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THE DUMBBELL ELECTROSTATIC IONOSPHERE PROBE: ENGINEERING ASPECTS

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1. INTRODUCTION

This is the second in a series of reports whose purpose is the documentation of the theory, design, and use of a rocket-borne electrostatic ionosphere probe which has been employed by University of Michigan researchers in their studies of the ionosphere. The instrument, shown in Fig. 1, has come to be known as the "Dumbbell." The first report in the series, 03599-5-S, described the theoretical aspects of the measurement; this report describes the engineering aspects of the Dumbbell instrument; while the third report, 03599-7-S, will present the ionosphere data gathered through its use in several measurements up to 420 kilometers.

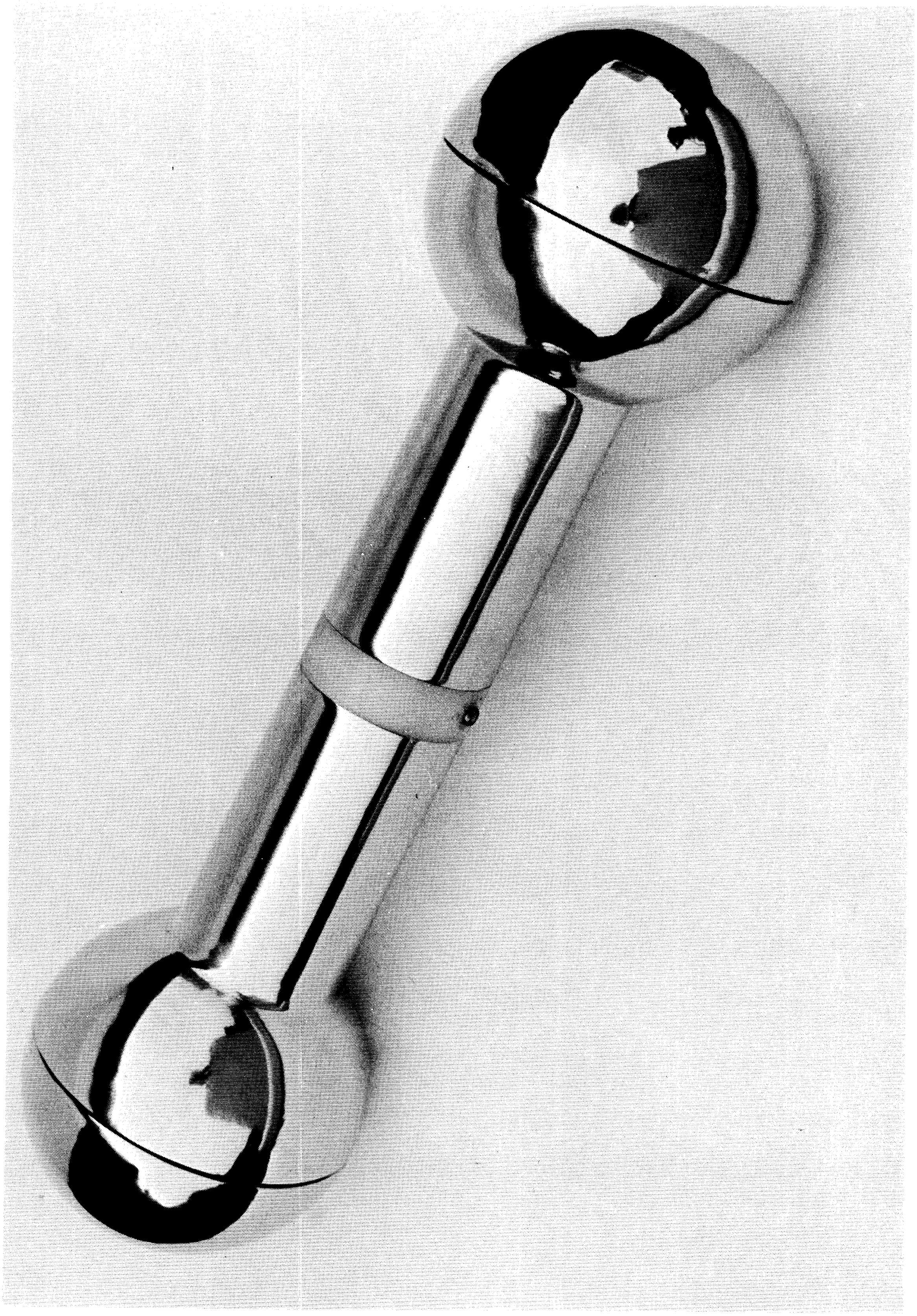


Fig. 1. The Dumbbell probe.

2. THE DUMBBELL IONOSPHERE PROBE

2.1 INTRODUCTION

The probe instrument, shown in Fig. 1, is designed to be rocket-borne into the ionosphere, ejected from the rocket, and thereafter to measure and relay to earth continuous volt-ampere characteristics of its collectors as it travels through the plasma. The instrument, since it is separated from the rocket, is completely self-contained, having a sweep voltage generator and current detectors for the volt-ampere measurement, as well as a telemetry transmitter, power supply, and auxilliary control and aspect-sensing instrumentation. The entire instrument serves as a halfwave dipole antenna for the r-f transmission.

