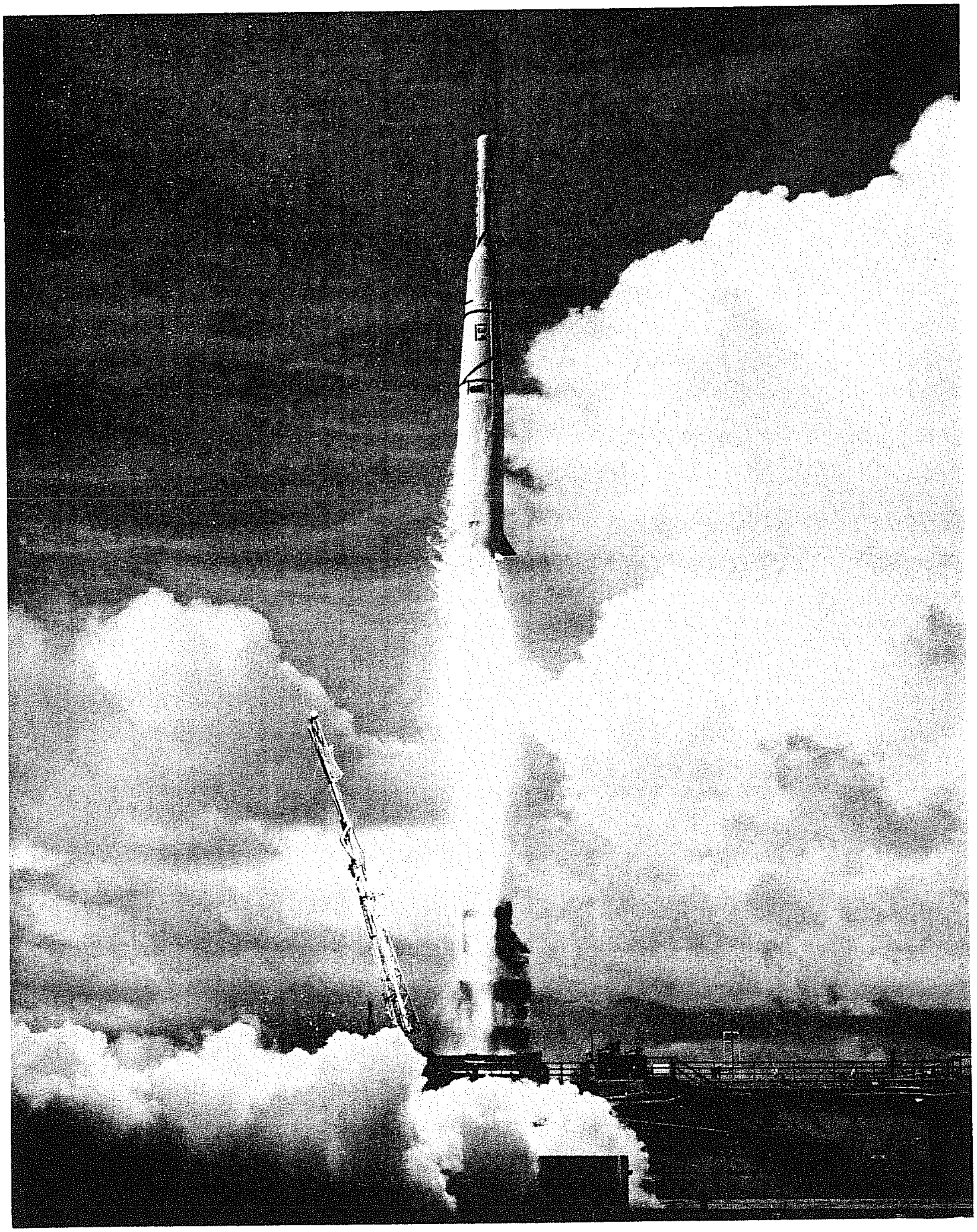

Figure 2. Launch of Explorer VI.

guidance from the ground, also pitches down gradually and undergoes careful guidance corrections in both pitch and yaw. The vehicle is now flying nearly horizontally with reference to the earth and at azimuth and flight path angle bearings accurate to within 1 milliradian. The second stage engine is shut down, and for a second or two the vehicle coasts. During this time the solar cell paddles on the payload are erected, if the payload has paddles, and spin rockets on the upper casing of the second stage fire. The third stage is ignited, separated by a timer, and the second stage falls to earth to be burned in the atmosphere.

Since the vehicle is not guided after second stage burnout, precautions must be taken to be certain that the direction of the velocity vector is not significantly affected by separation of the second and third stages. Figure 3 shows the mechanism developed in the course of the program by STL for accurately separating these two stages. The third stage rests on four hinged legs coming up from the second stage and joined to the third stage by a metal band above the nozzle on the rocket casing. After the joined second and third stages are spin-stabilized, the third stage is fired, the bolts holding the band are exploded, and the legs fold back under centrifugal force away from the stage, allowing separation of the stage without possibility of impedance or tipoff angle. Separation of the payload from the third stage is achieved by the mechanism shown in Figure 4. The moments of inertia of the joined third and fourth stages are carefully calculated so that the spin axis of the bodies to a fine tolerance is through the center of the spring that attaches to the top of the third stage. Thus when, on command from the ground, the band holding the two stages together is blown off, this spring separates the stages with sufficient relative velocity with, again, minimum danger of tipoff. It is necessary to separate these two stages even though the payload will achieve no further thrust, as was the case with Pioneer V, to prevent interference by the stage with the payload radio communication.

Throughout this launch flight large quantities of telemetered information on the function of the stages are being returned to the launch complex. For example, nearly 30 measurements of the Thor performance are telemetered

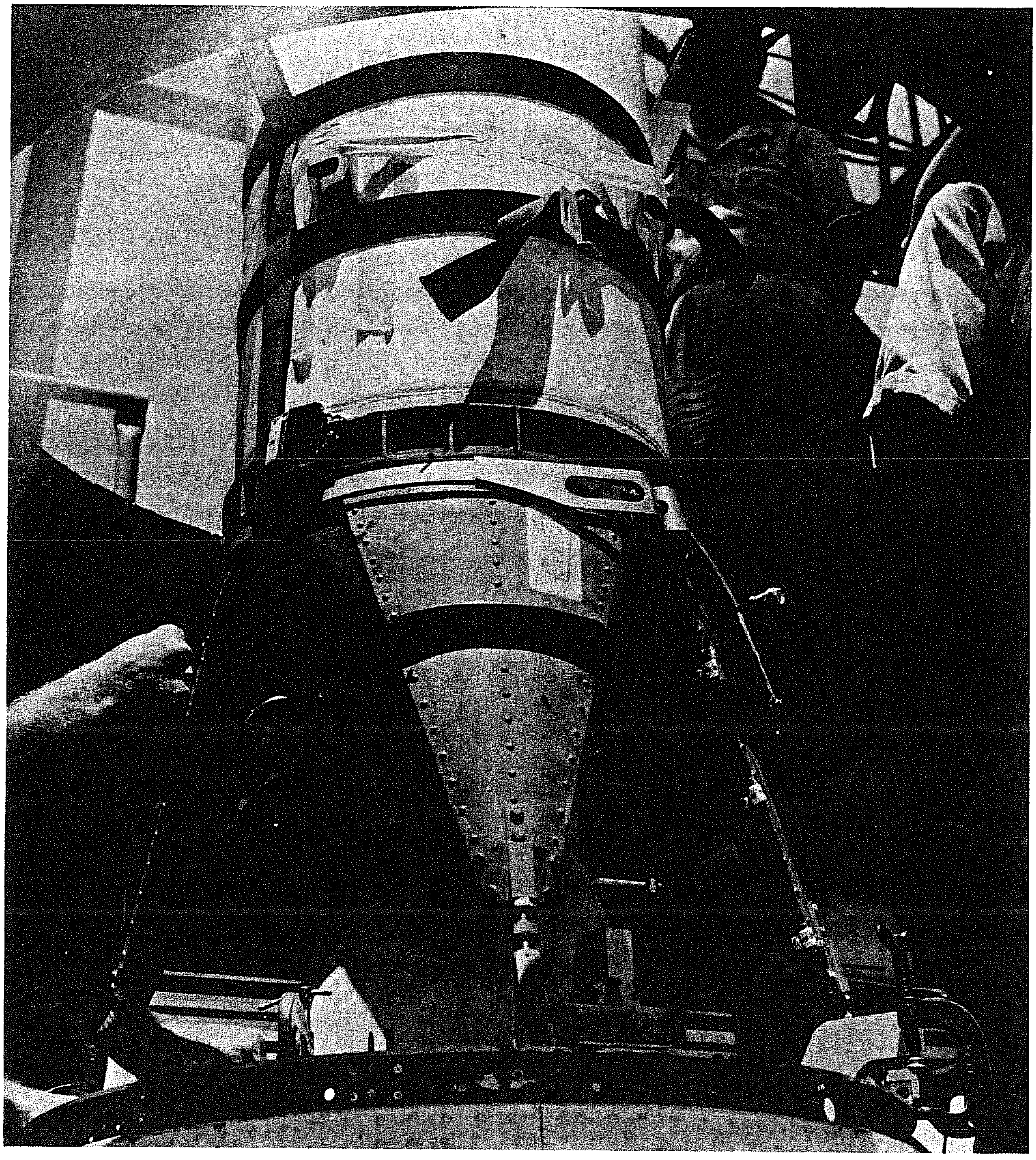

Figure 3. Juncture of Second and Third Stages.

