A TRACKING AND COMMAND SYSTEM FOR SPACE APPLICATIONS

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SUMMARY

This paper describes the payload command and tracking equipment developed by STL for use on the recent Able-3 and 4 space missions. This equipment consists of a coherent transponder and a digital command decoder which provide a tracking and command capability at interplanetary distances.

INTRODUCTION

In December of 1958, the National Aeronautics and Space Administration (NASA) directed STL to proceed with the Able-3 and Able-4 space programs with initial equipment deliveries scheduled 3-1/2 months later. These programs produced an elliptical orbit earth satellite used to study the space environment about the earth (Explorer VI), and a deep space probe (Pioneer V) extending our knowledge of the physics of the inner solar system. Both of these flights established basic parameters relating to communication and guidance for future space missions.

To meet the requirements of these missions, the tracking and command system had to provide for precise ephemeris determination and for control of up to 64 payload functions at distances in excess of 50 million miles. The vehicle payload capability of less than 150 pounds for each of the missions, the complexity of the scientific experiments, and the characteristics of the space environment imposed many severe constraints on the system design. Preliminary estimates indicated that a weight allowance of less than 15 pounds, and less than five watts of continuous power would be available for the tracking and command system. Moreover, the command system was required to operate continuously in order to permit ground control of the payload at all times. These considerations eliminated any possibility of utilizing vacuum tubes, except for intermittent, high power transmission. The equipment was required to perform not only during the severe acceleration and vibration associated with the boost phase, but also during the many weeks of unattended operation during coast thru space. A six-month lifetime goal was established; therefore reliability was a prime consideration.

The payload attitude was controlled on these missions by spin stabilization thus imposing a requirement for essentially an isotropic antenna system with its phase center on the payload spin axis to prevent phase modulation of the received and transmitted signals. The performance requirements imposed on the payload tracking and command system were primarily related to sensitivity, doppler accuracy, and command capability. The sensitivity required as a function of range for the various STL ground stations is shown in Figure 1. The 250-foot radio telescope at Manchester, England offered the greatest capability for transmission and reception, and was, therefore, selected as the primary ground facility for the Able-4 Thor deep space probe. An acquisition and command sensitivity goal of -140 dbm (.02 μv) was required to provide an adequate sensitivity margin for the payload receiver. The development of a coherent phase-lock transponder with an associated digital command decoder was undertaken as a means of satisfying these requirements without violating the several constraints mentioned above. The transponder consists of a transistorized, double-conversion, phase-lock receiver which provides a coherent drive signal to a UHF transmitter.[1] A flexible command capability was provided by a digital command decoder. This general type of transponder is, in effect, a narrow-band tracking filter for the doppler-shifted received signal. The retransmitted signal can then be processed at the ground station to extract precise doppler information since frequency drifts are not introduced in the airborne unit. The narrow noise bandwidth is achieved by proper design of the receiver loop filter and bears no relationship to the predetection IF bandwidth. In addition, coherent demodulation of command signals is provided at the receiver loop phase detector eliminating the signal-to-noise ratio degradation effects exhibited by conventional detectors.

Operating frequencies near 400 mc were selected after considering such items as system efficiency, receiver noise figure using solid-state devices, propagation anomalies, and galactic noise.

[1] An earlier single-conversion phase-lock receiver-transponder at 108 mc was developed by STL for use in the Able-1 program. See "Two Way Doppler and Command Link for Space Flight" by H. A. Samulon and R. E. Graves - STL internal publication, October 17, 1958.

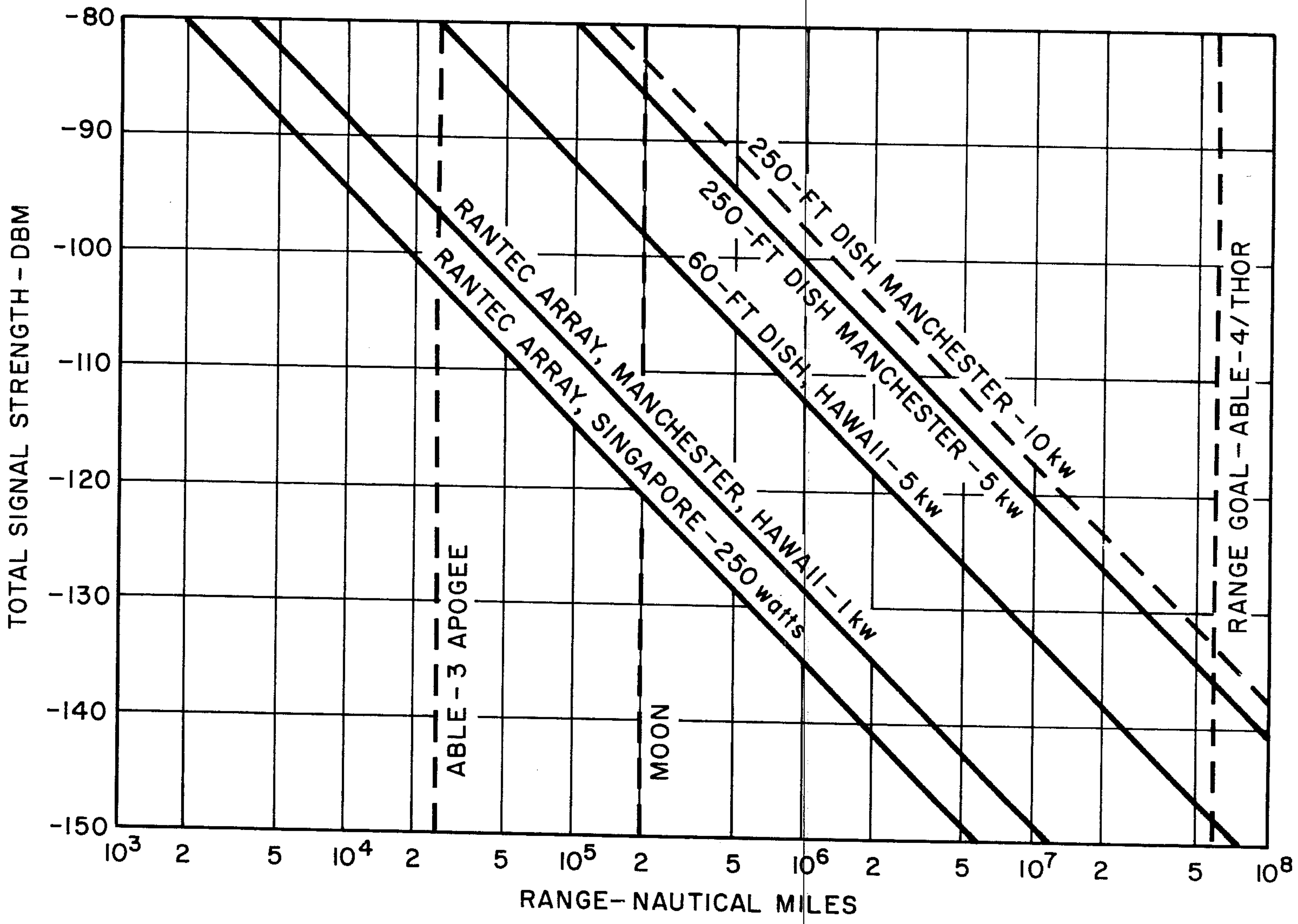


Figure 1. Signal Strength at Payload as a Function of Range from the Able Tracking Stations

A payload transmitter power of five watts for use up to approximately 10 million miles, and of 150 watts thereafter was specified based on attainable ground station sensitivities, payload power supply capacity, telemetry duty cycle, and information rate. The transmitters are activated on command and because of the high power levels required, utilize vacuum tubes as their active elements.

An abbreviated block diagram of the communication system is shown in Figure 2. The received signal (f_{rec}) is directed from the antenna, thru the diplexer, to the command receiver. The receiver processes this signal and provides a coherent output at exactly two-seventeenths (2/17) of the received frequency. This output serves as drive for the payload transmitter. The transmitter amplifies and multiplies the frequency of its input by a factor of eight to produce a coherent output at exactly 16/17 of the received frequency. This output is passed thru the diplexer and retransmitted on the common antenna.

The diplexer contains the necessary filter elements to isolate the transmitter output from the sensitive receiver input circuits and, in addition, contains the receiver preselection filters. The 16/17 ratio of transmitted-to-received frequency was selected after considering such constraints as antenna bandwidth, diplexer filter element capabilities, and convenience of mechanization in the phase-lock-loop.

The demodulated command subcarrier output from the receiver is fed to the digital decoder for command processing. This binary code is transmitted as the presence (1), or absence (0), of an audio frequency phase modulation on the carrier. Each command is a 13-bit sequence containing a 6-bit message plus seven bits for synchronization and error detection. The decoder output controls the various payload functions and is in the form of relay closures. The transponder is also used for transmitting digital telemetry by phase modulating the transmitter with a 1024-cps biphase modulated digital sequence from the payload telemetry system. This telemetry system processes all experimental outputs as well as several payload performance sensors. These basic elements thus form an integrated tracking, command, and telemetry system.