2.2 SYSTEM DESIGN PARAMETERS

Instrumentation to implement Langmuir probe measurements in the ionosphere can take many forms, as discussed in the theoretical report.[1] The fundamental requirement is that an electrode be immersed in the plasma and the current to it be measured as a function of the voltage applied between the electrode and some reference electrode. Previous experiments of this type have, in general, been conducted using a probe attached to the rocket vehicle which then becomes the reference electrode. The purity of the experiment is, however, compromised by the contamination of the environment due to gas escaping from the vehicle. It was therefore decided that the probe must be ejectable from its carrier rocket. This decision dictated use of a dual electrode or bi-polar system. Theoretical considerations[1] suggested use of spherical electrodes identical in geometry and size. Theoretical aspects, problems of ejection, instrumentation volume requirements, and performance characteristics of available vehicles were weighed to arrive at an optimum size for the spherical electrodes. Two spheres of 6-in. diameter were chosen, a size which suited the experimental requirements and could easily be carried in and ejected from existing rockets. A cylinder was chosen to connect the two spheres together, the length of which would make the entire structure a dipole at a standard telemetry frequency. The diameter of the cylinder was determined principally on the basis of volume and structural integrity.

The volume provided for instrumentation was small for the planned scope of the experiment, but with sufficient effort in circuit miniaturization and in system layout, it was deemed adequate.

Stainless steel was selected as the construction material because of its high work function to control photo-electric effects, its low permeability to allow magnetic aspect sensors to be used, and because of the ease of maintaining clean collector surfaces.

The basic structure, then, is two 6-in. spheres connected by a cylinder 12 in. long and 3 in. in diameter. Electrically, the external surface structure is divided into four parts as shown in Fig. 2. The two outer hemispheres are the collecting electrodes to which the current flow is measured. The inner hemispheres with their respective cylinders, forming two "funnels," constitute a guard electrode system. These inner electrodes minimize the electrostatic fringe effects at the hemisphere-guard insulator and thus make

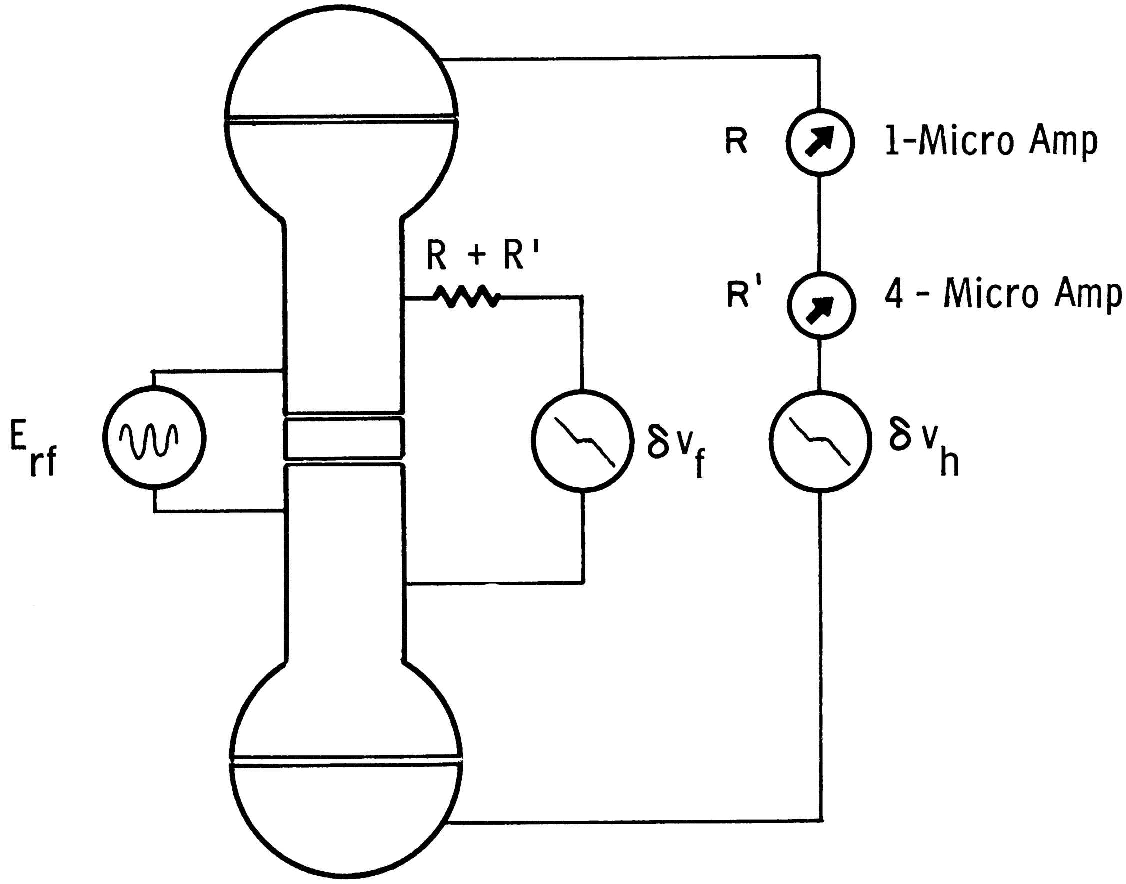


Fig. 2. Block diagram of the Dumbbell system.

a significant contribution to the purity of the experiment. Identical synchronized sawtooth voltage waveforms, δV, are applied between the electrodes of each system and the net current to the outer hemispheres is measured.