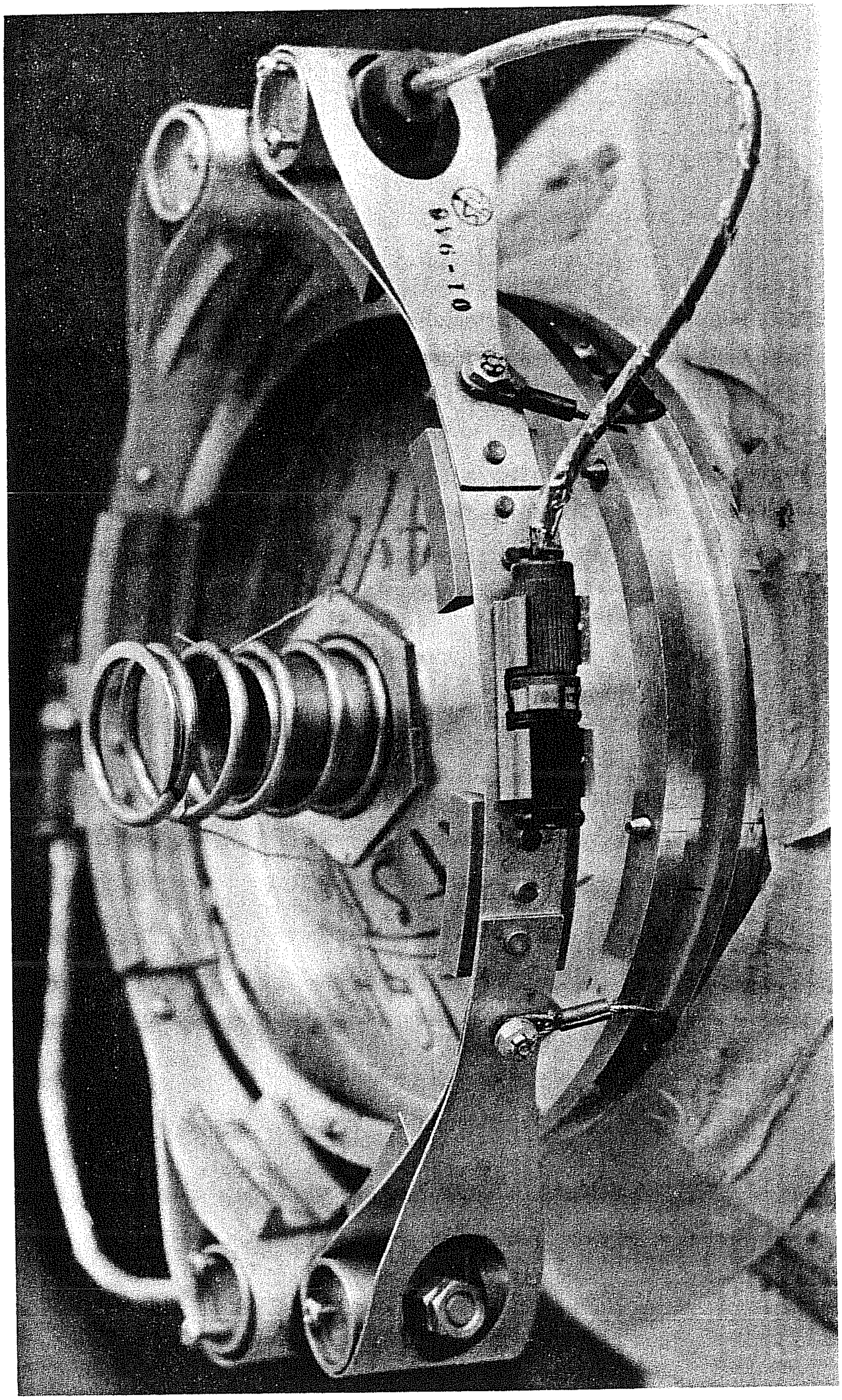

Figure 4. Third-Fourth Stage Separation Mechanism.

from the first stage and 50 from the second stage, including third stage separation events. In addition, the guided second stage acts on any of 10 commands from the ground, also including third stage separation.

As can be seen the launch program of the Able space probes involves many design details, but at the same time three additional objectives are imposed either by the nature of launch into space or by the desire to operate on a minimum budget of time. The vehicle operation must be as simple as possible, to increase reliability, and the structure and mechanisms involved as light as possible, to maximize the payload weight. The launch checkout and countdown equipment must be flexible enough to adapt to various space missions. The launch operation must be as reliable as the space operation, since the moment of launch for most space missions, given present booster limitations, is very narrowly defined. If, for example, on a lunar mission launch is not achieved within a half hour on one of two or three days, the launch must be postponed for an entire month.

3. The Payloads

3.1 Pioneers I and II

Compared to the later vehicles in the Able series, Pioneer I (Figure 5) was a simple vehicle, but at launch in October 1958 it represented the most sophisticated payload ever sent up and it was more than twice as heavy as any of the four previous American space probes. Conceived as lunar probes, Pioneers I and II carried five and six experiments, a command receiver, an analog FM-PM telemetry system, a transmitter at 300 mw in the IGY 108-mc frequency range used either for tracking or telemetry. Power was provided by mercury battery packs, which permitted a maximum transmitter lifetime of 10 days. Location of this equipment, balanced at the periphery of the payload equator to enhance the spin moment of inertia, is shown in Figure 6. The solid propellant retrorocket runs through the center of the payload. The experiments included:

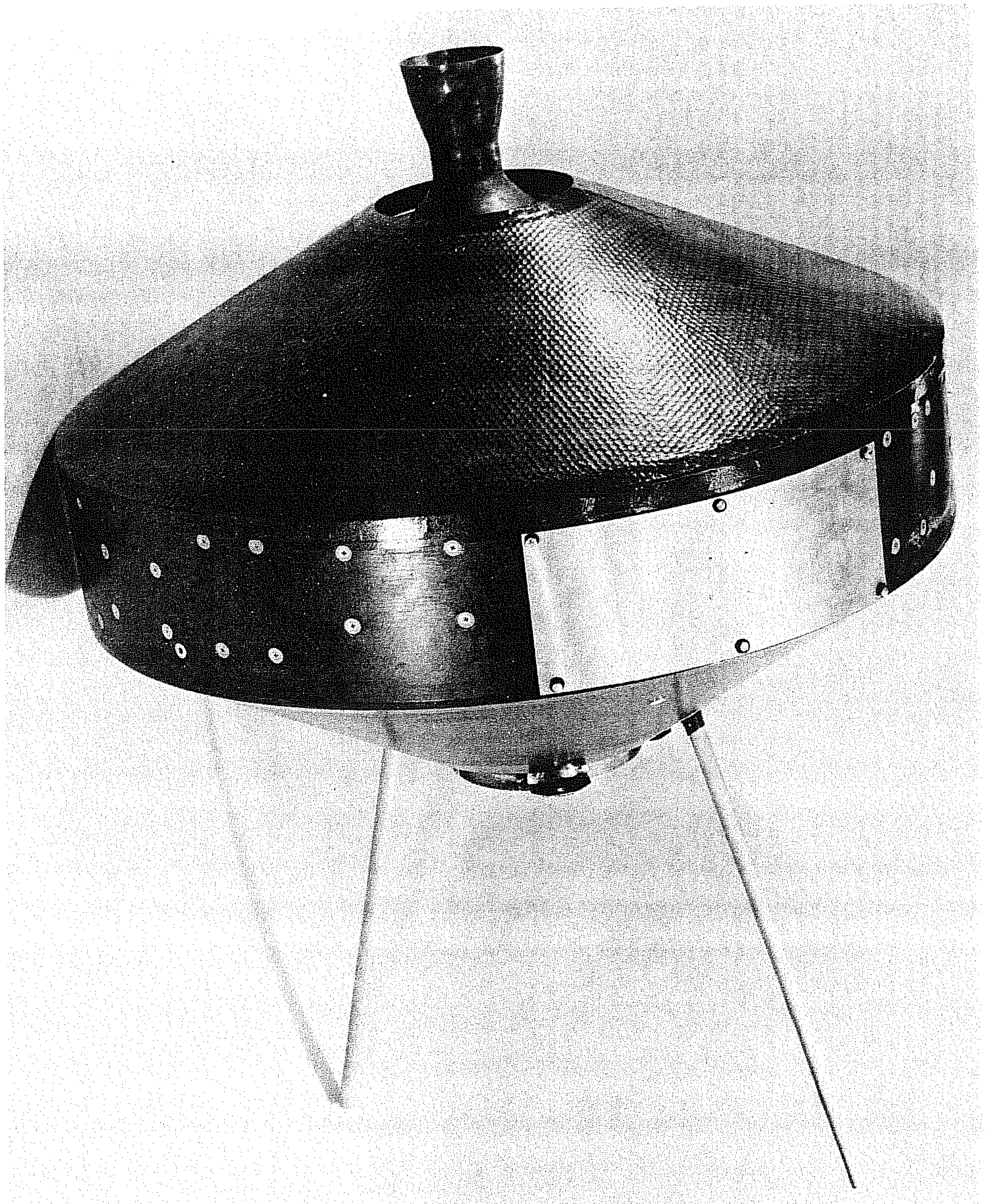

Figure 5. Pioneer I.