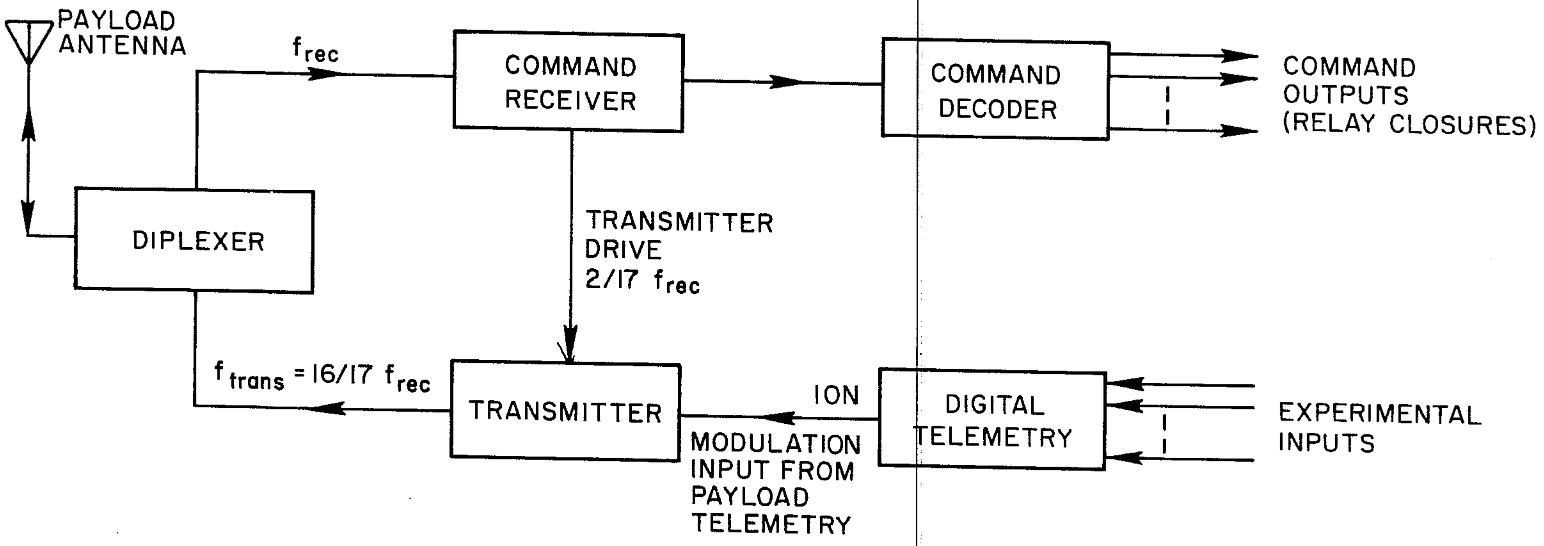


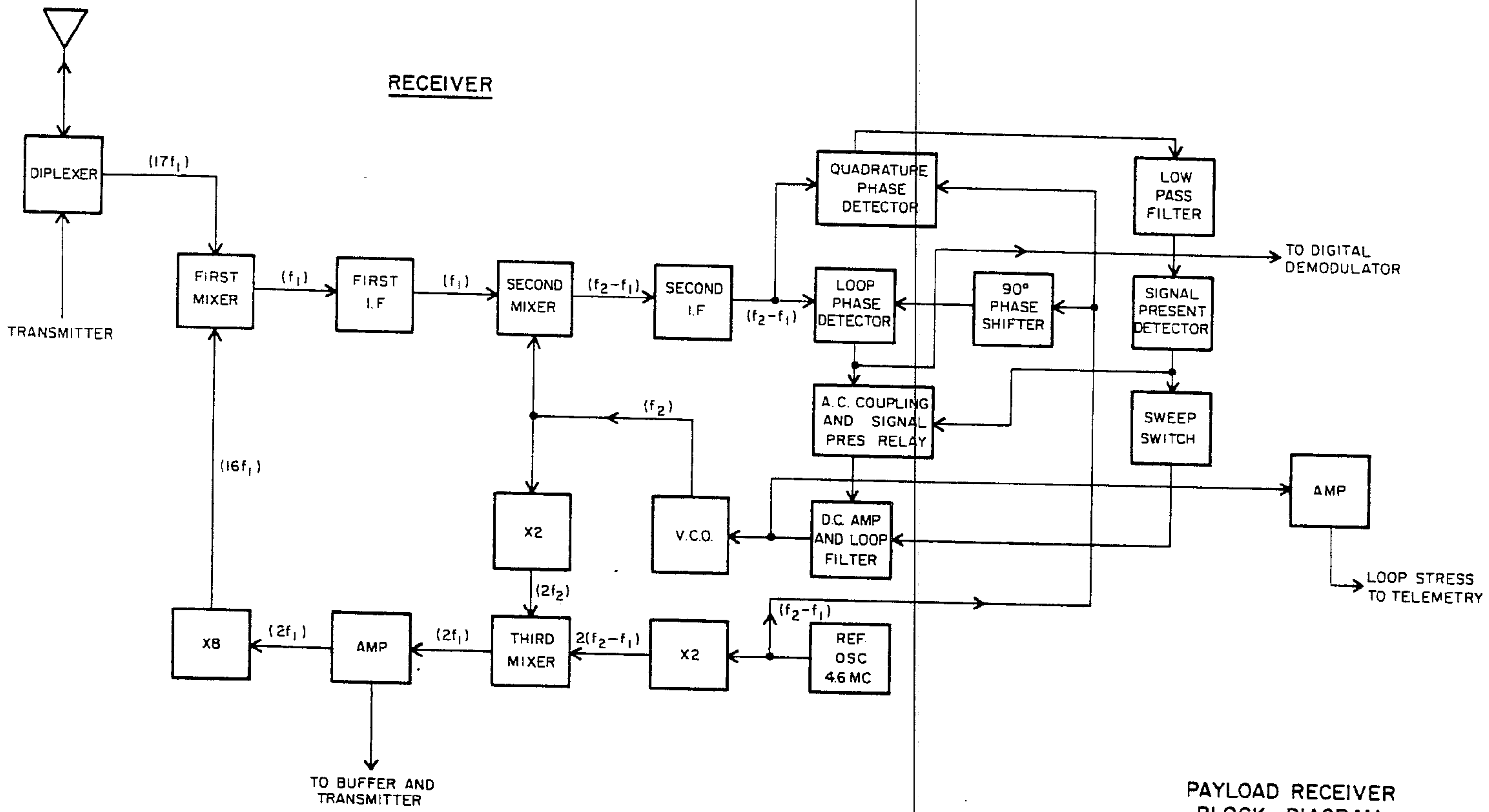
Figure 2. Simplified Block Diagram of Payload Communication System

RECEIVER DESIGN

A more detailed block diagram of the command receiver is shown in Figure 3. The received frequency ($17f_1$) is mixed in the first mixer with a locally generated signal whose frequency is approximately $16f_1$. The difference frequency, f_1, is amplified and band-limited in the first IF amplifier. This signal is then mixed with the voltage controlled oscillator frequency, f_2, to produce a difference frequency of $(f_2 - f_1)$. After amplification in the second IF amplifier, this signal is applied to the phase detector. The second phase detector input is a locally generated reference oscillator signal, $(f_2 - f_1)$. The outputs of the VCO and reference oscillators are doubled, and then mixed in the third mixer to produce an output at $2f_1$. This is subsequently amplified, multiplied by eight, and applied to the first mixer at $16f_1$, as mentioned earlier. The output of the phase detector is amplified, filtered, and returned to the VCO control input to complete the feedback loop. The feedback controls the VCO frequency and phase such that the coherent 16/17 ratio is maintained at the first mixer, and a quadrature relation between the two inputs to the phase detector is established.

This form of coherent loop has several rather unique features. First, it should be noted that a reference offset has been achieved, $(f_2 - f_1)$, but that instabilities in the reference oscillator frequency do not appear in the coherent outputs at $2f_1$ of $16f_1$. In addition, neither f_1 nor odd multiples of f_1 (such as $17f_1$) are generated in any of the oscillators or as mixer products. These can be created only by direct leakage of VCO and reference oscillator signals into the third mixer. It is clear that if this form of product were generated in a receiver of this general type, self-acquisition could occur, preventing a phase-lock to the desired signal. No tendency to self-lock has ever been observed in these receivers.

The receiver operates continuously and, since its bandwidth is considerably narrower than the received frequency uncertainty, its center frequency is repeatedly swept over a narrow spectrum searching for a carrier. The sweep generator is disabled after acquisition. Figure 4 shows an abbreviated block diagram of the loop amplifier-filter and associated sweep circuitry.



PAYLOAD RECEIVER
BLOCK DIAGRAM

Figure 3.

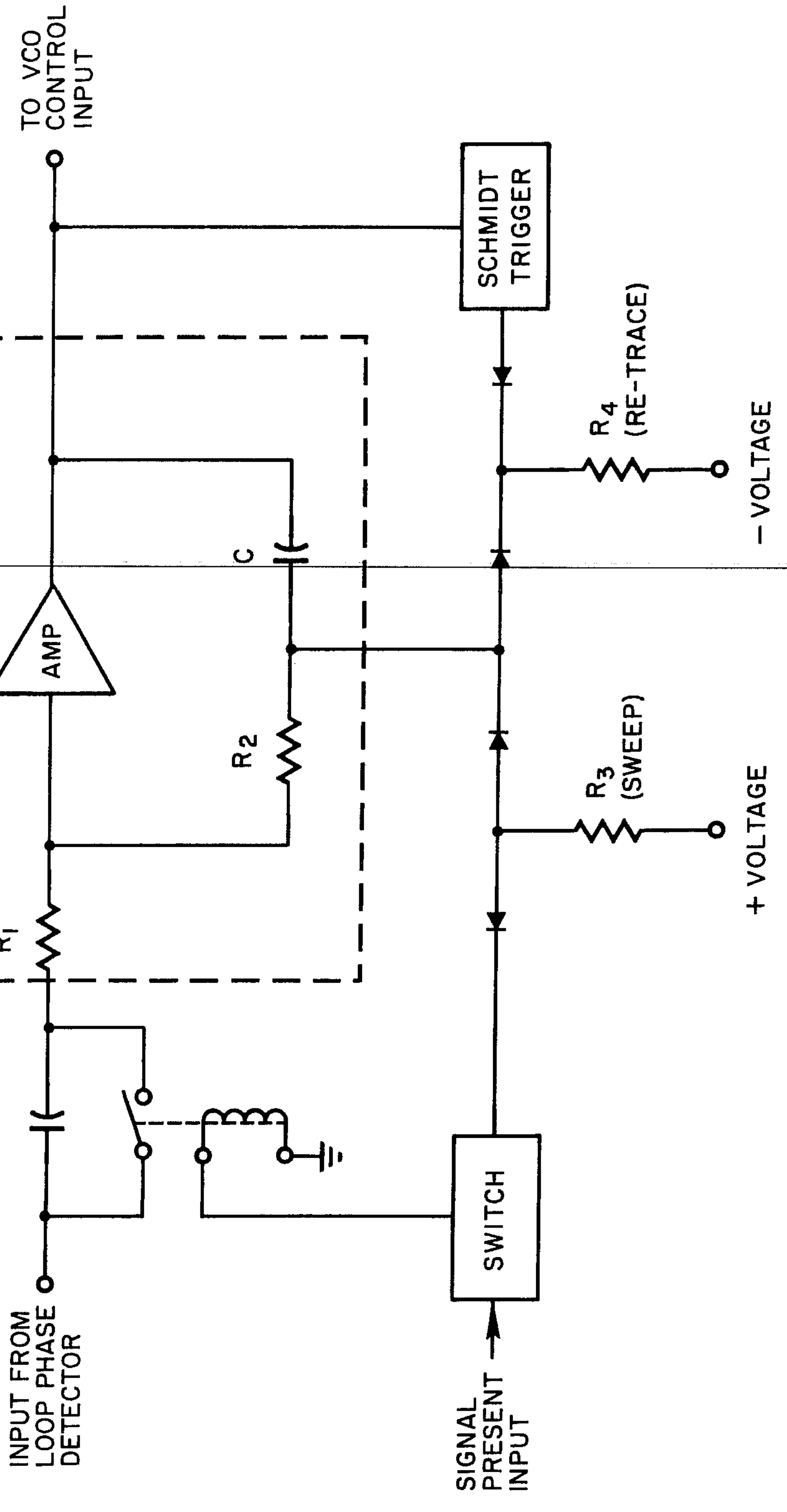


Figure 4 Simplified Loop Filter Block Diagram

This figure shows the feedback amplifier implementation of the double time constant filter which has been shown in the literature to be the optimum loop network for this application. The choice of loop bandwidth was a compromise between achieving maximum sensitivity and providing the dynamic tracking capability required to accommodate the rates imposed by vehicle acceleration and signal acquisition.

In order to meet all of these requirements it was necessary to provide a 240-cycle noise bandwidth for the early portion of the flight and a 40-cycle noise bandwidth for use at maximum ranges. These bandwidths, selectable on command, allow the receiver to search a 26-kc range in ten seconds in the wideband case, and 13 kc in three minutes in the narrowband case. With these bandwidths, the receiver will track, with an error of less than .1 radian, accelerations of seventy earth gs and 1.9 gs in the wide and narrow band cases respectively.

In order to provide automatic acquisition, a sweep voltage is superimposed on the output of the loop filter during the search mode by injecting a small charging current thru resistor R_3. This current is integrated and produces a voltage ramp to be applied to the VCO. The output is sampled by a Schmidt trigger which resets the sweep at a predetermined voltage. The receiver sweep range is determined by this voltage ramp and is, because of this sampling techniques, relatively independent of accumulated loop amplifier and phase detector drifts and offsets. The sweep circuitry is disconnected by a signal-present voltage derived from a quadrature phase detector.

DECODER DESIGN

After considering a number of command systems, both analog and digital, it was determined that, in view of the large number of commands required, a digital system would provide the needed capacity and flexibility with the greatest efficiency.

In determining the command structure, consideration had to be given to the number of commands required, the consequences of executing certain false commands (i.e. premature ignition of vernier engines or retrorockets), the required sensitivity, and the time available to transmit a command.

The time scale involved in vernier engine firings placed an upper limit of about twenty seconds for transmission of a command. Preliminary estimates of command requirements indicated that at least thirty-one commands would be required. In order to allow for contingencies, six command bits were provided. To minimize the possibility of executing a false command and to provide for simple implementation, the logic was designed to require that both the command and its exact complement be received. This required a total of twelve bits. A thirteenth bit provides a synchronization pulse.

Since a successful command reception requires the correct interpretation of thirteen successive pulses, a signal-to-noise ratio of 18 to 20 db must be achieved to obtain a satisfactory error rate. Considering the available signal power and the noise characteristics of the receiver, an effective noise bandwidth of 1 to 2 cps must be achieved in the decoder filters. Thus each pulse should be at least one second long.

A command structure was therefore adopted which consisted of thirteen pulses (one sync, six command and six error-detecting) each one second long with a repetition rate of 1 pps. This repetition rate was used since it was consistent with clock pulses available from the digital telemetry unit to be carried in the payloads.

A simplified block diagram of the digital decoder is shown in Figure 5. This transistorized unit takes the command-modulated subcarrier and converts it to relay closures. The subcarrier is filtered, amplitude detected, further filtered, and applied to a threshold detector which determines if a "1" or a "0" is being received. The programmer generates a synchronous clock pulse and shifts the message into the 6-stage shift register. The second six bits are compared, as they are received, with the first six bits and, if a legitimate message (second six bits are the complement of the first six) is received, the programmer enables the command matrix, and the command is then executed. The 6-bit shift register and an 8 by 8 command matrix give a 64-channel command capability.