The assembled probe has the shape of a Dumbbell, a descriptive name which has been adopted to distinguish the system from other Langmuir probe configurations.

The symmetry of the measuring probe system permits operation of the experiment using alternately one hemisphere and then the other as the measuring electrode, which has the advantage of making nearly simultaneous measurements with 180° shift in probe orientation and permits evaluation of the effect of solar radiation and the effect of the motion of the probe through the plasma. To permit this, the sawtooth voltage function, δV, applied between the hemispheres, varies between equal negative and positive values and causes a net current which is measured by detectors sensitive to either direction of current flow. Figure 3 illustrates the δV waveform. The flat in the sawtooth

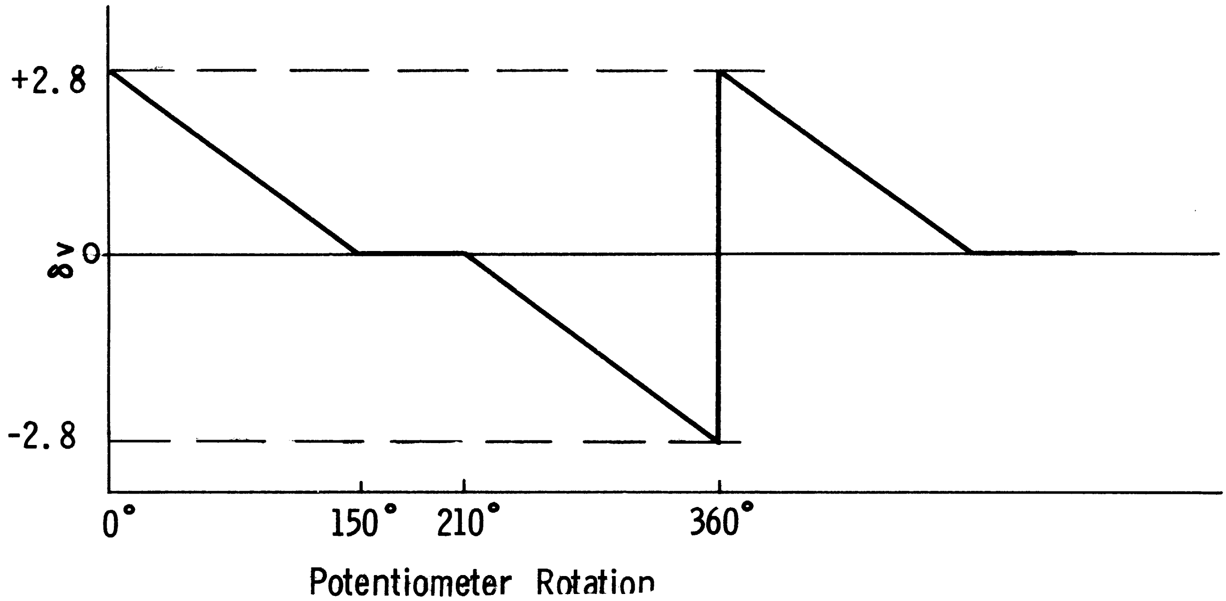


Fig. 3. The difference voltage, δV, applied between the hemispheres.

voltage, occurring at zero volts, provides positive identification of this point and permits evaluation of the current to the probe with no voltage applied. The temperature and density of the plasma, the area of the probe, and its motion determine the amount of current to the probe at a given applied voltage. The voltage excursion required is a function of the plasma temperature, and on this basis was chosen to be approximately plus and minus three volts. Reasonable estimates of the various ionosphere parameters indicated that the maximum current to the probe during a typical flight to 400 km would be about 4×10^{-6} amp. At the planned ejection altitude, however, the current would be considerably less. Instead of using a logarithmic detector, which would have meant contending with its inherently low resolution, it was decided that two linear current detectors with overlapping ranges would be used. Full-scale sensitivities of 1 and 4 μamp were selected. The current detector best suited to the requirement of range, bi-directionality, space, and power limitations appeared to be a transistorized ring-modulator type. A detector system was developed and miniaturized for this application.[2]

To provide probe orientation data, it was decided to use two aspect magnetometers which, together with other data inherent in the measurement, would sufficiently describe the probe orientation.

The data-transmission requirements could be adequately met with three analog data channels, one of which would be time-shared among various sources of auxiliary information. On the basis of data-transmission requirements, power and space limitations, a fm-fm telemetry transmitter with three subcarrier channels was chosen.

The power requirements of the entire system is approximately 30 watts. To meet this requirement and to provide about one hour of system operation, a 24-volt pack of HR-1 Silver Cells operating a d-c—d-c converter was selected to provide power, and a 6-volt pack of HR-1's to provide filament power to the transmitter. Approximately 2 watts are radiated as r-f power, and 28 watts are dissipated as heat principally in the form of transmitter and filament and plate dissipation.

The principal design parameters have been stated. Other more detailed parameters such as environmental specifications, frequency response, and system accuracy are discussed later in the appropriate sections.