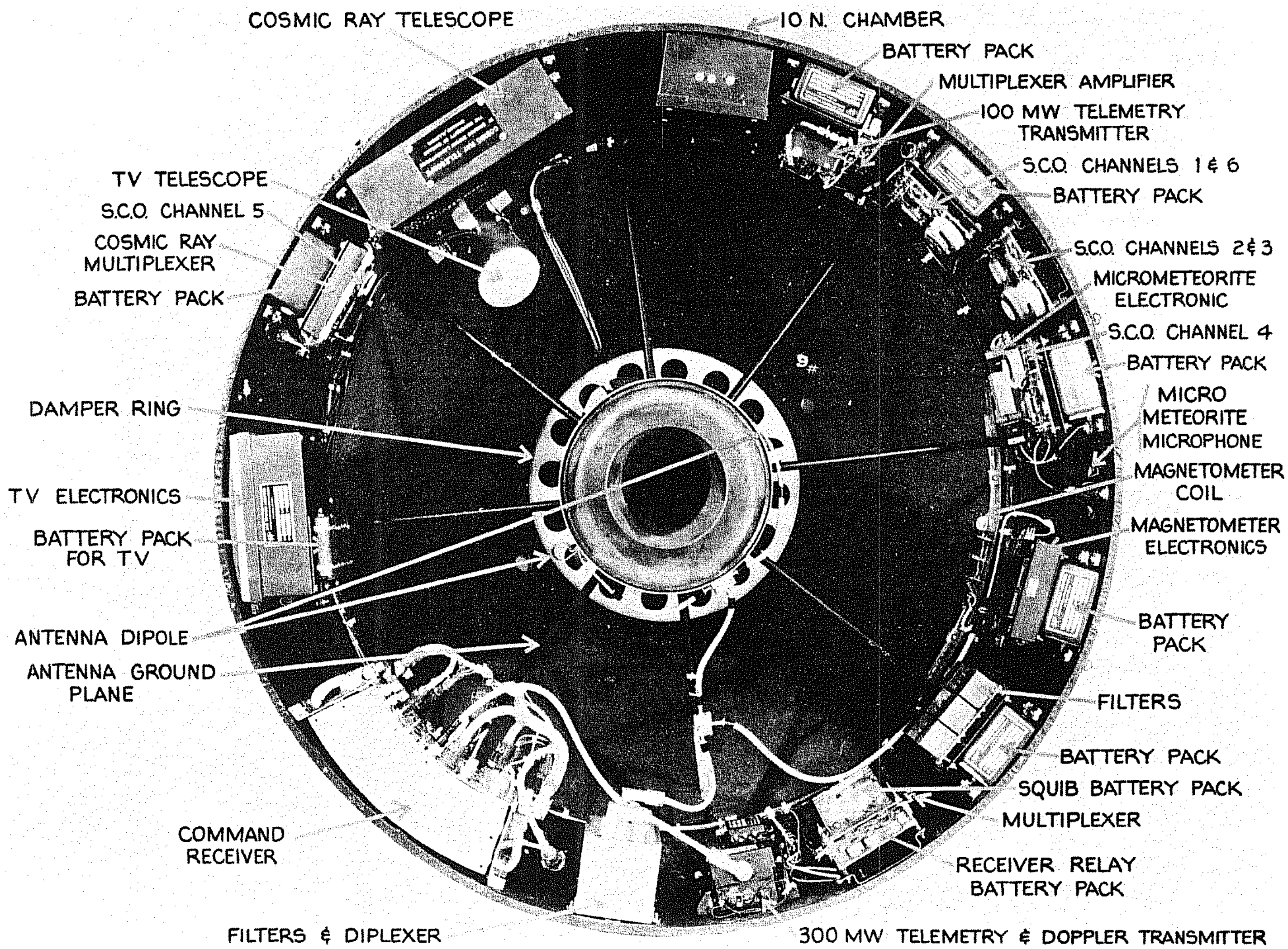

Figure 6. Pioneer II Internal Components.

1. Micrometeorite detector
2. Spin-coil magnetometer
3. Ionization chamber
4. Cosmic-ray telescope (Pioneer II only)
5. Image-scanning television system
6. Temperature sensor.

The differences between Pioneer II and Pioneer I were not large, but represented the first of the adjustments made in the series on the basis of experience with previous flights. Thus results of Pioneer I indicated the need for increased sensitivity range in the radiation detectors and in the magnetometer, and this was incorporated into Pioneer II. Pioneer II also included a television scanner of less weight than that of Pioneer I but more sensitive in resolution, and a second transmitter at 100 mw.

Both Pioneer I and II reached far into space, Pioneer I considerably farther than had any previous space probe, but neither achieved the moon. Had the flights of Pioneer I and II been more successful, a staggering volume of data would have been accumulated, enough to saturate any existing data reduction procedure. The experience on these flights therefore led directly to revised data handling procedures on Explorer VI. This, in fact, was probably the major developmental advance between Pioneer II and Explorer VI.

3.2 Explorer VI

Explorer VI (Figure 7) was improved in four general ways over the earlier Able vehicles. Pretransmission data processing was incorporated in the payload instrumentation. The satellite carried a self-sustained power supply system utilizing solar cells constantly charging nickel-cadmium storage batteries. It incorporated the airborne portion of an integrated telemetry, tracking, and command system to permit more efficient use of its weight and power and to permit a more sophisticated ground command system. And it carried additional and more expertly integrated experiments.

It incorporated two magnetic field measurements, a flux-gate as well as a spin-coil magnetometer. It carried three particle radiation experiments, a

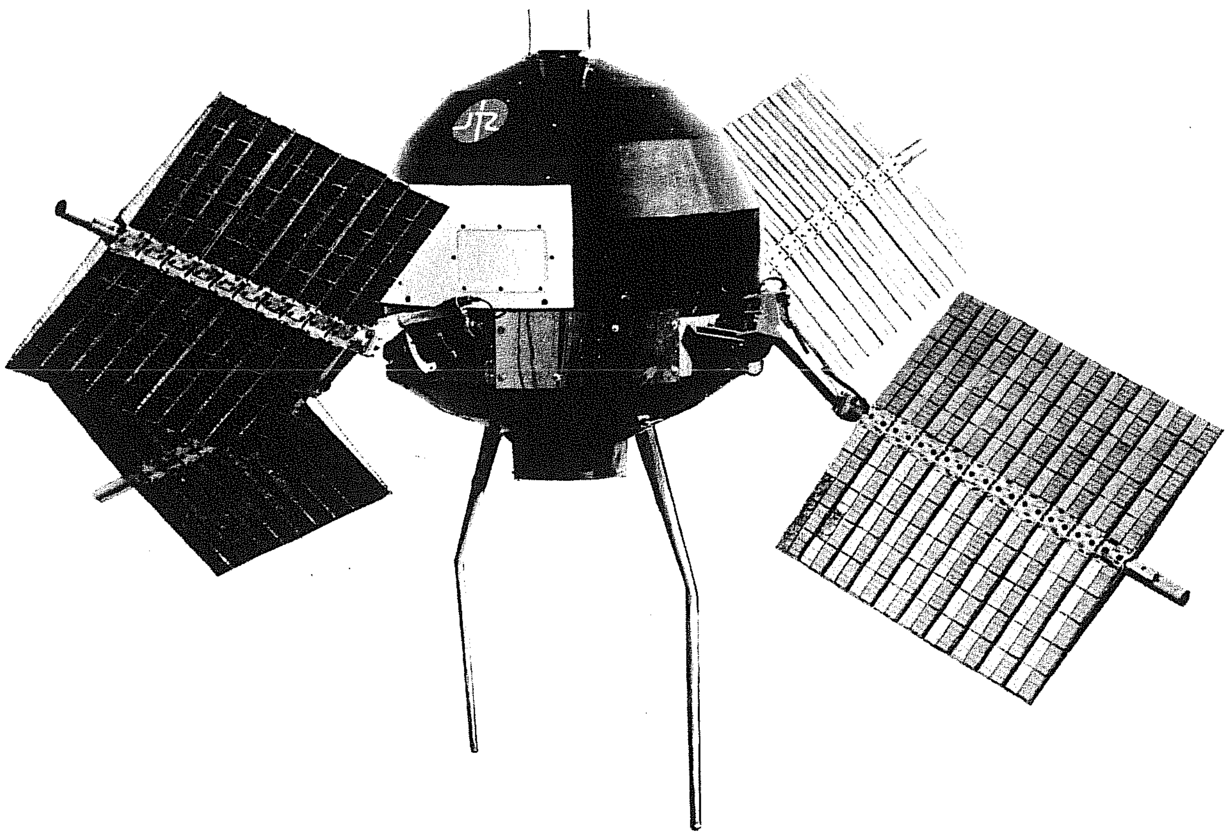

Figure 7. Explorer VI.

Geiger-Mueller and ionization chamber combination, a scintillation counter, and a proportional counter telescope. It carried essentially the same image scanner and micrometeorite detector as had Pioneer II. It included also a VLF radio wave receiver for analysis of the whistler mode propagation phenomena. Location of Explorer VI equipment is shown in Figures 8 and 9. Moreover, the satellite subcommutated 15 measurements of payload characteristics, in contrast to the one temperature sensor on the earlier Pioneers. Finally, it permitted electron density experiments by means of ground examination of its carrier frequency. It was, and remains, the most sophisticated space probe launched by the United States.

Two telemetry systems were carried: an analog system similar to that of the Pioneers made use of two lower-power transmitters in the 108-mc range, and a digital system transmitted at 378 mc at 5 watts.

To optimize the information gathered, a highly elliptical geocentric orbit was chosen, completely traversing the Van Allen radiation belts in each orbit. In addition to sampling an extremely large portion of the space about the earth, this orbit was also valuable because it precessed in its plane, i. e. , the line intersecting perigee and apogee, initially inclined about 45 degrees to the equator, moved with time toward the equator. As a result of this motion the portion of space measured up to apogee and down to perigee constantly changed and the total amount of space covered was thereby greatly increased. The orbit achieved by Explorer VI was even better than planned in that its apogee was slightly higher, and as a consequence it was never necessary to fire the adjustment rocket, carried expressly to raise apogee or perigee if needed.

The micrometeorite detector, essentially like that of the earlier Pioneers, employed a diaphragm equalling a known fraction of the total surface area of the payload with a microphone attached to the inner side of the diaphragm. Two-level discrimination of impact energy permitted analysis of the statistics of both total flux and energy level of the micrometeorites encountered.