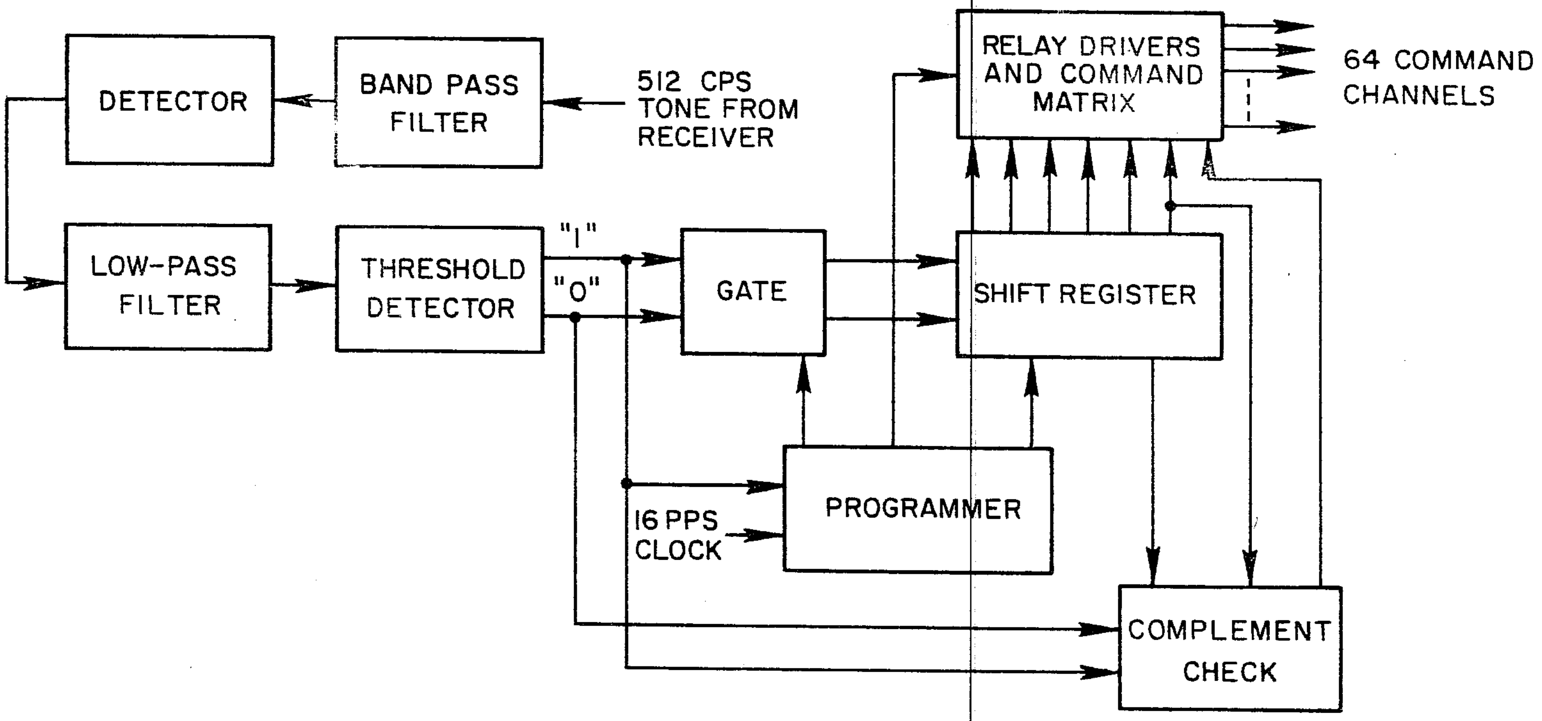


Figure 5. Simplified Command Decoder Block Diagram

Early scheduled delivery required that a more or less conventional technique be utilized to achieve the requisite filtering. The configuration adopted utilizes a 50-cycle bandwidth LC filter followed by a Q-multiplied LC filter providing an 8-cps bandwidth. The temperature-stabilized and aged toroidal coils utilized in the filter provided a drift of less than .2 cycles/month due to aging and about the same drift over the anticipated temperature range. The input wideband filter was used to reduce the dynamic range of the noise signals delivered to the Q multiplier. The 8-cycle bandwidth of the narrow filter assured that the signal-to-noise ratio at threshold would be above 8 to 10 db at the detector, preventing deterioration of signal-to-noise ratio during amplitude detection. The low pass filter following the detector provides the required 1- to 2-cps bandwidth.

The filtered command pulses are passed thru a fixed threshold circuit whose level is set at about four times the rms noise level. This circuit produces a "1" output for all pulses above this level and a "0" output for all pulses below this threshold.

The digital decoder was designed to incorporate many of the available TELEBIT[2] logical elements in order to meet equipment delivery schedules. A two-transistor flipflop is the basic binary storage element. Diode logic is utilized to provide logical gating of all counter and shift register elements thus providing a controlled shape trigger pulse for all flipflops. The gating technique used is similar to that described by C. L. Wanlass.[3] Figure 6 illustrates a basic AND gate which produces an output in synchronism with the clock pulse when all logical inputs are high.

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[2] R. E. Gottfried, "Explorer VI Digital Telemetry, TELEBIT." STL Internal Publication, February 3, 1960.

[3] C. L. Wanlass, "Transistor Circuits for Digital Computers" IRE Transactions PGEC, Vol. EC-4, No. 1, pp 11-16, March 1955.

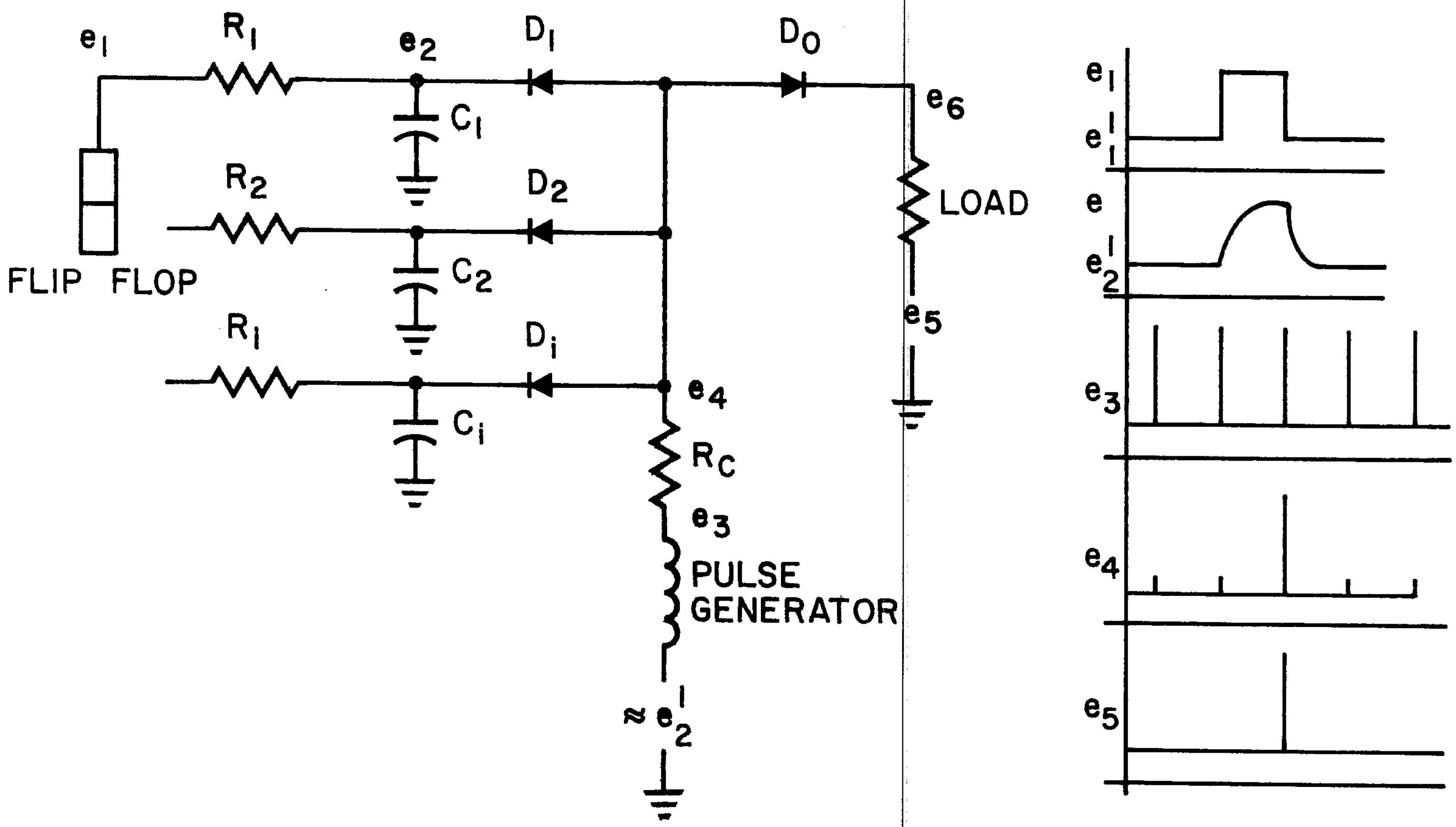


Figure 6. Typical Gate Circuitry and Wave Forms

As can be seen from the waveforms shown on this figure, the biases are chosen such that the clock pulses are "dumped" into capacitor C_1 when the corresponding input or inputs are in the "0" or low state and the resulting pulse at E_4 is therefore too low to overcome the back bias on diode D_o. When all of the inputs are in the "1" state, the pulse E_4 is allowed to rise to the input level E_1, thus exceeding the bias on D_o and triggering the load, The low counting rates utilized in the decoder allow large values of R_1 to be used, thus providing buffering of the flipflop. The elements R_1 and C_1 are included in the flipflop modules and are chosen in conjunction with R_c to provide a satisfactorily low level of logical noise.

A logical diagram of the decoder is shown in Figure 7. For simplicity, the internal gating required to cause programmer sections 1 and 2 each to count to 16 and the shift register to shift properly is not shown on this diagram. Waveforms S and S_1 represent a typical 13-pulse message sequence and its complement as provided by the threshold circuit. Time is taken as increasing from left to right on this figure. At T_o all flipflops in the programmer are in their initital condition with stages A to H in the "1" state. Under this condition, there is no output at gate 1. Sixteen-pps clock pulses are being supplied to gate 1 by the DTU. The first "1" pulse (sync) in the S signal opens the upper AND section of gate 1 allowing the next clock pulse to enter programmer 1. As soon as either section of the programmer is out of the "0" condition, OR gate 2 holds gate 1 open until a complete sequence is completed. Programmer section 1 now divides the 16-pps clock pulse by sixteen to produce a 1-pps clock train (T) at the output of gate 3. This gate is connected such that the first pulse in T occurs at the ninth clock pulse beyond T_o. This places each of the T pulses in the approximate center of the incoming message pulses. Programmer section 2 now counts sixteen 1-pps T pulses at which time it again reaches its initial position along with programmer section 1, thus closing gate 1 and ending its sequence. Gate 4 produces twelve sampling and shift pulses (Y) which are coincident in time with the twelve S pulses corresponding to the 6-bit message and its complement. These pulses sample the S and S_1 inputs in gate 6 and set the first stage of the shift registers to the corresponding state. At the same time the state of each stage is shifted down one stage. After the first six Y pulses have occurred, the first six message

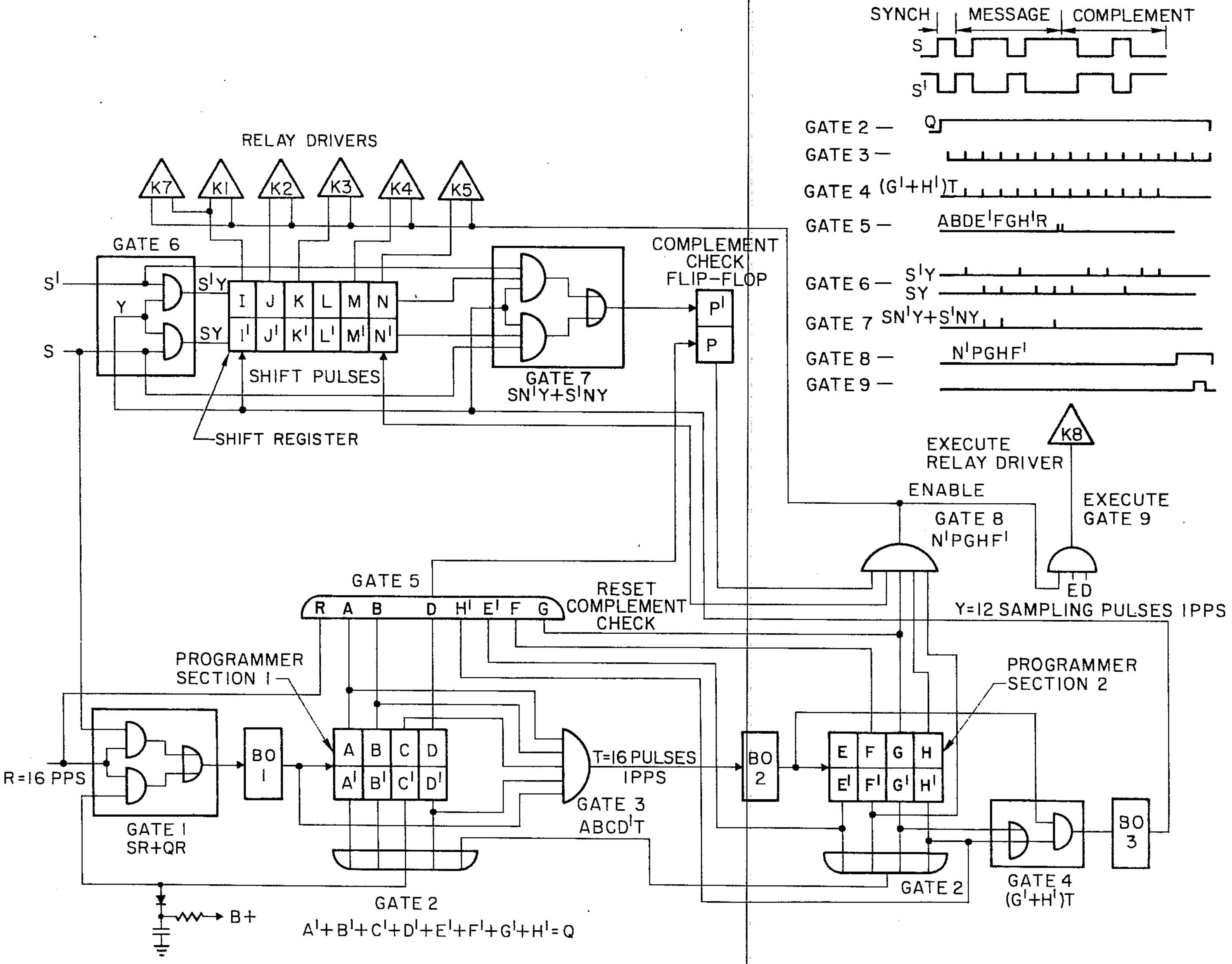


Figure 7. Digital Decoder Logical Diagram

pulses are stored in the shift register. At this time gate 5 provides a pair of reset pulses to the complement check flipflop (p), setting side P in the "1" condition. Gate 7 compares the input pulses with the state of the sixth stage and, if at any time they are not complementary, an output pulse is produced, setting complement check flipflop in the P_1 or "0" condition, indicating an invalid message. The remaining six pulses are now shifted into the register. Gate 4 closes at this time, removing the sampling and shift pulses and storing the message in the shift register. Gate 8 now opens for two seconds if a valid message has been received, and allows the matrix relay drivers to set the matrix relays to the proper states. One second later the execute gate (gate 9) opens for 1/2 second, closing the execute relay. The matrix shown is a 4 x 8 matrix providing 32 commands. The matrix relays connect the appropriate vertical line to B+ and the horizontal line to ground energizing the command relay or relays connected to the corresponding intersection.