2.3 MECHANICAL DESIGN

The four stainless-steel electrodes, two hemispheres and two "funnels," are fabricated by a metal spinning process. Each electrode must be electrically isolated from the others and to effect this, the funnels are threaded back to back onto a nylon insulating and supporting cylinder with "O" rings used for pressure seals. The hemispheres are mechanically secured to the funnels with threaded nylon coupling rings as shown in Figs. 4 and 5. The two sections screw against and compress a separative "O" ring to provide a pressure seal and electrical insulation. The nylon ring used at one end of the probe has an inner lip to support a component mounting deck which must be electrically insulated from the funnel and hemisphere. Steel couplings are welded into the hemispheres and funnels and threaded to mate with the nylon couplings. The assembly is 24 inches long with a sphere diameter of 6 in. and a cylinder diameter of 3 in. The sphere diameter is just large enough to accommodate the transmitter being used, and the funnel diameter was dictated by the size of a dual aspect magnetometer package developed for the Dumbbell to be mounted in one of the funnel cylinders. Figure 6 shows a disassembled probe. The hemisphere and funnel shown on the left of the figure contain the transmitter, control Ledex, d-c—d-c converter and batteries. The right half contains a magnetometer package and auxiliary instrumentation can, a small d-c motor, a mounting deck, the δV potentiometers, a battery pack, a Ledex, a relay and a plug-in can containing most of the probe electronics.

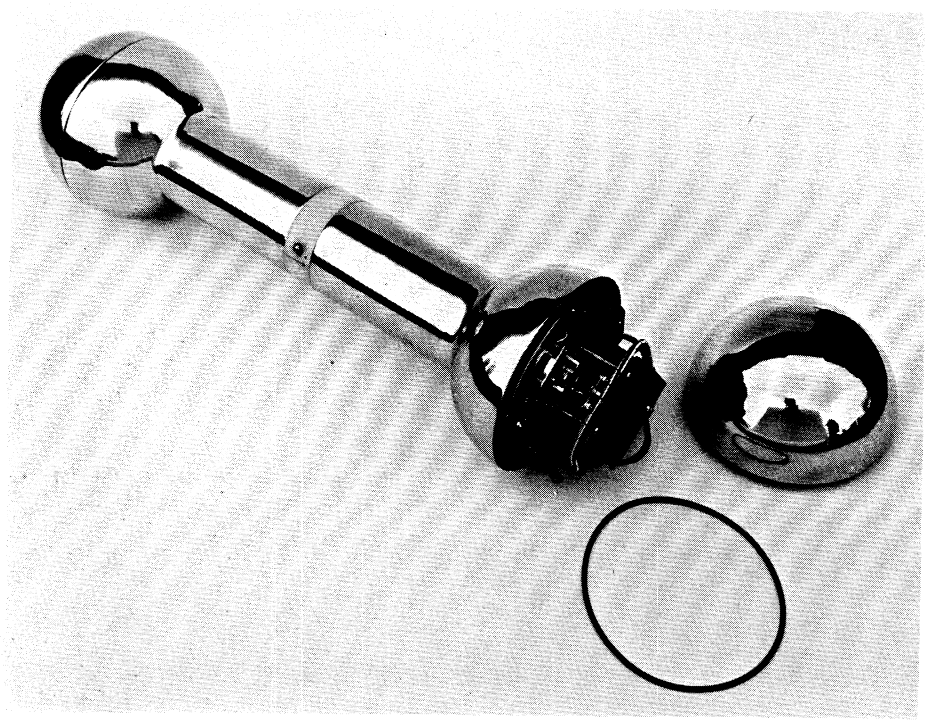


Fig. 4. Dumbbell assembly with one hemisphere and "O" ring removed.

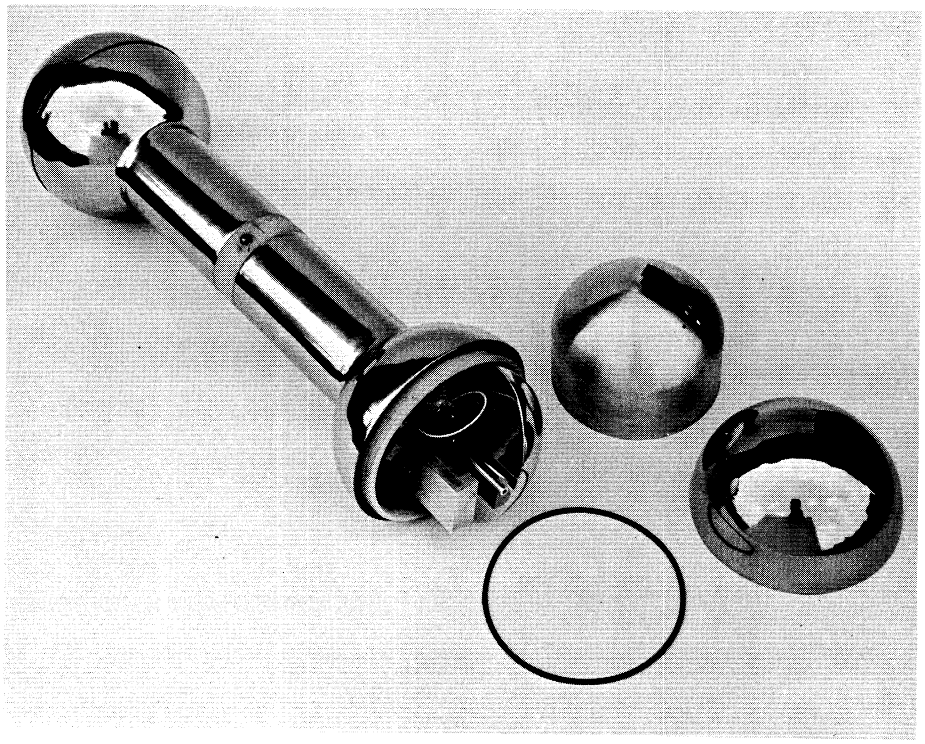


Fig. 5. Partially disassembled Dumbbell showing "O" ring and nylon coupling ring.