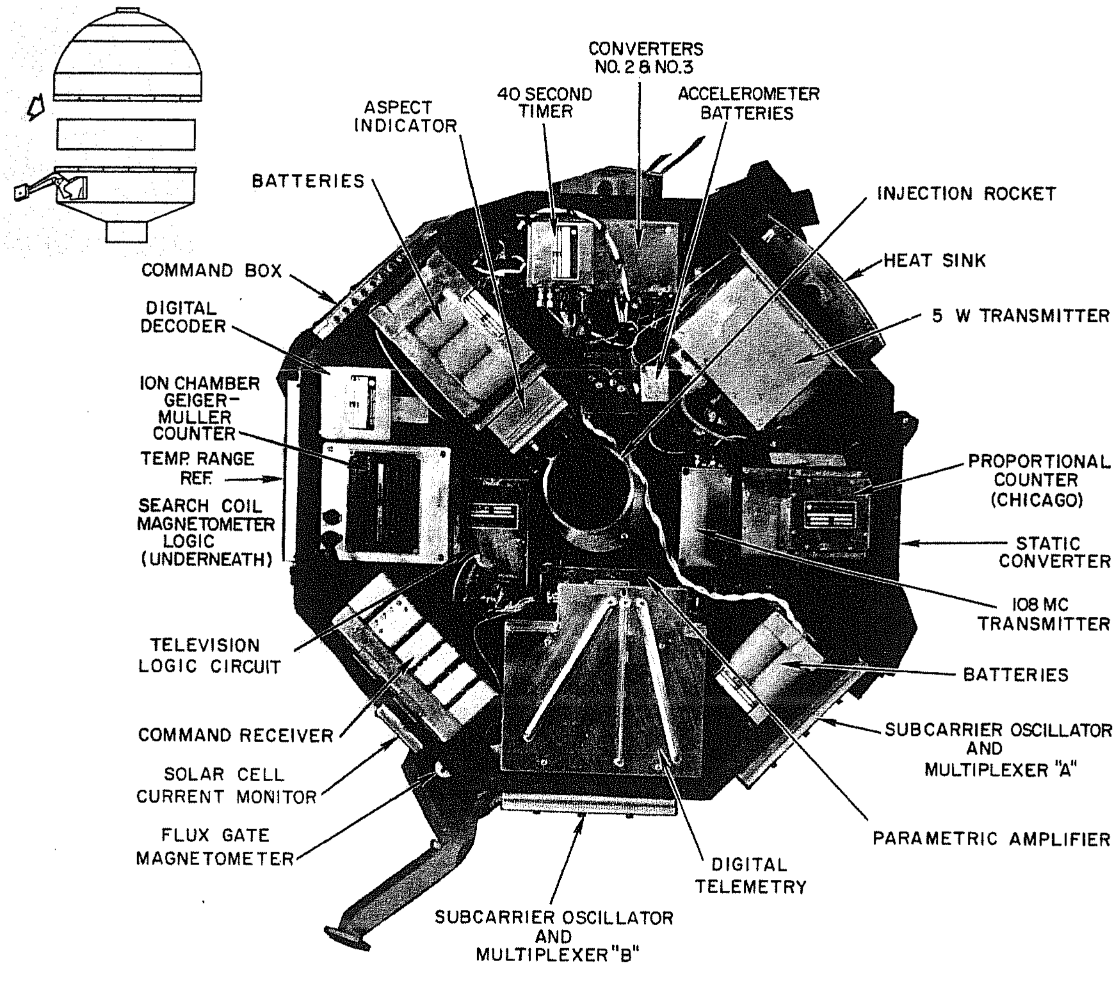

Figure 8. Able-3 Payload (Top View).

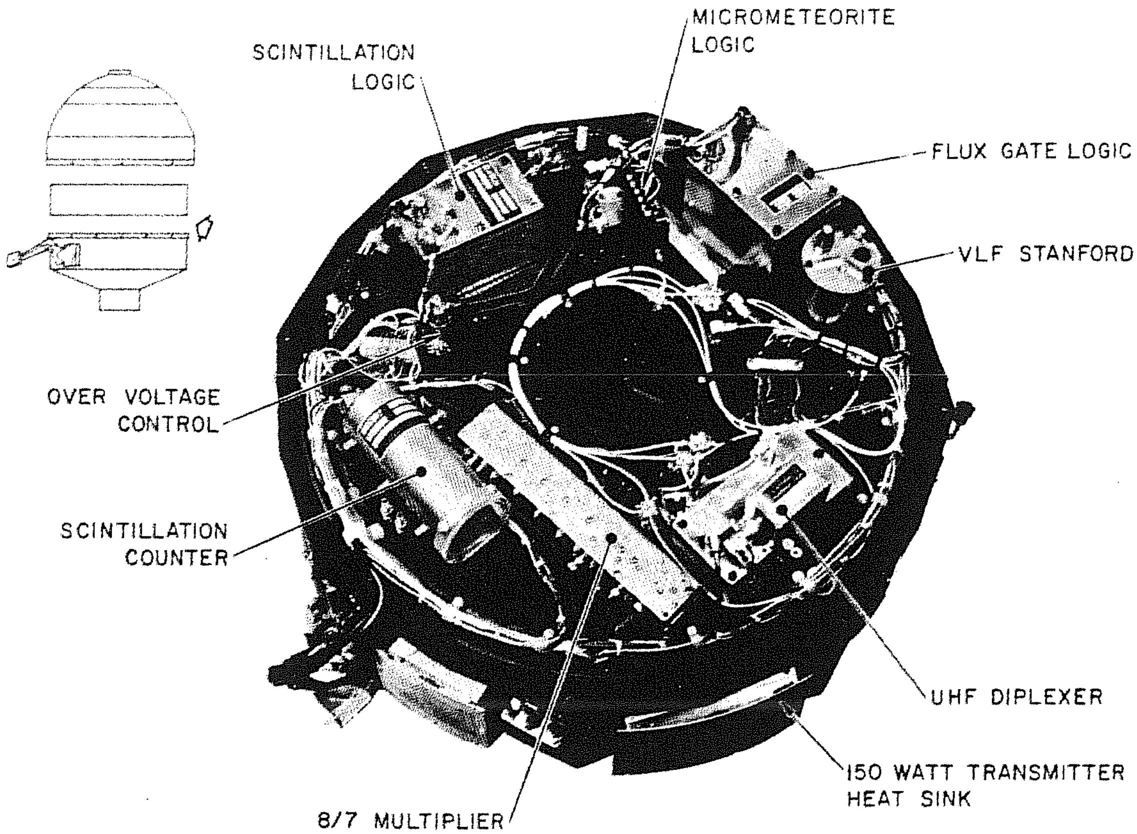

Figure 9. Able-3 Payload (Bottom View).

The proportional counter telescope used a series of binary scalers to reduce the telemetered count of cosmic ray impingement to a known fraction of the total to permit a rate of counting which was low enough to be handled within the available telemetry channel capacity.

The television scanning device consisting in essence of a photodiode in conjunction with a lens system, incorporated an unusual form of pretransmission data filtering. Optical scanning was made in one direction by means of the payload rotation and in another by movement along the trajectory. The rate of rotation required for stability was so high, however, that an enormous telemetry channel capacity would have been needed to transmit the scans directly. At the same time the forward motion of the payload was relatively so slow that great overlapping of lines would have occurred. Pretransmission filtering techniques balanced these effects by scanning only one dot at a time. During each rotation a new dot was accepted whose brightness value was held and transmitted as a constant amplitude for the balance of that revolution.

The spin-coil magnetometer also incorporated pretransmission data filtering. Its output signal was approximately a logarithmic function of its input. In this manner weak magnetic fields at great ranges from the earth could be measured with precision while with the same equipment the earth's field could be measured at low altitudes.

The digital telemetry system was developed for three reasons. It permitted some pretransmission data processing in addition to the filtering techniques such as those just described, techniques which had been utilized on the previous Pioneers. By improving the efficiency of the communication system it increased the telemetry channel capacity. And it made unnecessary a large number of human operations required on the ground between the time of reception of data and delivery to the final analysis.

A principal advantage of the system, called Telebit, is its flexibility in adapting to range variations, of vital importance in its application to a deep space probe such as Pioneer V. During periods when the transmitter is on, information can be transmitted at three rates, 64, 8, or 1 pulse per second, as range requires. In addition since interplanetary space probes will have to use a very low transmitter duty cycle for some time to come, Telebit adapts to this condition by accumulating data during the intervals between transmissions.

Digital data arrives at Telebit as a pulse representing the occurrence of event, analog data as a voltage proportional to some measured quantity. The analog data is converted to digital by Telebit, both types are processed to binary numbers and accumulated in a unit called a shifting accumulator. This unit can either accept pulses and total them or it can take the total number stored in the accumulator and shift the information out to a modulator.

The UHF carrier is phase modulated by Telebit to carry the binary numbers to the ground in a sequence of 10-bit words constituting a frame. On Explorer VI 10 words made up a frame, the first nine giving experimental measurements, the tenth word subcommutating the 15 vehicle measurements. The internal construction of the airborne Telebit unit is shown in Figure 10.

The payload receiver operates continuously, repeatedly sweeping 30 kc in the 401-mc range searching for a carrier, on which it then automatically locks. On command it can be operated with either a 250-cps or a 40-cps bandwidth. When it acquires a ground signal, the signal is delivered slightly offset in frequency to the transmitter to serve as the transponded carrier and at the same time to the command decoder, which for Explorer VI distinguished among 14 commands and delivered appropriate signals to the payload equipment.

Explorer VI performed flawlessly except for some difficulty at paddle erection. It appears that the paddles were fouled in the cord which had held them down under the fairing and did not fully erect until spin-up. The centrifugal force of this action was considerably stronger than the paddles had been designed to withstand and evidently some solar cells on the paddles were damaged and one of the paddles stabilized in a position below its latch. The result was a spin axis slightly off center and a considerably reduced battery charge current. Two months after launch the automatic undervoltage cutoff shut off transmissions, and the payload has not been acquired since. A total of 827 hours of analog and 23 hours of digital telemetry was obtained, however, and fundamentally significant results achieved.