EQUIPMENT DESCRIPTION

Figure 9 shows the various components contained in the Pioneer V communications system. These are the receiver, decoder, 5-watt and 150-watt transmitters, and diplexer.

Construction details of the first mixer and associated frequency multiplier module from the receiver are shown in Figure10. A Western Electric 2N509 transistor was selected as a 400-mc mixer, giving an overall noise figure of 10 db with 12-db conversion gain. The "times eight" frequency multiplication was achieved with a transistor doubler and a varactor quadrupler.

Figure 11 shows the first IF amplifier. This module exhibits a power gain of 70 db at approximately 25 mc. A 5.0 kc bandwidth is synthesized with a 4-element crystal lattice filter.

The second IF amplifier is shown in Figure 12. This chassis contains the second mixer, second IF amplifier, and phase detectors. The amplifier gain is approximately 80 db including 15-db conversion gain in the second mixer.

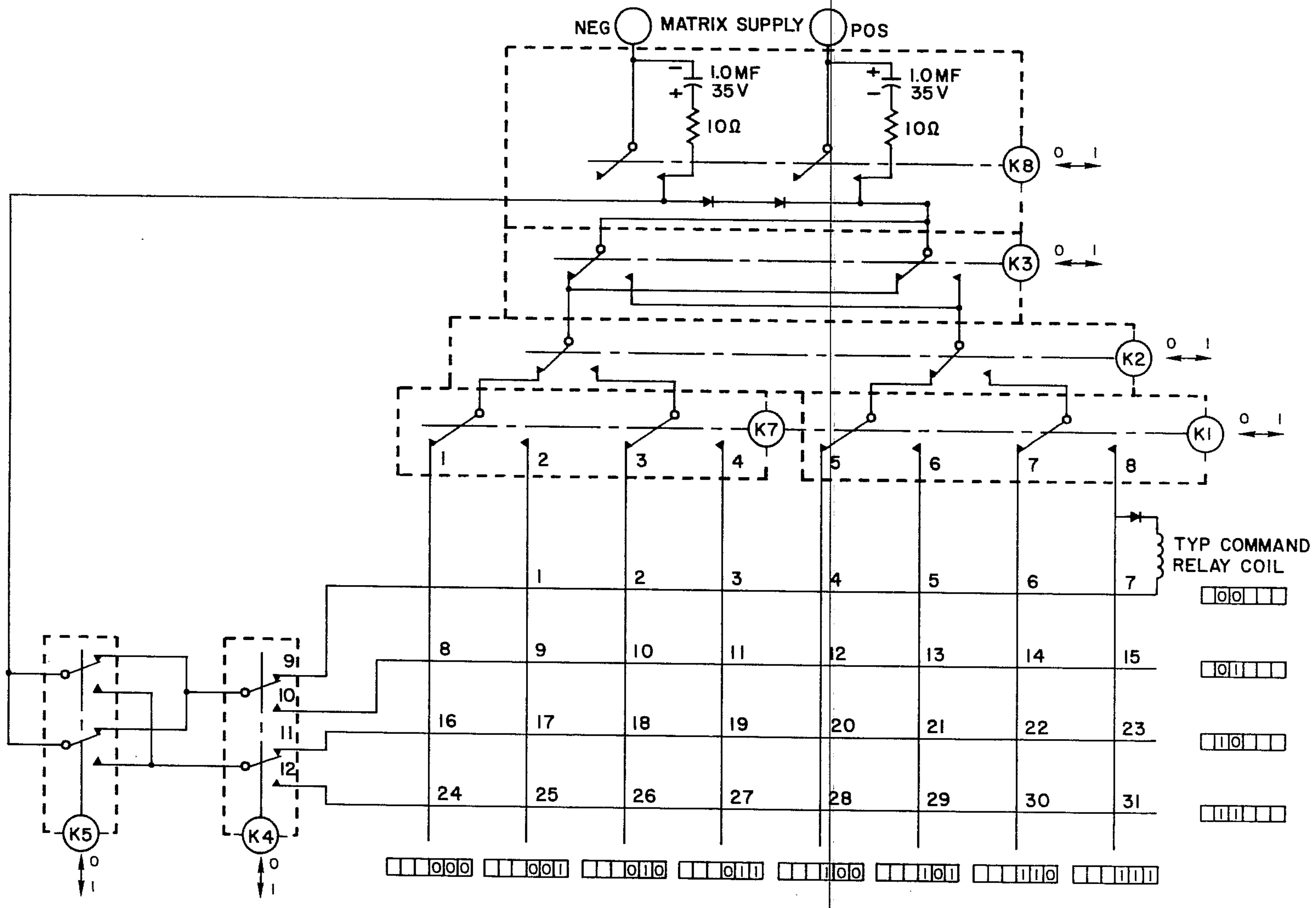


Figure 8. Command Matrix

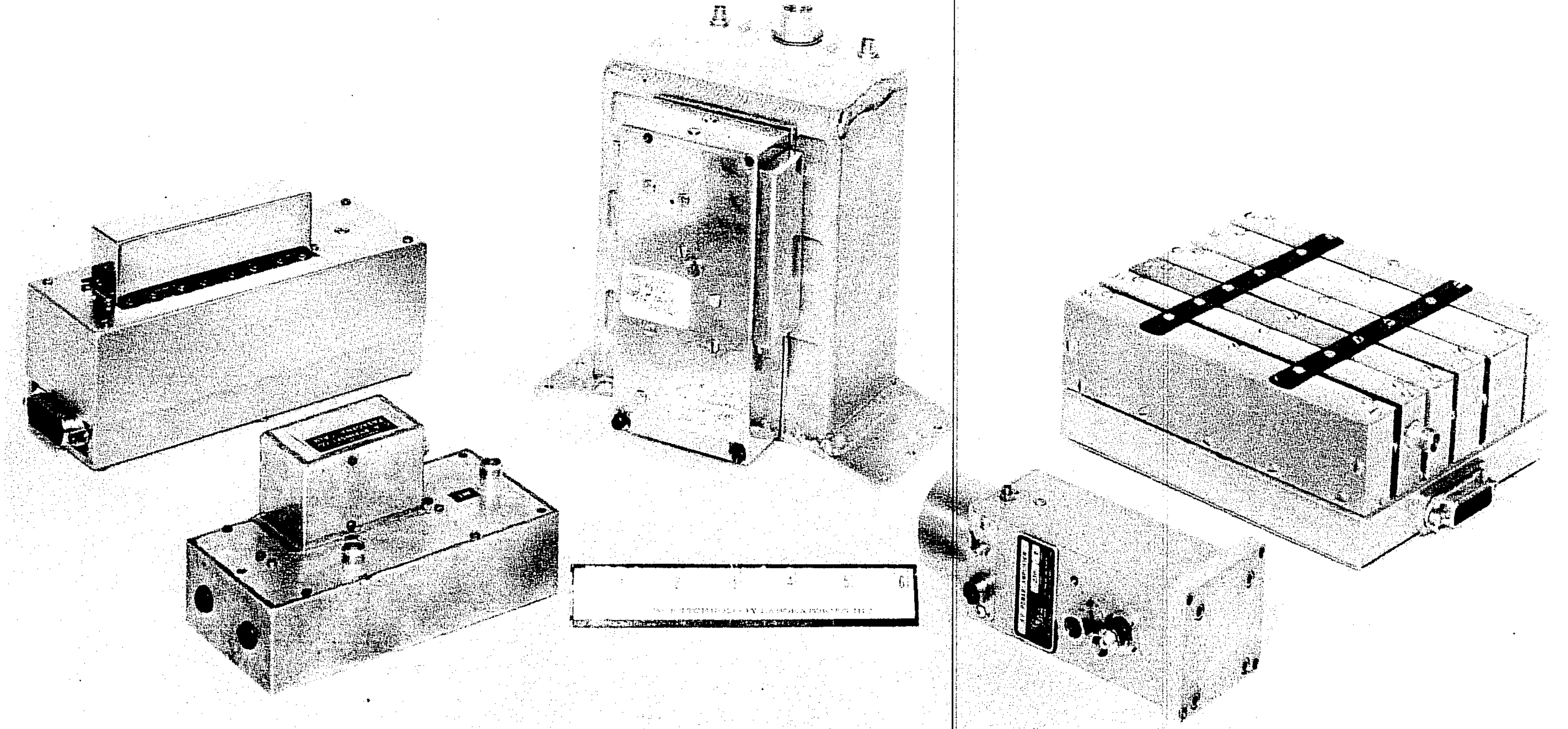


Figure 9 - Pioneer V S

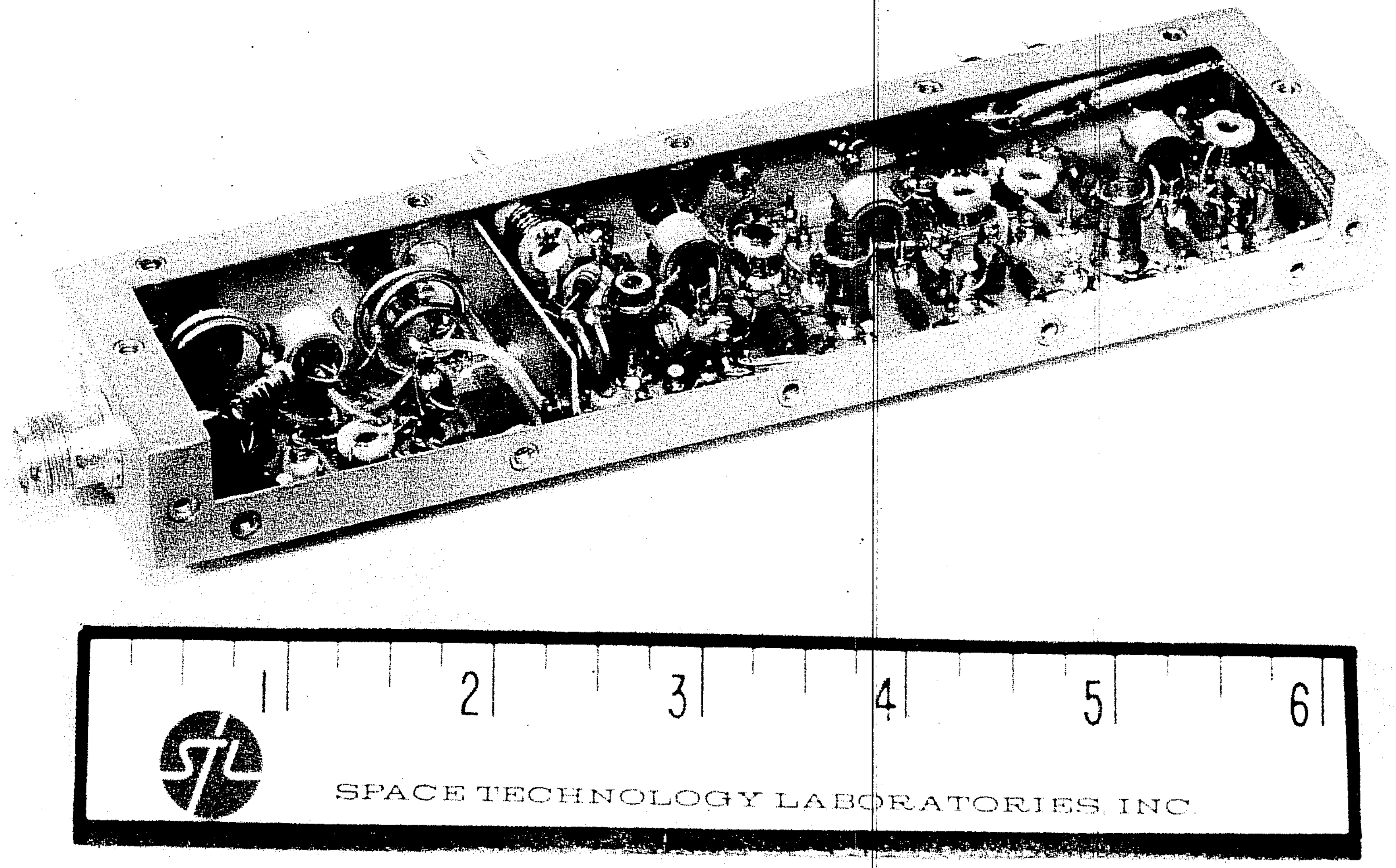


Figure 10 Frequency Multiplier

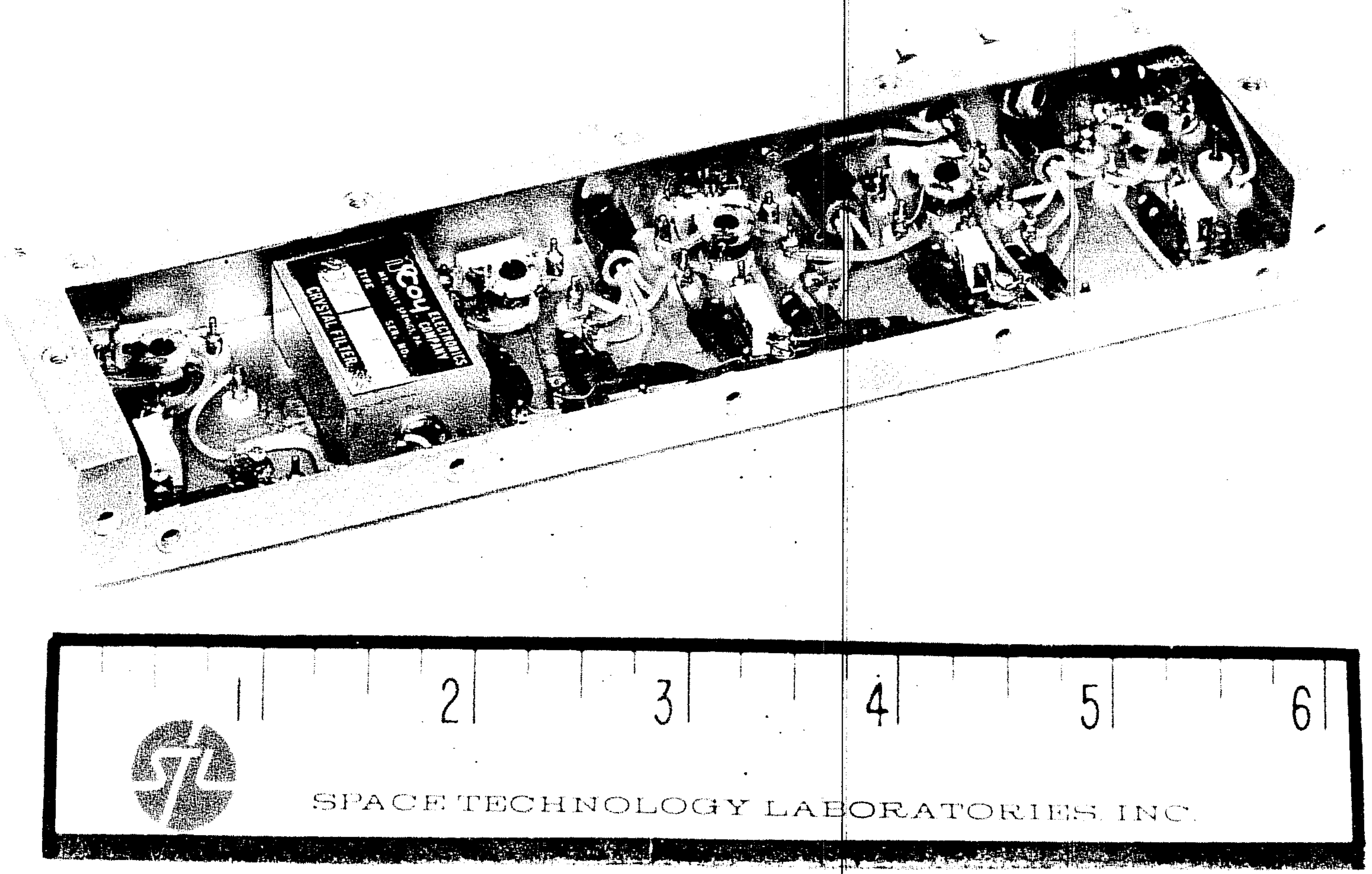


Figure 11. First IF Ampli

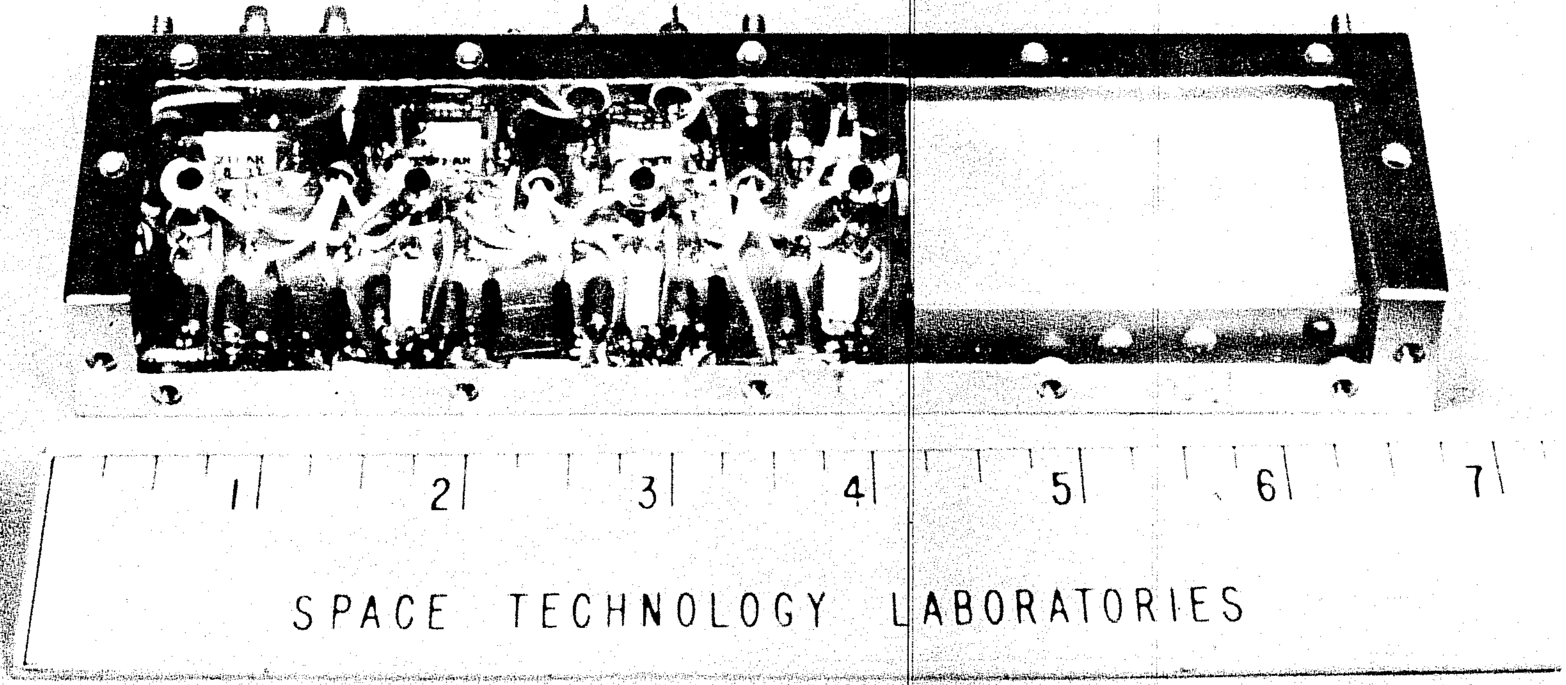


Figure 12. Second I-F Amplifier

Details of the VCO module are shown in Figure 13. This chasses also includes isolation amplifiers and a balanced frequency doubler. The oscillator frequency is controlled by a varactor diode in series with the crystal.

DECODER