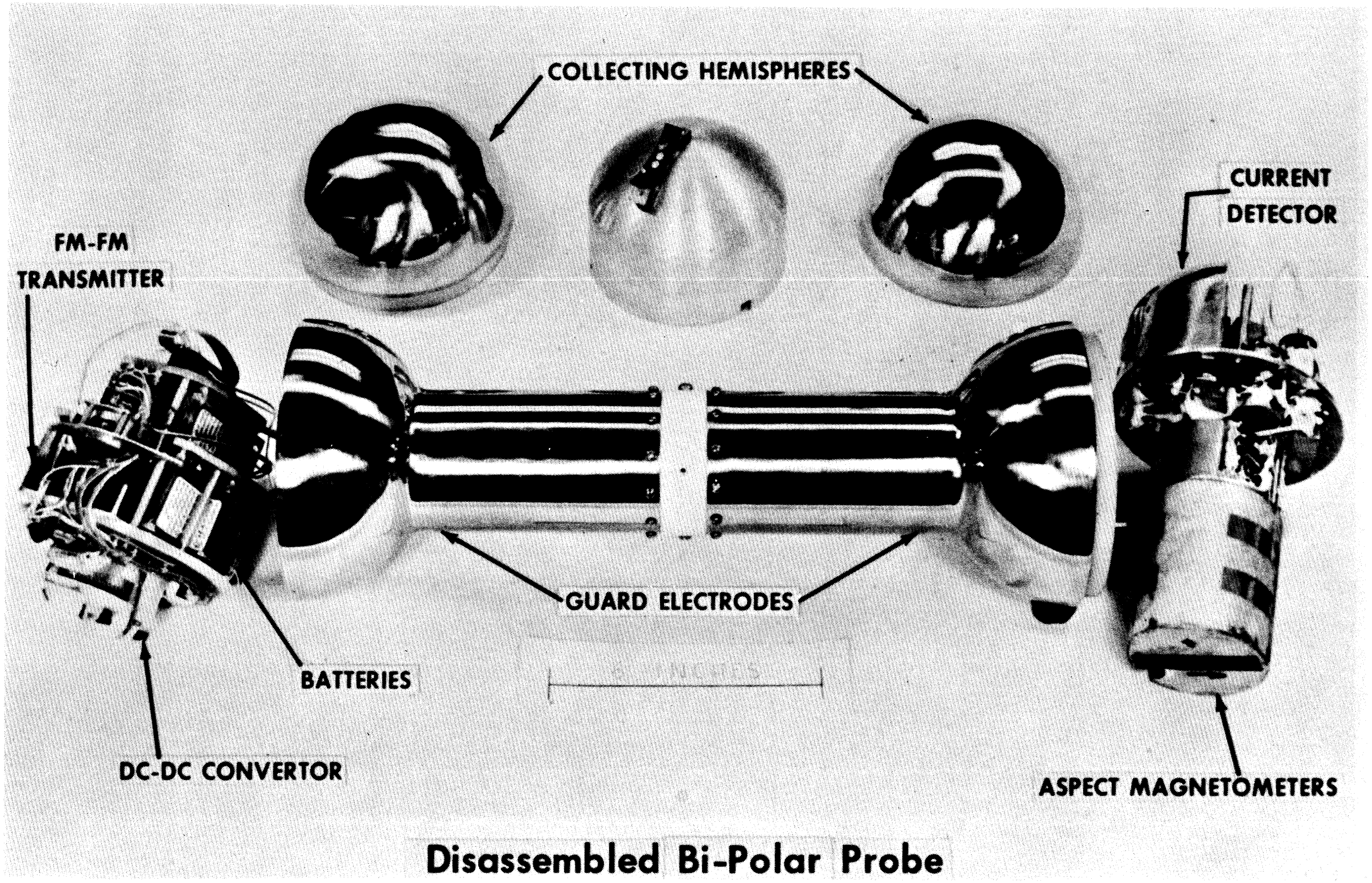


Fig. 6. Disassembled Dumbbell.

In the end which houses the transmitter, the structural foundation is a circular aluminum deck contoured to fit the curvature of the funnel. The deck is secured to the funnel by two screws which thread into welded feet in the funnel. The d-c to d-c converter is mounted on the bottom of the deck and extends down into the cylindrical portion of the funnel. The transmitter is secured to the top side of the main deck. A second deck is supported from the main deck by four brass tubes, and is used to mount the control Ledex and one battery pack. Three battery packs are mounted in this end. A pack of four HR-1 Silver-Cadmium cells is mounted on each side of the transmitter and rests on the main deck. A third pack of 12 cells is mounted on the top deck. All the battery packs are secured by linen-base-phenalic plates tightened against the batteries with screws threaded into tubular standoffs. The cover for the top set of batteries is also used to mount a phosphor bronze strip which provides electrical contact to the hemisphere when it is screwed into place. Figures 6 and 7 show the assembly.