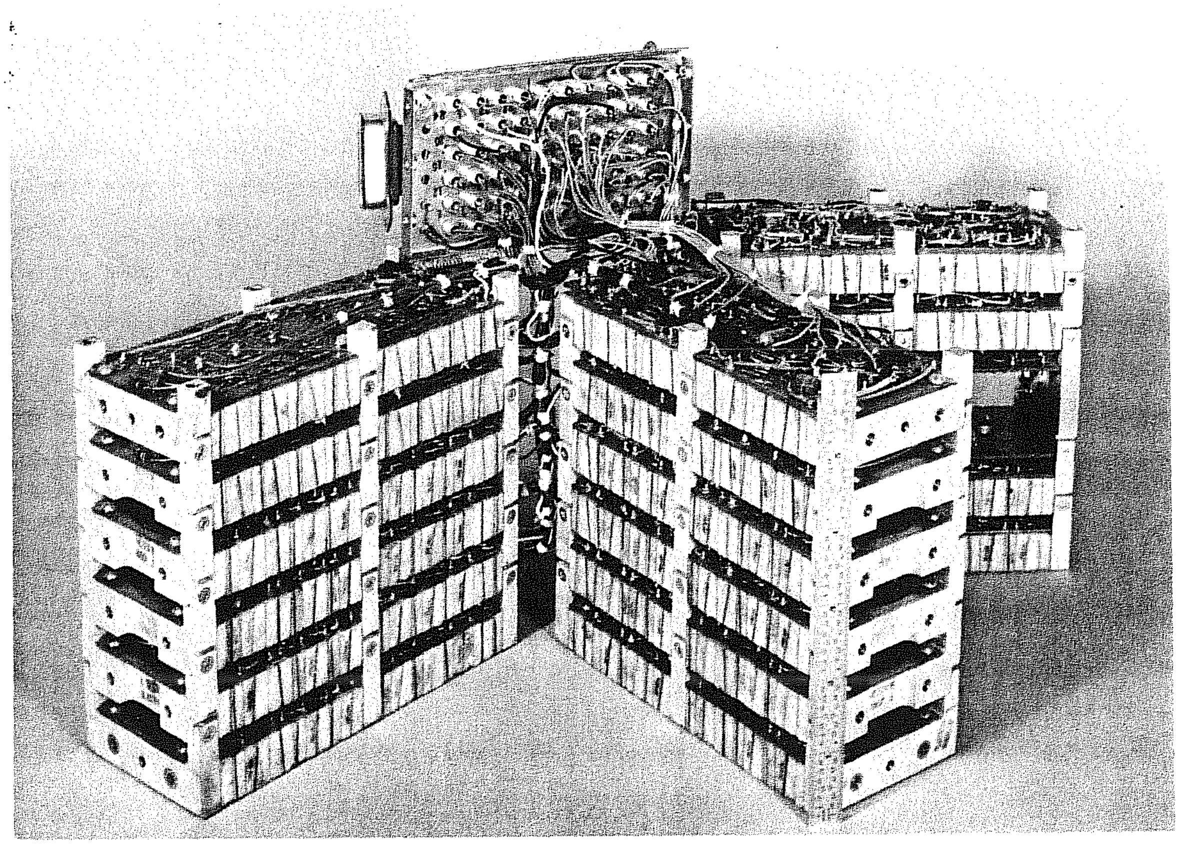

Figure 10. The Airborne Telebit Unit.

3.3 Pioneer V

Pioneer V (Figure 11) is quite similar to Explorer VI except that it is lighter, carries no rocket, carries fewer experiments, carries only the Telebit telemetry system, and includes a 150-watt amplifier for which, on command, the 5-watt transmitter can act as a driver. The mission of Pioneer V is to explore space in toward the sun to the maximum range of current communication capability, estimated on the basis of present experience with Pioneer V to be in the neighborhood of 60 to 70 million miles.

Launched on March 11, Pioneer V on May 20 is 10 million miles from the earth and still moving out. Its planetoid orbit will carry it to the vicinity of the Venus orbit. It will reach its perihelion on August 10, at which time the distance from earth to Pioneer V will be about 47 million miles. It will continue to recede from the earth until it is separated by the diameter of the earth's orbit. Long before that, however, it will have exceeded communication range.

Three methods are incorporated into Pioneer V which on ground command can be used to stretch this communication range to its maximum: the variable information rate, the receiver narrow band search frequency, and the high-power payload transmitter. Each of these three must be employed at the expense of the total quantity of information received from Pioneer V, but the flexibility of the system permits maximizing telemetry information as a function of range.

Telebit on Pioneer V includes three fewer words than on Explorer VI and eight subcommutated payload performance measurements as compared to the 15 on Explorer VI. The decoder in Pioneer V accepts any of eight possible commands.

As in Explorer VI the batteries in the power supply system operate at 17 to 19 volts. Since this voltage is inadequate for all of the electronics, a series of static converters is incorporated to provide a variety of voltage levels. An automatic undervoltage control is included which removes the transmitter load from the batteries in case battery discharge goes so far as to threaten to disable the receiver or reduce battery lifetime.

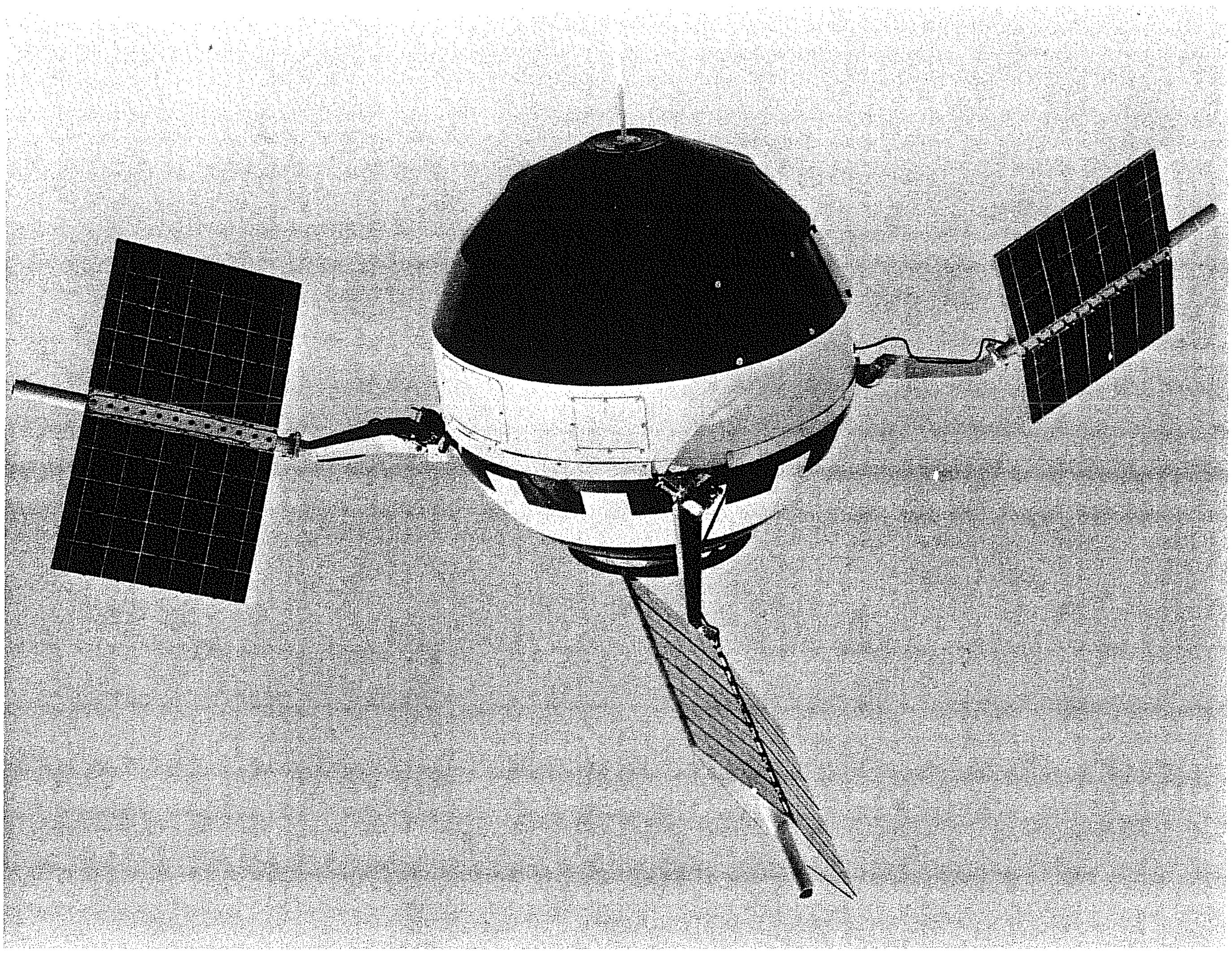

Figure 11. Pioneer V.

The interior of Pioneer V is shown in Figures 12 and 13. A block diagram of the payload is given in Figure 14, a block diagram which can also serve to illustrate the generic operation of Explorer VI.

3.4 Able-5

The final member of the Able series of space probes (Figure 15) designed for capture orbit about the moon is the largest by a substantial margin. Some of this weight and size is utilized to double the payload's reliability with redundant components such as the 5-watt transmitter, but most of the weight is used for system improvements.

The most notable advance is represented by the engine carried in this payload (see Figure 16). It is a monopropellant liquid hydrazine engine using nitrogen gas pressurization and incorporating fore and aft nozzles and multi-start capability. The engine can thus be used for vernier velocity corrections on its transfer trajectory to the moon, for injection of the payload into orbit about the moon, and finally for adjustment of that orbit as needed.

This payload will also incorporate an active temperature control system. The previous four Able space vehicles have relied exclusively on heat sinks and paint patterns on their shells. A result of that system has been the need for a different paint pattern for different times of launch, and consequently separate payload shells on standby in the event launch is postponed. Able-5 will carry instead 50 small propeller-like disks on its shell. These automatically rotate through 45 degrees to cover or uncover a paint pattern of either deep blue or white in order to vary as necessary the emissivity-to-absorptivity ratio of solar thermal energy at that point.