Figure 14 shows the assembled decoder with duct covers removed. Figure 15 is a detailed view of the filter and detector card. Figure 16 shows the digital module collector card. Most of the logical elements are contained within the modules, however, those elements which changed from payload to payload were mounted directly on the printed circuit card. A detailed view of a typical logical element is also shown.

FLIGHT HISTORY

Explorer VI

The first flight for this system was in Explorer VI (Thor Able-3) illustrated in Figure 17. This payload was successfully placed in orbit with a Thor-Able rocket on August 7, 1959. A highly elliptical orbit was chosen with an apogee of 22,926 nautical miles and a perigee of 136 nautical miles. The communications system was successfully interrogated from ground stations in Hawaii; Singapore; Manchester, England; and Cape Canaveral, Florida. The satellite's 5-watt transmitter was activated by command fifty-nine times during the two months of radio contact. This payload contained a dual-coherency system with transmitters at 16/17 (378 mc) and 32/119 (108 mc) of the received frequency. The 108-mc transmitter was used for propagation experiments. An incoherent 108-mc telemetry transmitter was also included. The 108-mc transmitters were essentially operated continuously. Last transmission from the Explorer VI was on October 6th.

Figure 18 contains details of the payload system for this mission. Vast amounts of data were accumulated on radiation, magnetic fields, meteoric dust density, and radio propagation.

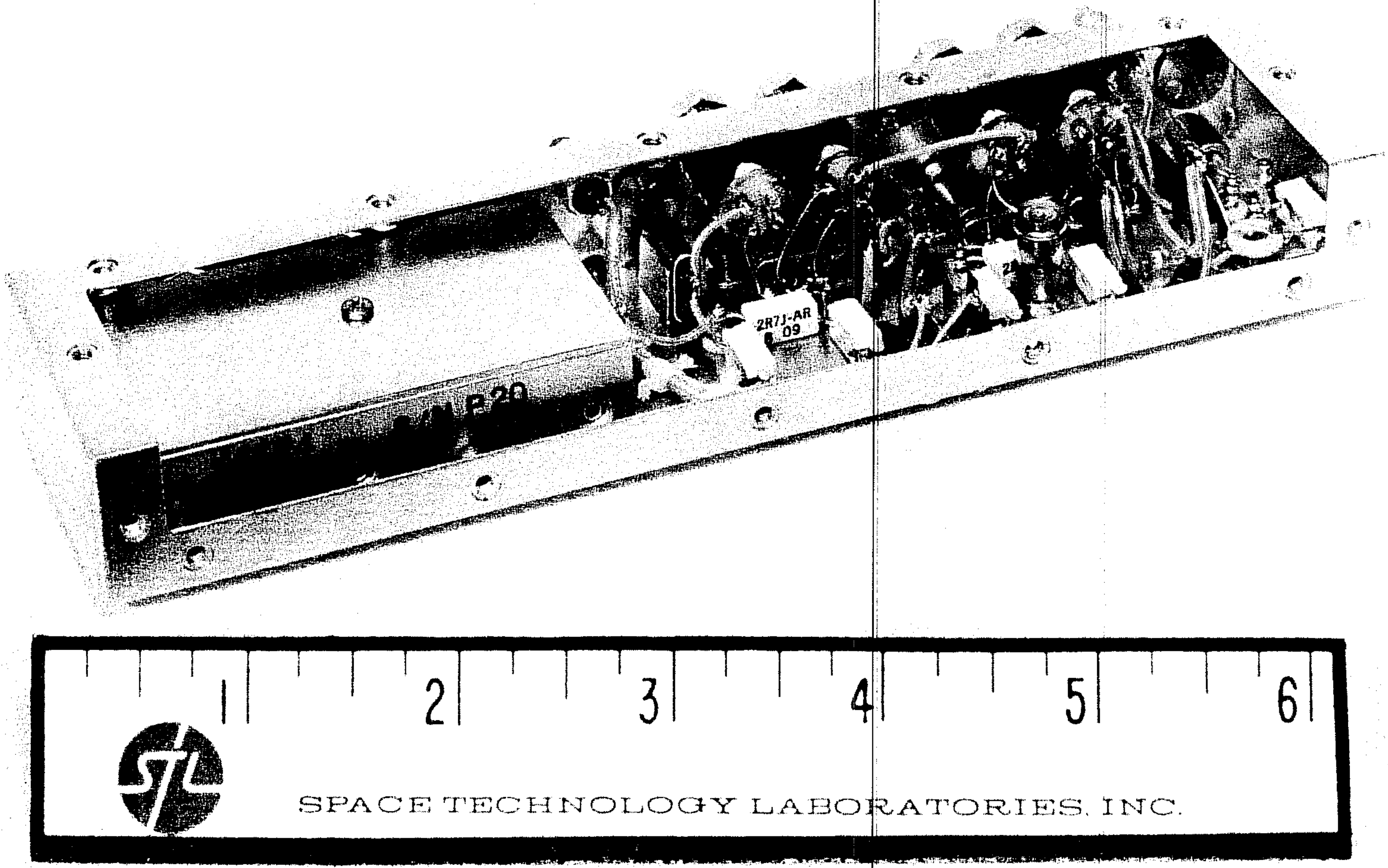
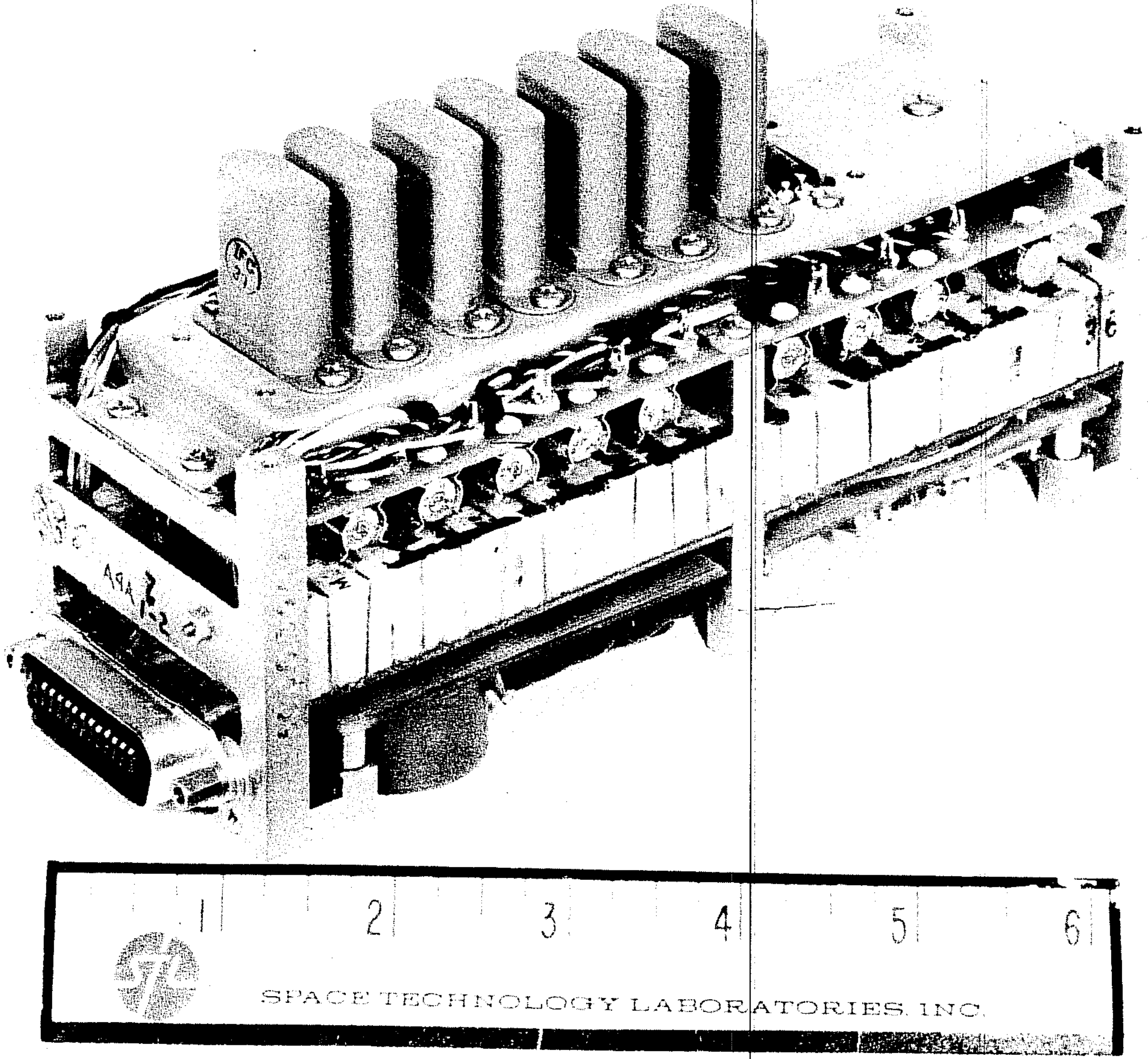