Since the telemetry transmitter is a tube type and generates a significant amount of heat, the transmitter mounting deck is made from 1/4-in. stock to provide an additional heat sink, and the contour fit with the funnel distributes the heat effectively to the funnel. The converter transistors are shown mounted on a 1/4-in. aluminum heat sink on the bottom of the converter. The assembled probe will operate continuously for 30 minutes before the temperature reaches a critical level. This is more than twice planned flight times and so provides a good margin.

In the other end of the probe, Fig. 8, an aluminum deck seats on a shoulder in the nylon connecting ring and is held by three screws threaded

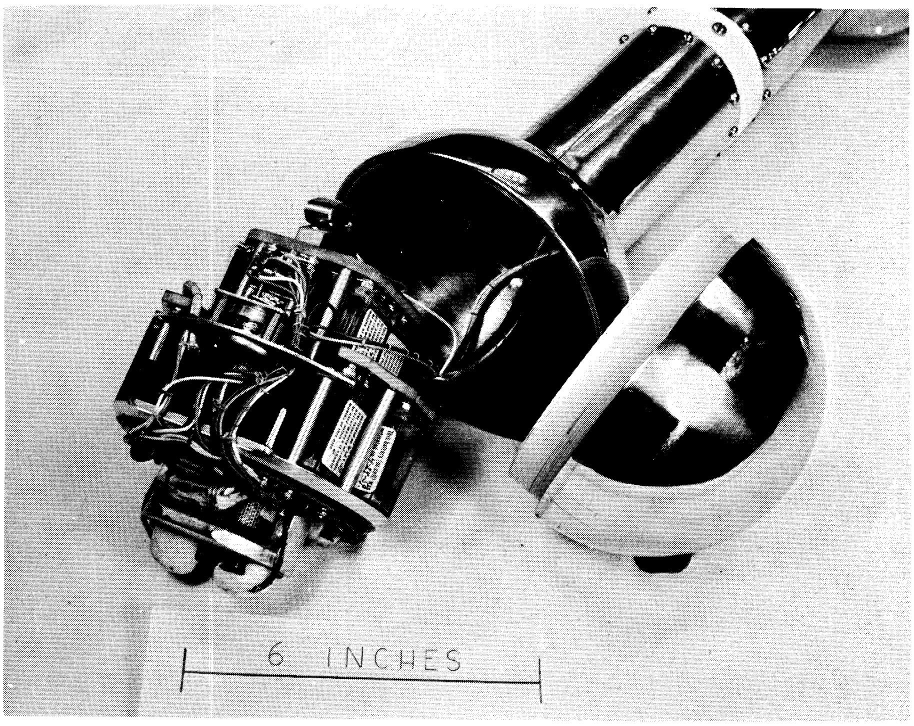


Fig. 7. Close-up of transmitter end of Dumbbell.

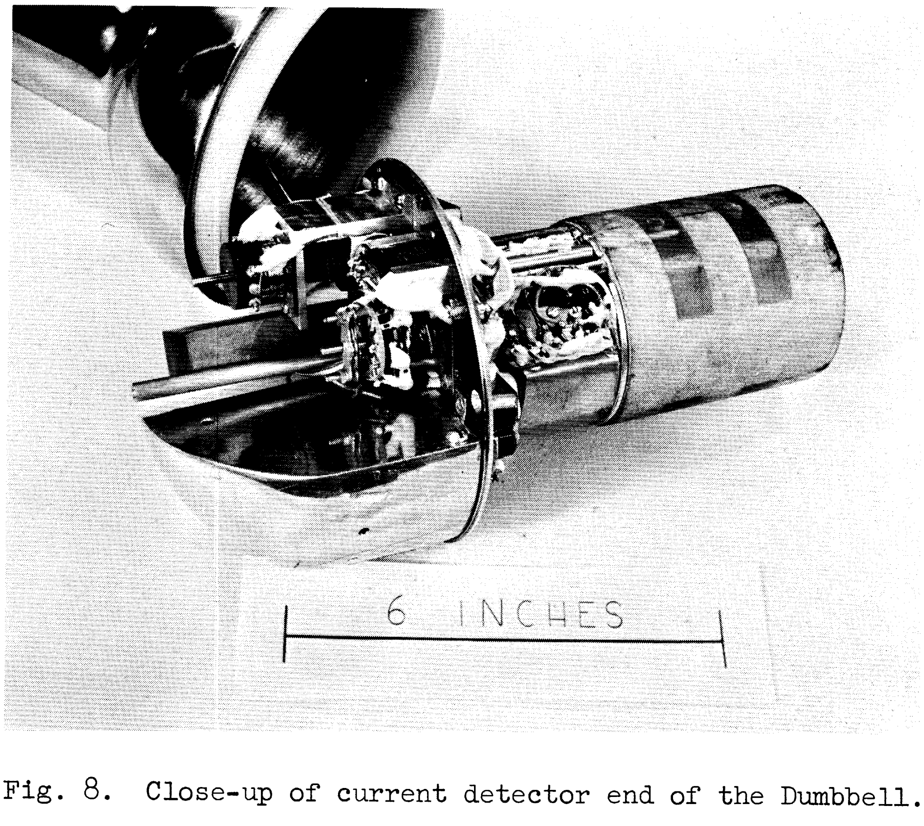


Fig. 8. Close-up of current detector end of the Dumbbell.