Finally, the Able-5 will use an Atlas ICBM as its first booster vehicle (Figure 17). It is this fact which permits its weight to be twice that of Explorer VI and still achieve the velocity needed to reach the moon. Other than the first stage, however, the launch vehicle will be the same as the previous Able series.

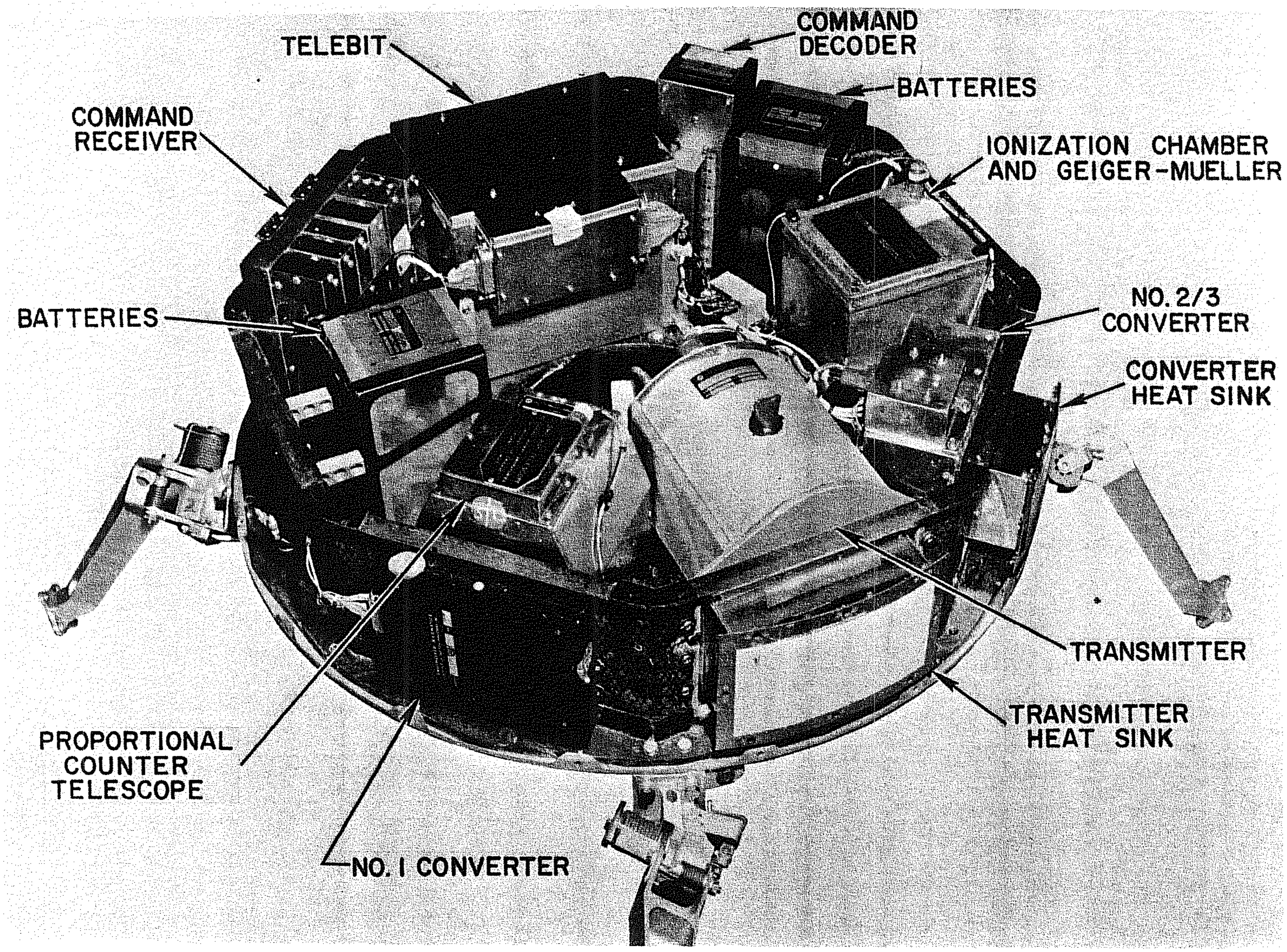

Figure 12. Interior of Pioneer V (Top View).

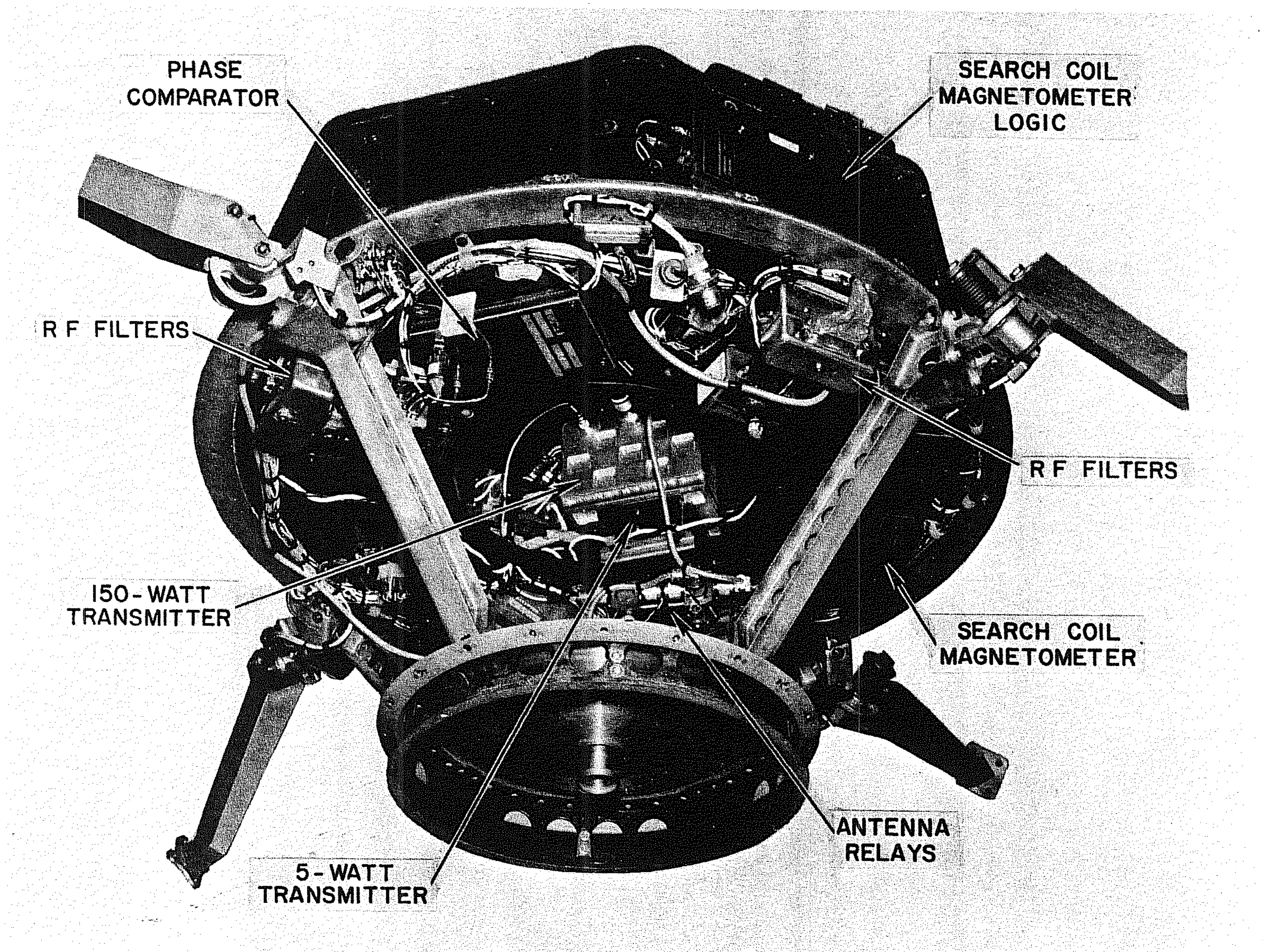

Figure 13. Interior of Pioneer V (Bottom View).