Figure 12. Voltage Controlled Oscillator



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SPACE TECHNOLOGY LABORATORIES, INC.

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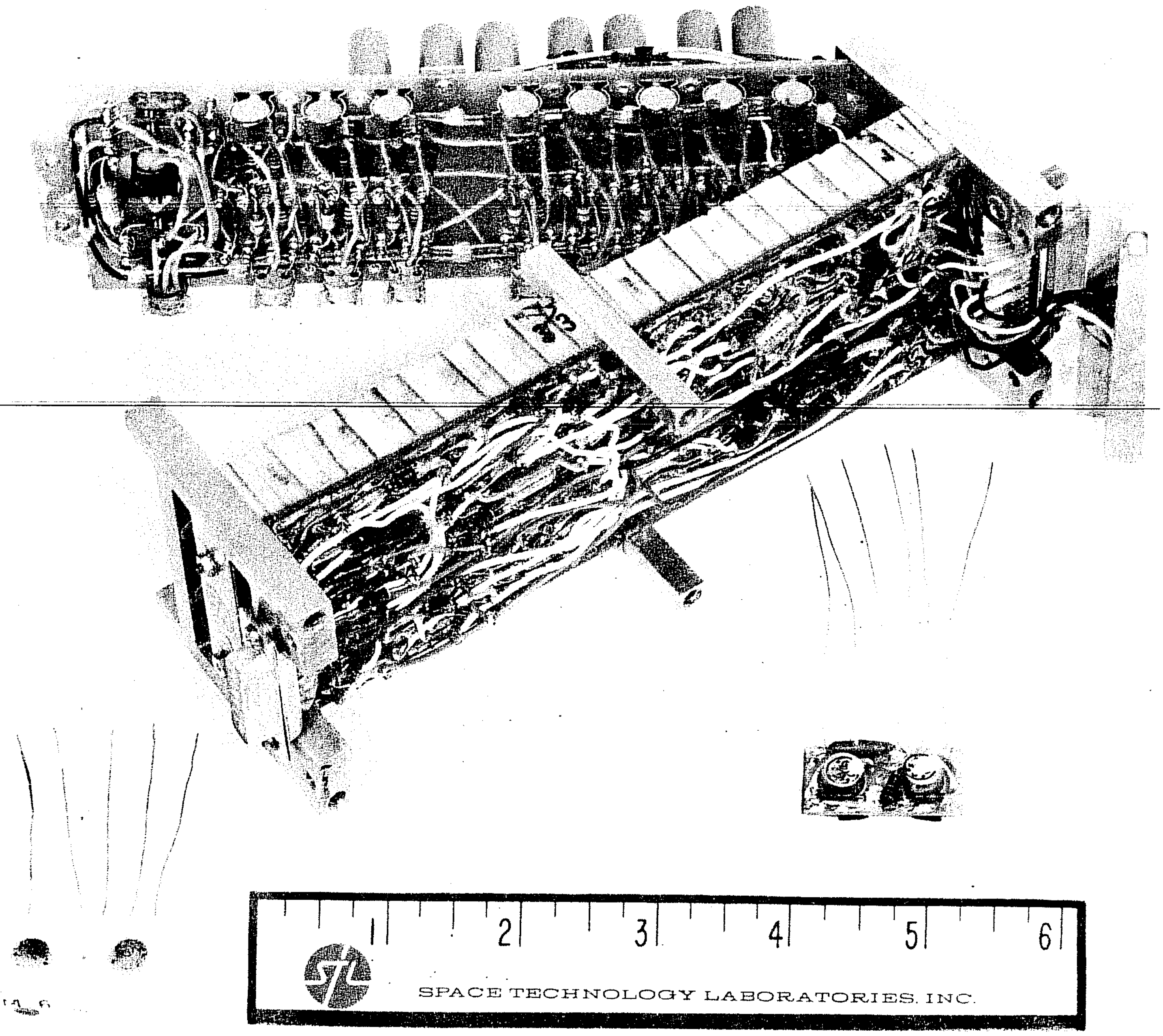