into the nylon. This deck provides structural support for the other components. The cylindrical aspect magnetometer package is mounted on the bottom side of the deck on two tubular standoffs. The magnetometer package fits snugly into the cylinder of the funnel and extends down to about 1/2 in. from the top of the insulating nylon cylinder which joins the funnels. The side of the package is slotted to pass a cable interconnecting electronic units in the two ends.

On top of the magnetometer package, and mounted to it, is the auxiliary instrumentation can, Fig. 8. This brass can contains the electronic selector and VCO used in conjunction with the magnetometers. The bottom side of the main deck is used to mount various terminal boards, plugs, and the δV motor (a small d-c motor with a worm gear on its shaft). The δV potentiometer, a continuous-rotation dual-potentiometer, is mounted on the top of the deck with its shaft extending through the deck. A spur gear on its shaft mates with the worm gear on the motor shaft. The gear ratio is such that the δV pots generate a 3-cps sawtooth as shown in Fig. 3.

A Ledex, a small can containing two packs of mercury batteries, and the probe circuitry can are also mounted on the top of the main deck. The electronic circuitry is mounted in a plug-in can secured to the deck with three screws, one through the back of the can into a post and two through tabs into the deck. The can itself contains several circuit boards, interconnecting wires, and a plug, through which all interconnections are made. The plug is screw-fastened to the can and the circuit boards are suspended in plastic foam upon which they depend for structural support. An aluminum shield covers all components on top of the main deck. It is secured with a screw into a brass rod standoff to the main deck. The same screw is used to mount a phosphor bronze strip on an insulating block to make electrical contact to the hemisphere at this end. Figures 6 and 8 show the assembly. Finally, the screw heads in the center nylon insulator are used for electrical connectors for remote operation and Ledex position indication.

The assembled probe weighs approximately 15 lb and has a specific density of approximately 1.3.

The probe is placed in the rocket with the transmitter end up with the long axis in the direction of flight.

2.4 ELECTRONIC SYSTEM

The various components of the electronic system and their integration are discussed below. Testing of the system is described and its performance is evaluated. Figure 9 is a functional block diagram of the Dumbbell probe.

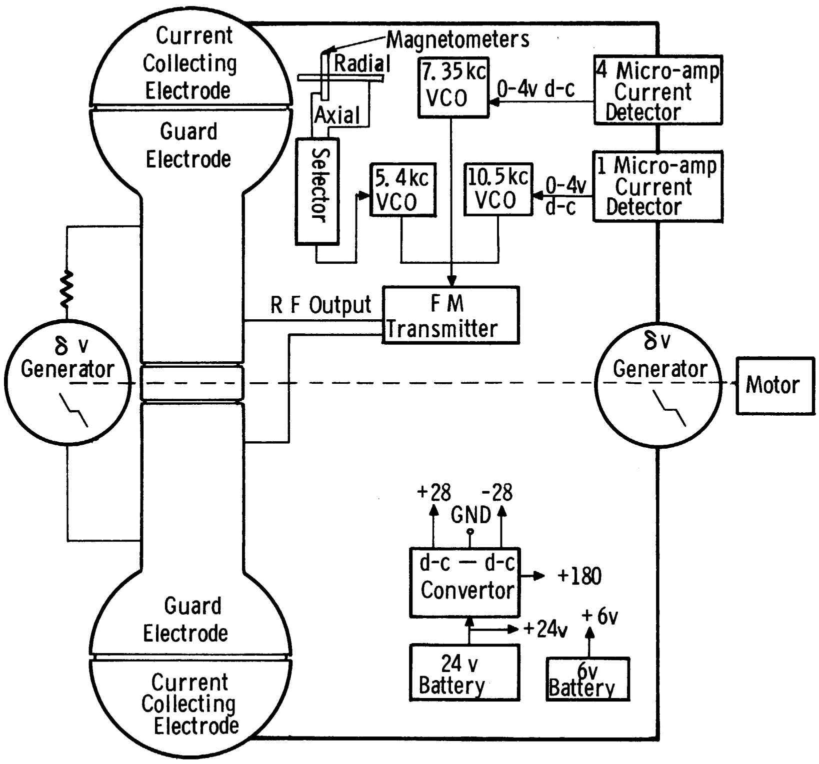


Fig. 9. Functional block diagram of the Dumbbell probe system.

2.41 The Current Measurement

The current measurement system consists essentially of a sawtooth voltage generator, δV, two current detectors with relatively low input impedance, R_{in} and two electrodes emersed in a plasma.

The voltage source for the δV generator, shown in Fig. 10, is a 9.4 pack of mercury cells regulated at approximately 6 volts by a zener diode and a 1000-ohm limiting resistor. A 5-K-ohm trimpot connected in series makes the source variable from 4 to 6 volts. The potentiometer is necessary since the two sections must be adjusted to provide identical δVs. The voltage across the motor-driven δV potentiometer is normally set to approximately 5.6 volts, adequate for probe operation in the F region of the ionosphere.