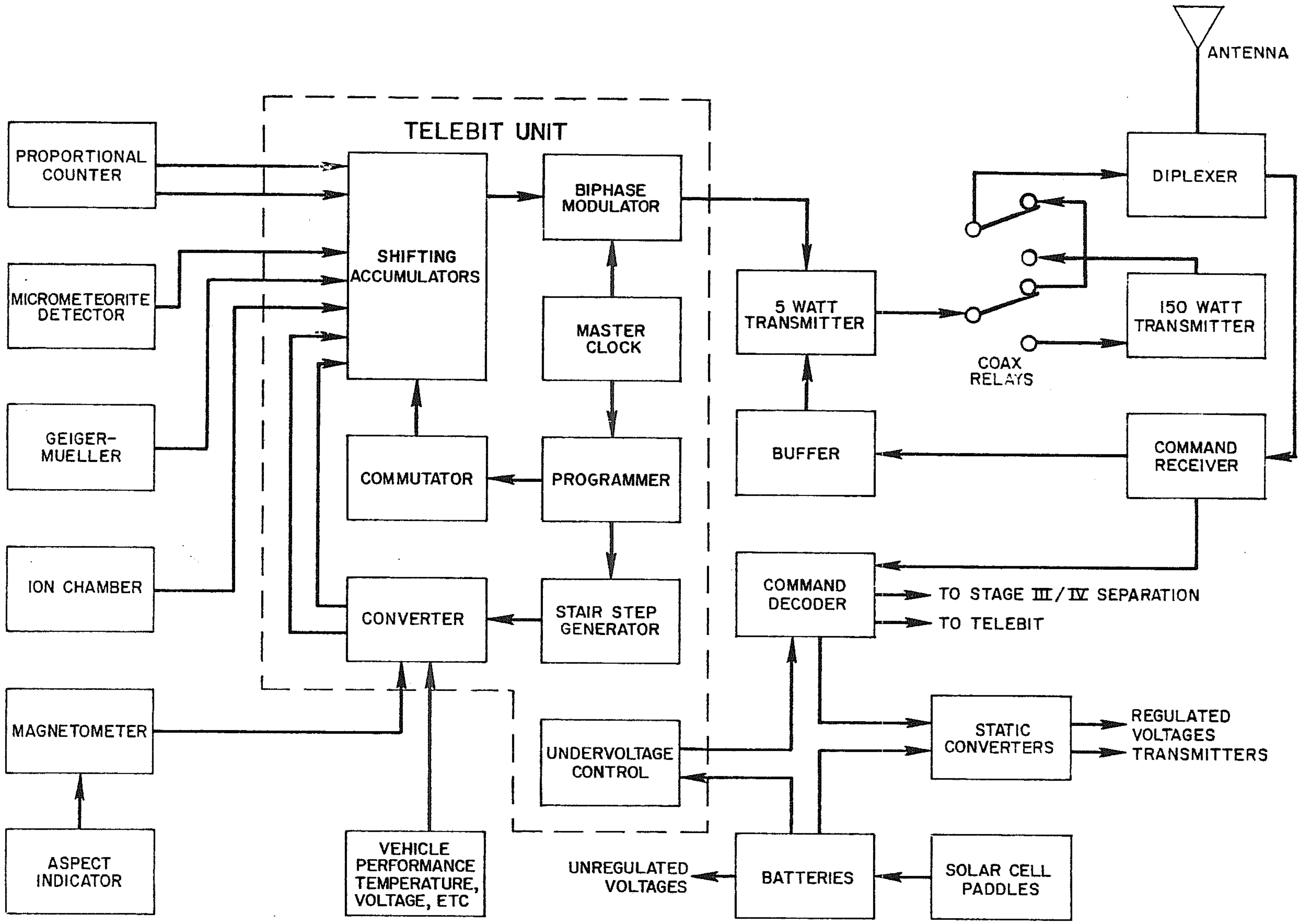

Figure 14. Functional Block Diagram of Pioneer V.

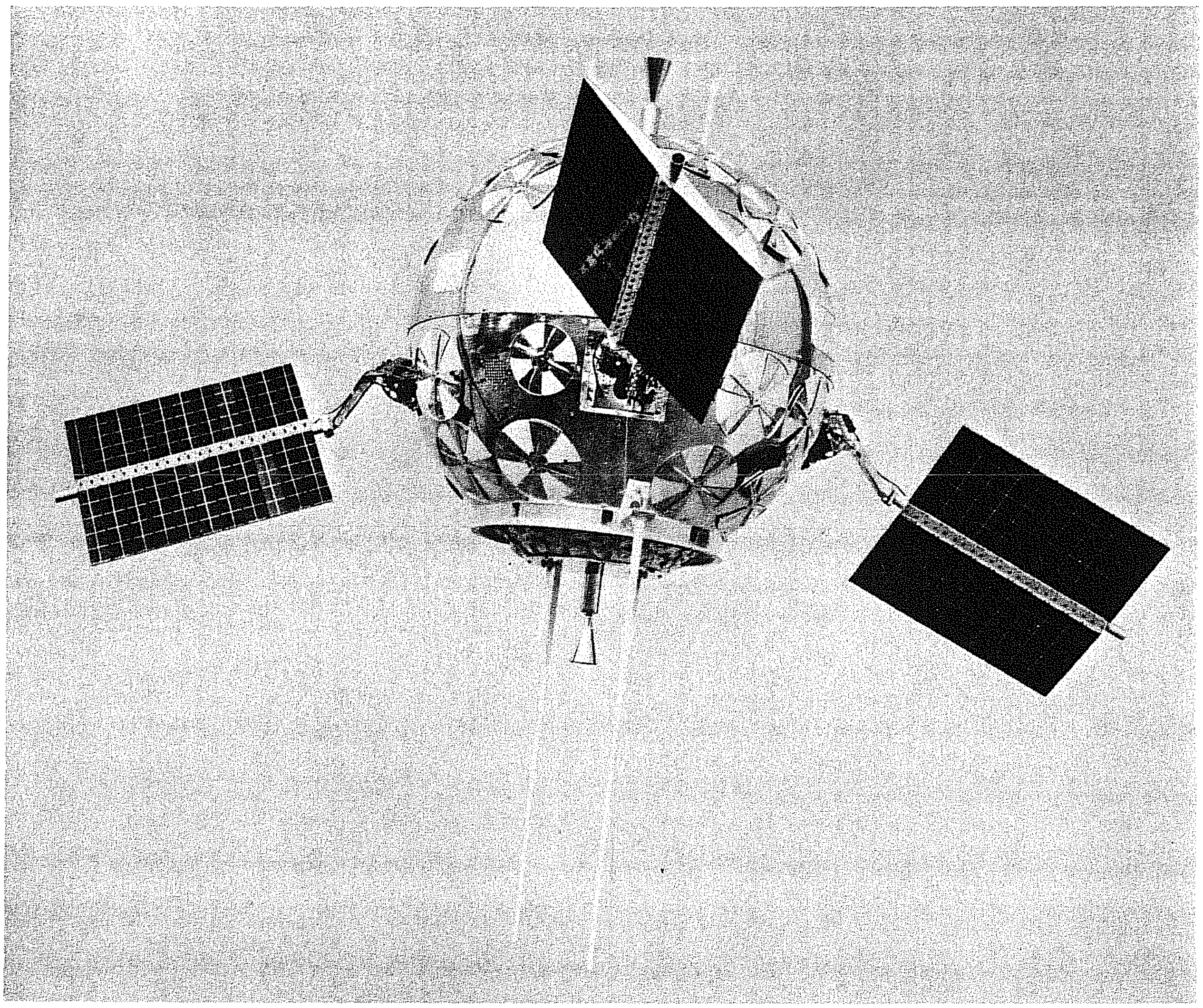

Figure 15. The Able-4 Atlas Payload.

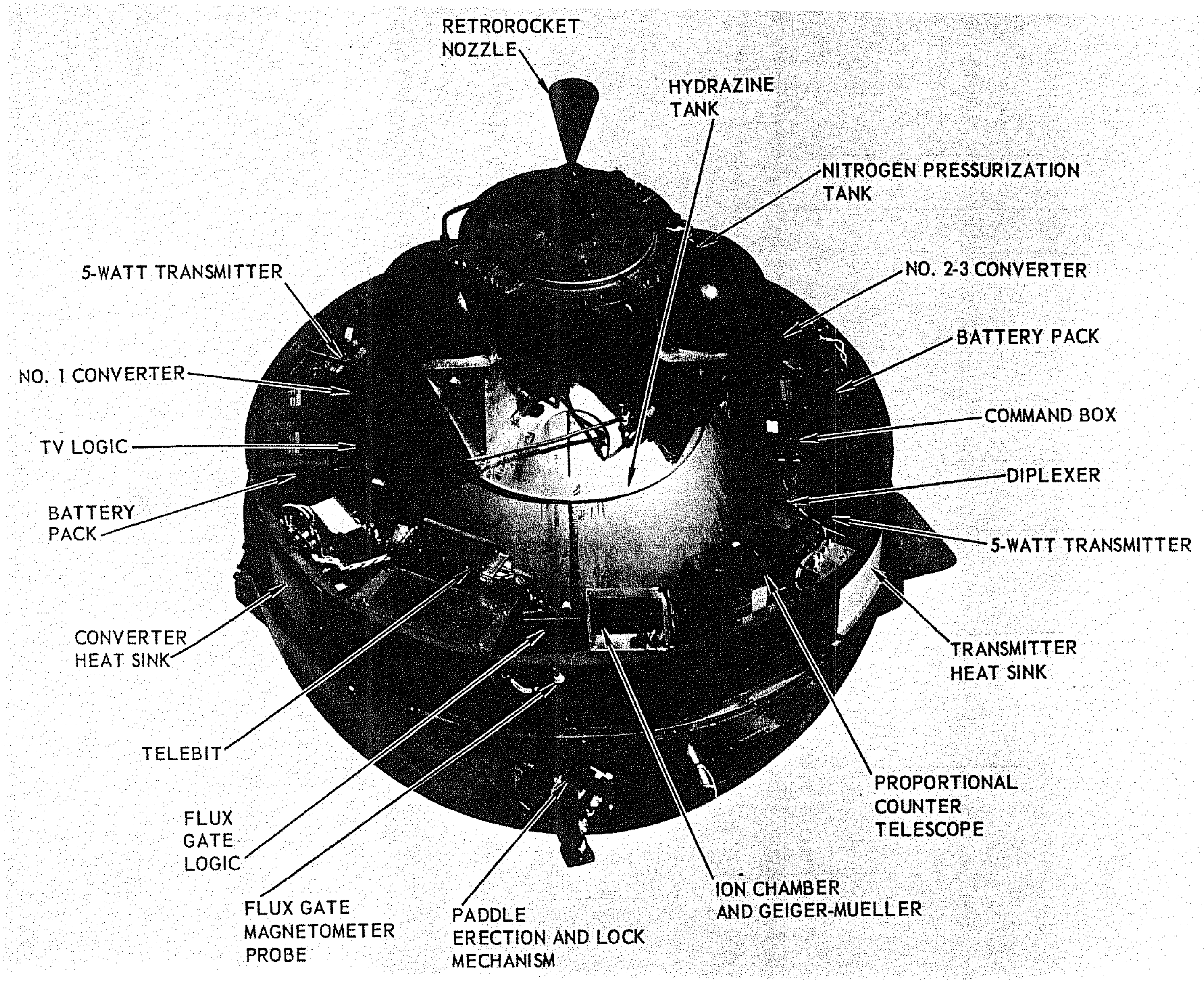

Figure 16. Internal View of Able-4 Atlas.