Figure 15 Decoder Assembly

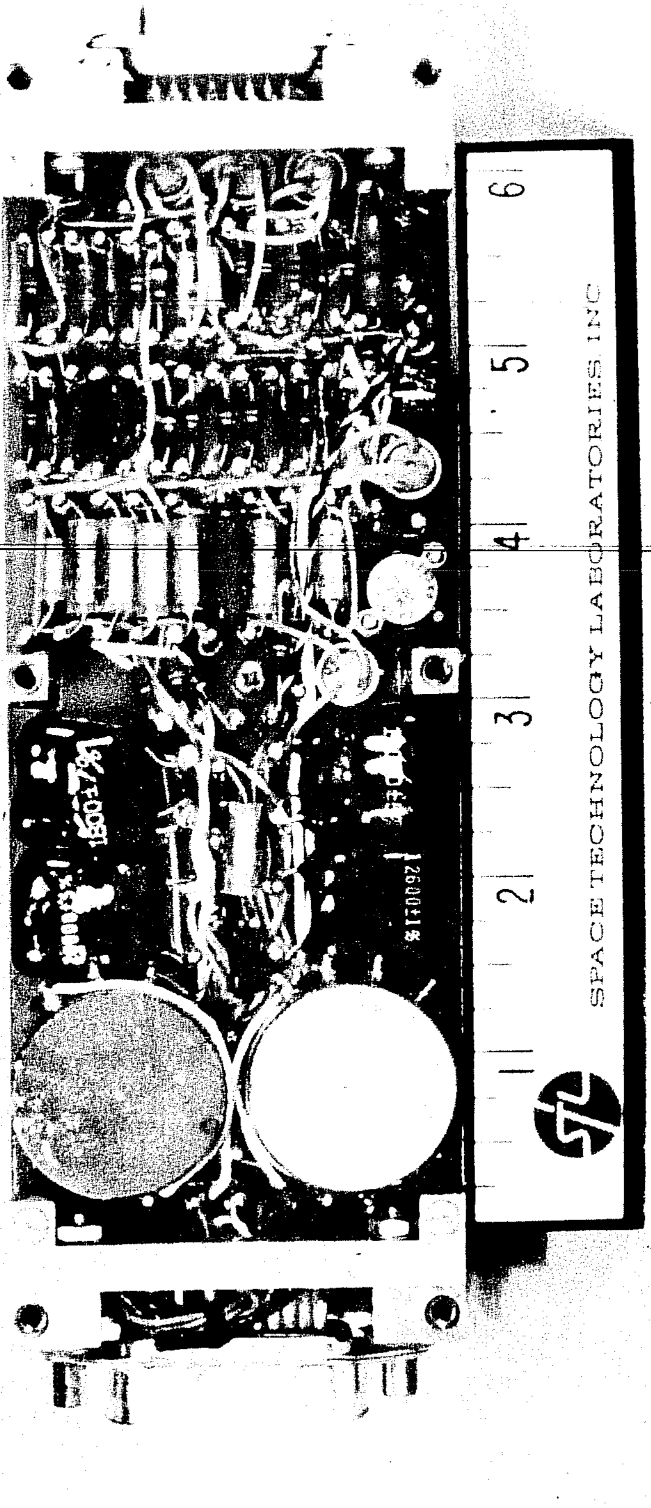


Figure 16. Digital Module Collector Card

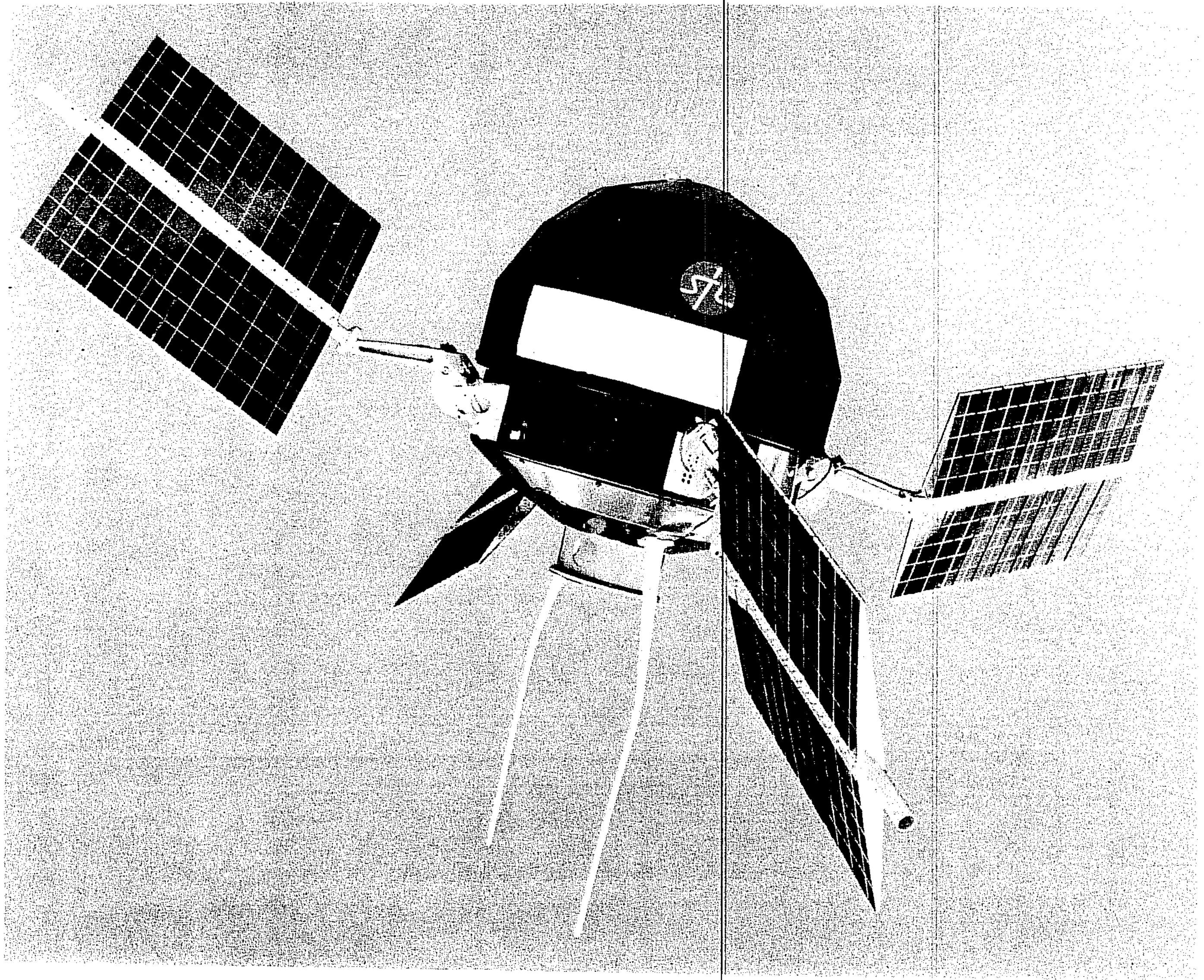


Figure 17. Explorer VI Spacecraft

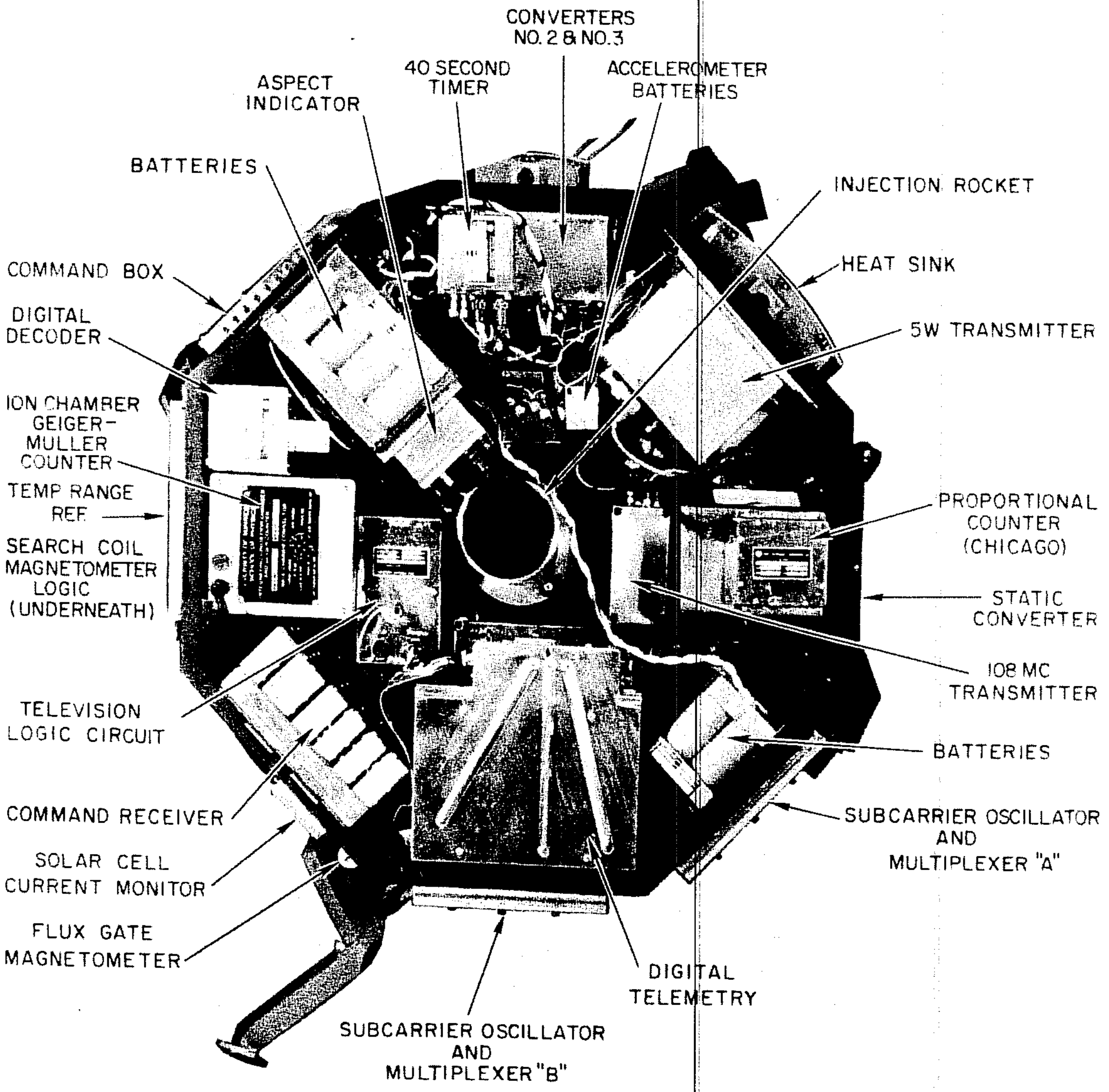


Figure 18. Explorer VI Payload Details

Atlas Able-4 Lunar Probe

The Atlas-Able Lunar probe which was launched on November 26, 1959, is shown in Figure 19. A premature loss of the vehicle nose fairing aborted this effort. The payload details are shown in Figure 20.

Pioneer V

The Pioneer V deep space probe was successfully launched on March 11, 1960, as shown in Figure 21. The payload has been successfully interrogated from all STL ground stations. On April 16, 1960, when the payload was approximately 5 million miles from the earth, the payload receiver loop noise bandwidth was changed, on command, from 240 cps to approximately 40 cps, and the sweep period altered from 10 seconds to 3 minutes. An acquisition and command sensitivity of -140 dbm was achieved with this configuration. The 5-watt UHF payload transmitter was utilized until May 8, 1960, when the 150-watt payload transmitter was activated by command. The maximum communications range achieved with this system was 55 million miles. The previous record established by Pioneer IV was 406,000 miles. Details of the Pioneer V payload are shown in Figure 22.

Transit 1B

A modified version of the Able communications system was used as a radio guidance transponder on the Able-Star second-stage vehicle used to launch the Transit 1B navigational satellite. (See Figure 23.) This guidance version was also used on the Able stage of Explorer VI and Pioneer V.

CONCLUSIONS

Figure 24 is a tabulation of the achieved communications system design and performance characteristics.

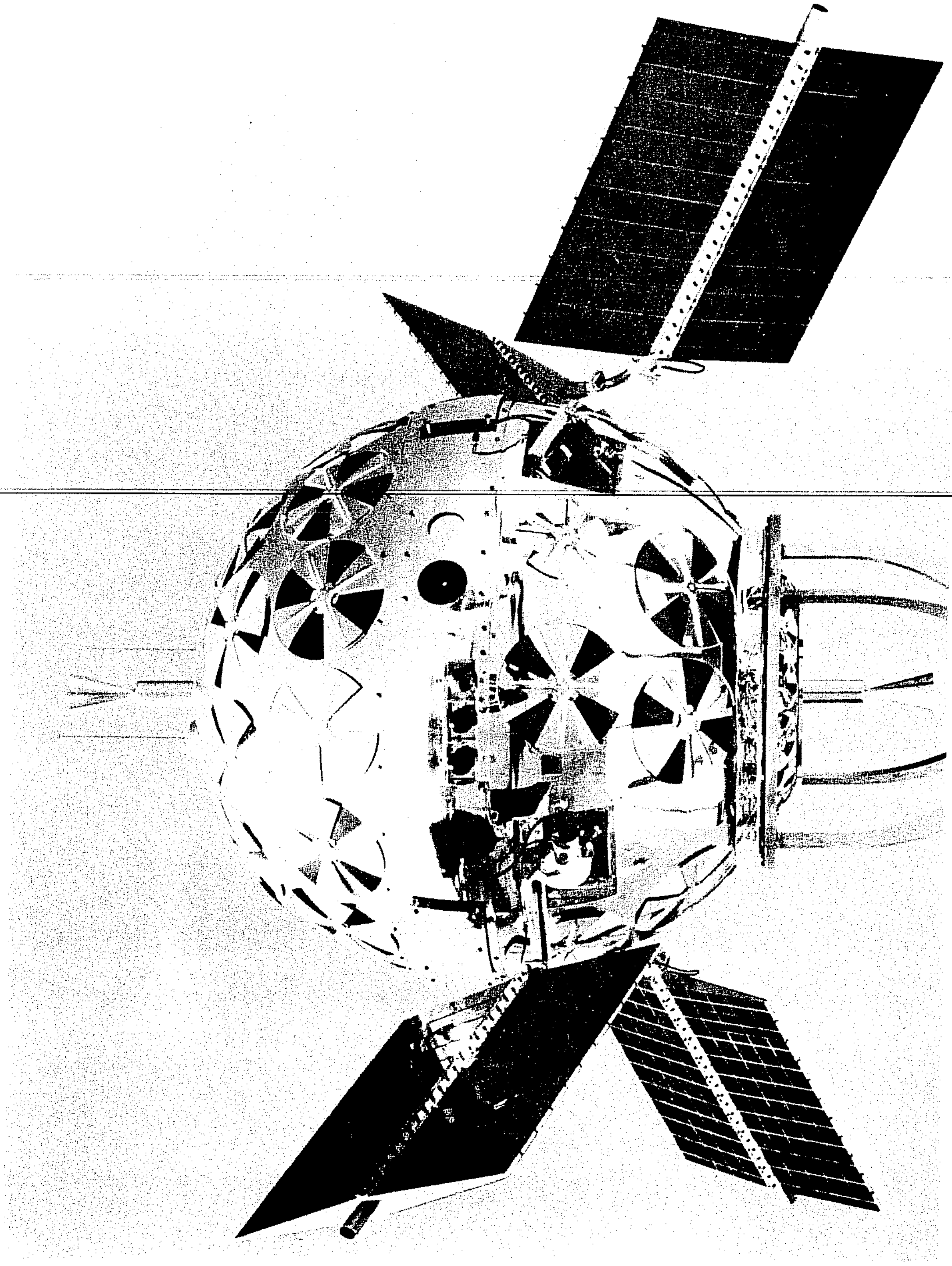
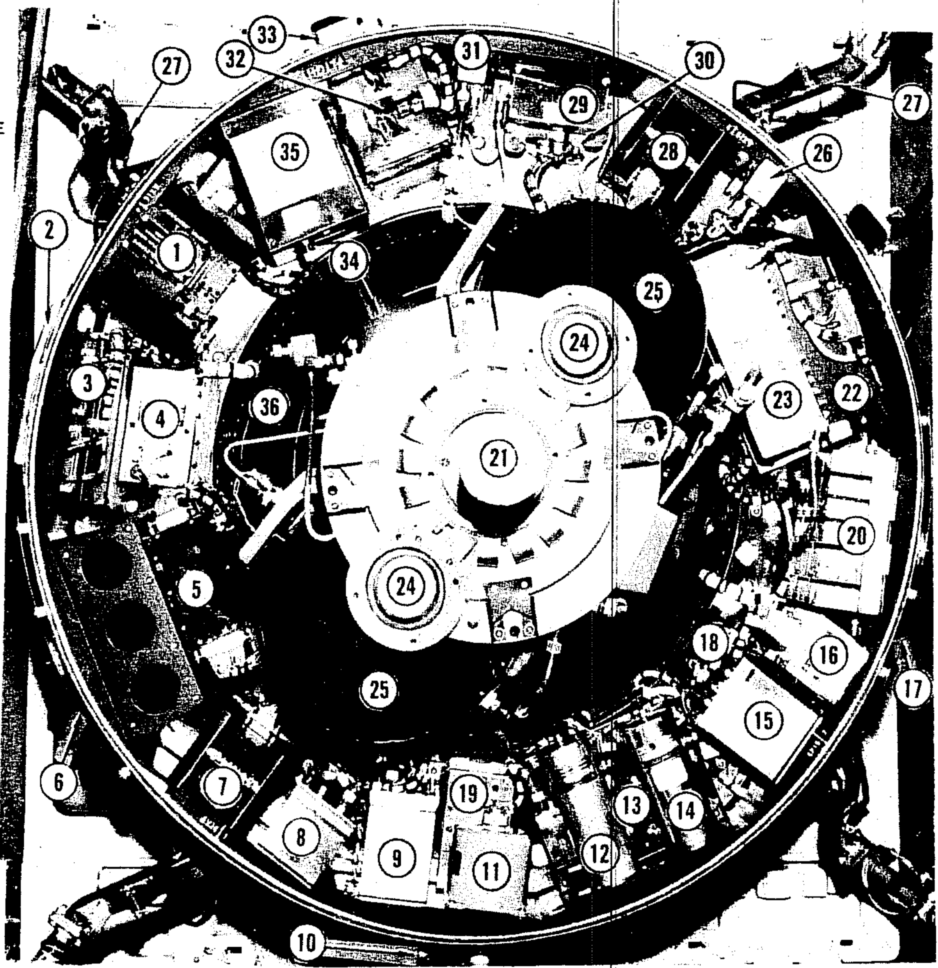


Figure 19. Able-5 Spacecraft



1 COSMIC RAY TELESCOPE
2 PLASMA PROBE
3 TELEMETRY SIGNAL CONDITIONER
4 PHASE COMPARISON ANALYZER & SPIN COIL
5 DIGITAL TELEMETRY UNIT
6 MICROMETEORITE DIAPHRAGM
7 BATTERY PACK, 1-2
8 LOW ENERGY SCINTILLATION LOGIC
9 SCINTILLATION SPECTROMETER LOGIC
10 MATERIAL COATING PROBES
11 ANGULAR ACCELEROMETER
12 SCINTILLATION SPECTROMETER SENSOR
13 NO 1 CONVERTER (EXPERIMENT SUPPLY)
14 LOW ENERGY SCINTILLATION COUNTER
15 FLUX GATE MAGNETOMETER LOGIC AND AMPLIFIER
16 DIGITAL DECODER
17 MICROMETEORITE DIAPHRAGM
18 MICROMETEORITE AMPLIFIER
19 MICROMETEORITE SCALER
20 RECEIVER

21 INJECTION THRUST CHAMBER
22 POWER DISTRIBUTION BOX
23 DIPLEXER
24 ANTENNAS
25 NITROGEN TANKS (MAIN PRESSURIZING)
26 COHERENT MODULATOR
27 SOLAR CELL PADDLE ARMS
28 BATTERY PACK, 3-4
29 NON-COHERENT TRANSMITTER (TOP)
30 COHERENT TRANSMITTER (BOTTOM)
31 NON-COHERENT MODULATOR
32 COHERENT AND NON-COHERENT CONVERTERS
33 SUN SCANNER
34 AUXILIARY PRESSURIZATION NITROGEN TANK
35 ION CHAMBER, GEIGER-MUELLER COUNTER
36 HYDRAZINE TANK

ABLE 5 PAYLOAD (VIEW LOOKING AFT)

Figure 20. Able-5 Payload Details

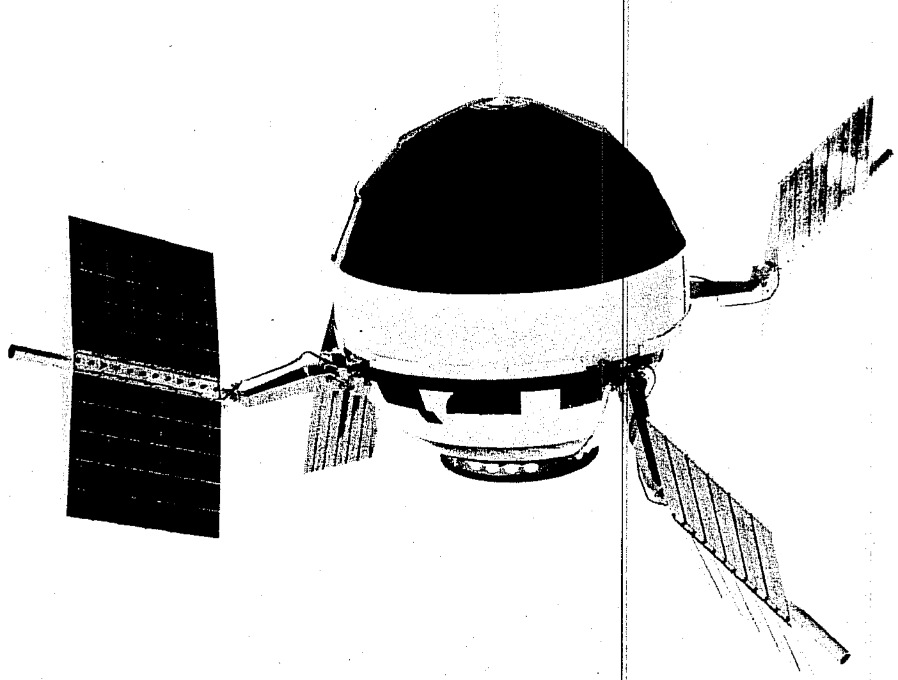


Figure 21. Pioneer V Spacecraft

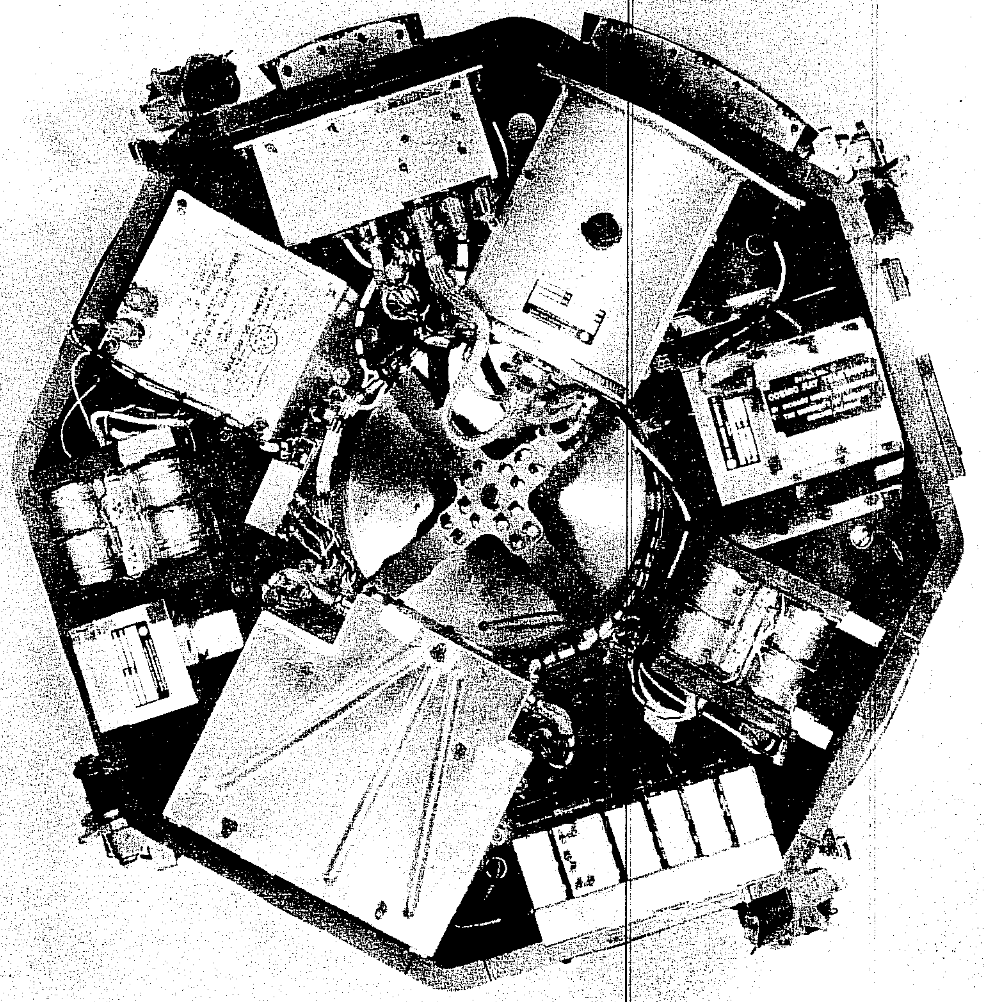


Figure 22. Pioneer V Payload Details

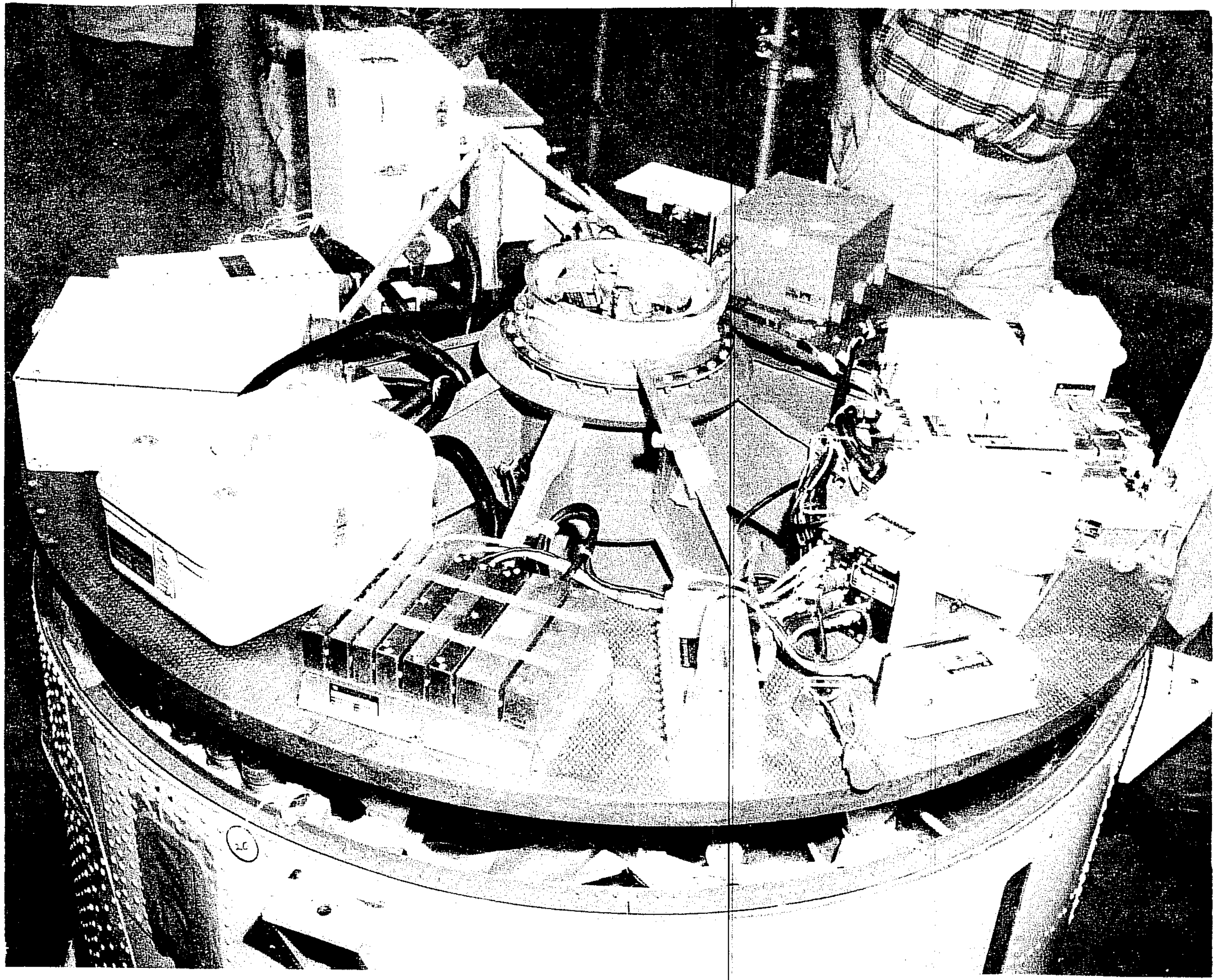


Figure 23. Able-Star Second Stage

PERFORMANCE DATA

1. Receiver Acquisition Sensitivity	
Wideband	-130 dbm
Narrow band	-140 dbm
With parametric preamplifier	-148 dbm
2. Command Sensitivity	-140 dbm
With parametric preamplifier	-148 dbm
3. Loop Noise Bandwidth at Threshold	
Wideband	240 cps
Narrow band	40 cps
4. Sweep	
Wideband	26 kc with 10-second period
Narrow band	13 kc with 180-second period
5. Number of Commands Available	64
6. Input Power	
Receiver	1 watt
Decoder	0.5 watt
7. Radiated Power (Pioneer V)	
Low Power	3 watts
High Power	100 watts
8. Antenna Gain	0 db nominal
9. Equipment Weight Breakdown	
Receiver	4 pounds
Decoder	2.4 pounds
Transmitter (Low power)	1 pound
Transmitter (High power)	5.7 pounds
Diplexer	0.8 pounds
10. Noise Figure	
Without parametric preamplifier	10 db
With parametric preamplifier	2 db

Figure 24. Tracking and Command System Performance Data

FUTURE IMPROVEMENTS

1. Noise Figure. - Tunnel diode amplifiers, parametric amplifiers, tunnel diode down-converters, as well as some of the new low-noise transistors are being investigated in an effort to improve the receiver noise figure.

2. Bandwidth Reduction. - Local oscillator phase-stability measurements indicate that some considerable reduction in loop bandwidth may be made. However, since the acquisition time for a given sweep range increases as the square of the bandwidth reduction factor, other acquisition techniques must be considered. These should make maximum use of a priori knowledge of doppler shift and accumulated system drift.

3. Coding. - Command encoding using error correcting as well as error detecting codes are being considered.

4. Command Subcarrier Filtering. - Filters incorporating magnetostrictive elements in place of the "Q" multipliers have been built with excellent results. These appear to offer a considerable reduction in weight as well as an assumed improvement in reliability.

5. Packaging. - Several new packaging concepts are being investigated in an effort to improve the overall system reliability.

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