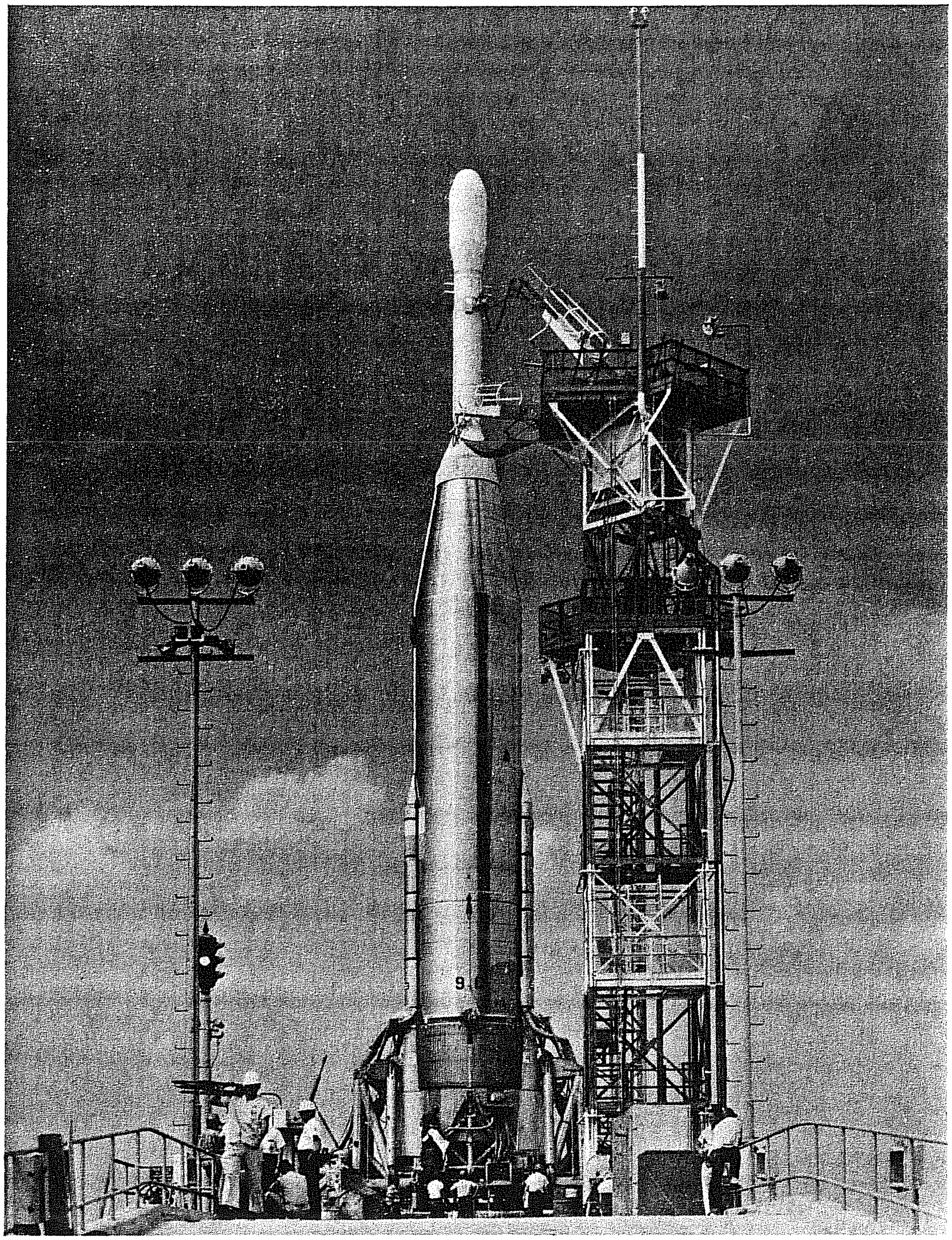

Figure 17. The Able-4 Atlas Vehicle.

4. The Space Navigation Network

The Space Navigation Network established for the Able probes consists of four ground stations and a central control center which can be linked with additional cooperative stations when necessary. The four stations are located near Manchester, England, at the Cape Canaveral launch site, on the island of Hawaii, and near the city of Singapore. The control center is at the headquarters of Space Technology Laboratories in Los Angeles.

The ground stations employ both parabolic and helical antennas for space communication, both types steerable by remotely-controlled motors. Two sizes of parabolic antennas are used both for transmission and reception, 60 feet at Hawaii and 250 feet at Manchester. The helical antennas are 21.5-turn, 5-element arrays.

The stations use several types of receivers for tracking and telemetry reception in the VHF or UHF range. All are phase-locked loop receivers utilizing correlation detection for recognizing weak signals. The antenna feeds the incoming signal through a parametric amplifier and a second preamplifier to the first mixer. Front end receiver noise is thereby limited to 2 db.

Two principal types of transmitters are used in the SpaN Net stations, differing principally in their power outputs. Maximum power is 10 kw.

All telemetered data, both digital and analog, are recorded as received, along with various other items, on magnetic tape recorders. The digital and analog forms of data are each recorded additionally in special ways.

The digital information received is decoded and punched into paper teletype tape, along with interlaced time signals. The decoding consists of punching into the paper tape a sequence of 1's and 0's representing the original sequence of bits in the payload registers.

Analog data from the VHF telemetry is detected at the ground stations, and transcribed on reproducible oscillograph paper, in parallel with the magnetic tape recording.

The perforated tape is used to teletype quick-look digital data to Los Angeles, following which all of the tape is mailed. When teletyped, a duplicate paper tape is punched from the transmitted message as it is received at the STL SpaN Center. The oscillogram strip charts are also mailed to STL, along with the primary magnetic tapes containing the raw data.

For exact time information, the stations are provided with very-stable crystal oscillators accurate to one part in 10^9 on a long-term basis. These oscillators generate basic frequencies for the transmitter, receiver, and digital clock.

Before the launch of any space probe, nominal trajectories are computed, on the basis of which antenna steering data are computed and sent to all stations planning to track the vehicle. These are used to plan tracking periods and to aim the ground antennas until more accurate data from postlaunch tracking is available. After the missile is launched, tracking data is teletyped to the SpaN Center, where increasingly more accurate estimates of the actual trajectory are calculated on an IBM 709 to provide refined antenna steering data to all ground stations.

The recalculation of trajectory and steering data proceeds on a continuing basis throughout the useful life of the payload. The task operates on a full-time basis from launch until a satisfactorily accurate trajectory has been determined. During this initial postlaunch period the goal is to establish a sufficiently accurate trajectory to determine the probable degree of success of the operation and to insure that all tracking stations have accurate steering data. Thereafter, trajectory recalculations are performed as the particular mission requirements dictate.

Before each launch a detailed data acquisition plan is established by SpaN Center, covering the periods when the individual ground stations will track, command the various functions of the payload, and record telemetry. Power supply and power drain in the payload are calculated to maximize the operating lifetimes of the payload instrumentation. After launch SpaN Center keeps watch of telemetered payload conditions and views these in the light of the total postlaunch conditions. It may be necessary, as in the case of Pioneer I, to direct commands to the payload quite different from those anticipated.

The Manchester and Hawaiian stations are used as the principal command stations. The Florida site concerns itself with early guidance commands, but, with Singapore, is used primarily for tracking and telemetry reception. The fact that Manchester and Hawaii are on opposite sides of the world permits almost complete command capability for a space probe throughout 24 hours, until the range of the 60-foot antenna at Hawaii is exceeded, which for Pioneer V will be about 15 million miles.

5. Results

Not all of the scientific results from even the first of the Able space vehicles can be known yet because exhaustive study of the great quantity of information obtained will take years, and major conclusions may still be forthcoming. Particularly interesting will be the results of comparisons of parallel measurements, such as the quantitative relationships among the various radiation and magnetic solar flare effects at extremely high altitudes.

However, these vehicles have given us many measurements whose value has indeed been promptly apparent. Pioneer I provided the first experimental verification of the Van Allen radiation belt and told us the depth of the belt. Thus the orbit of Explorer VI could be shaped to traverse the belt entirely and give us a complete map of its shape and energy content. Explorer VI discovered contours and irregularities in the outer regions of the belt, at 35,000 to 40,000 km.

The Pioneer I magnetometer discovered the existence of fluctuations at the fringe of the geomagnetic field, a discovery so startling that it was thought incredible until verified by both Explorer VI and Pioneer V. These fluctuations, at altitudes of 42,000 to 45,000 km, provide evidence of an interface of the magnetic field with a plasma wind originating at the sun, and provide data to test the hypothesis that this is the cause of the radiation belts. Explorer VI showed on the other hand that at lower altitudes the geomagnetic field is more regular than had been anticipated.

Moreover, the existence of a large electrical current system at the outermost edge of the earth's atmosphere, ranging from 1.5 to 3 million amperes, has been uncovered by the series. Pioneer V has indicated that this phenomena extends to the sunlit side of the earth; Explorer VI observed it on the dark side. This current is very possibly the cause of the polar aurora.

Results of the series of micrometeorite measurements seem to show that space is emptier of these particles than radar study of atmospheric ion trails has led us to expect.

The Able series has in addition provided major advances in space technology. Most important of these are the integrated tracking, telemetry, and command system now in operation with Pioneer V; the self-sustaining solar cell power conversion system for long-term payload operation; the passive and active temperature control schemes; and the radio system for accurate midcourse guidance of space vehicles.

In sum, it can be said that the Able development program has led to space vehicles and a supporting system of some noteworthy achievements. On the basis of these achievements the immediate future should see significant growth in at least four areas: (1) improved reliability, (2) greater sophistication in telemetry preprocessing, (3) extended range capability, and (4) more precisely defined space experiments as this environment becomes more completely understood.