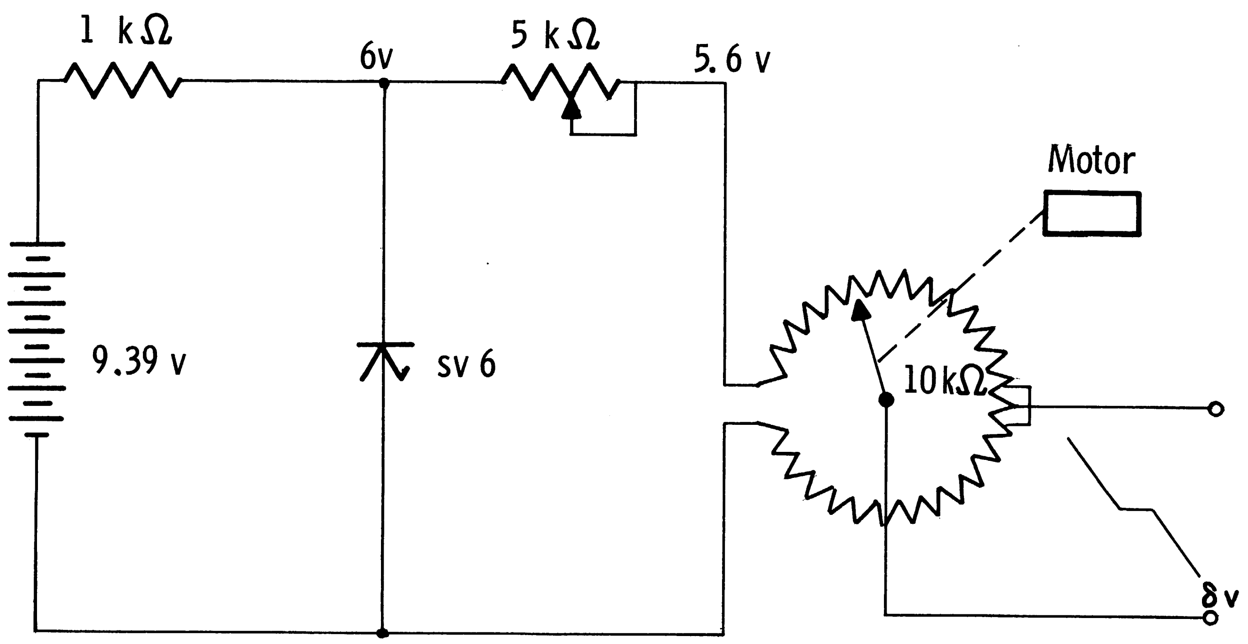


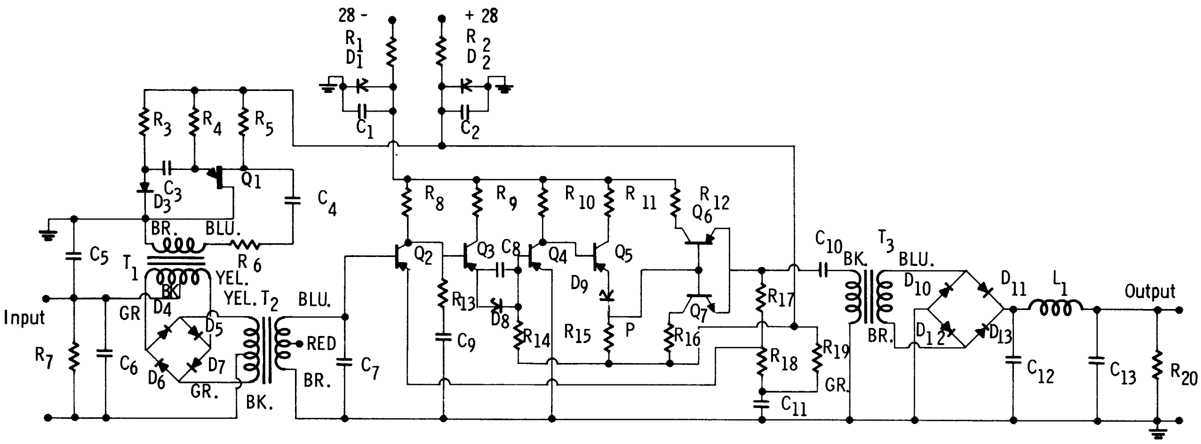
Fig. 10. A single δV generator.

The δV potentiometer is a 10-K-ohm precision continuous-rotation wire-wound type with three taps, one located in the center and two 30° each side of center. The center tap and the two taps at 30° are normally shorted together to provide zero voltage for a portion of the δV cycle. Thus, with 5.6 volts across the potentiometer, the output between each center tap and wiper varies between +2.8 and -2.8 v with a flat at 0 volts, as previously shown in Fig. 3.

The current detector, a transistorized ring-bridge-modulator, amplifier and demodulator, is shown in Figs. 11a and 11b. This basic system has wide application and has been described in detail.[2,4] The two detectors used in series in the Dumbbell probe have full scale sensitivities of 1 and 4 μamp, respectively. Typical input-output curves, Fig. 12, show that the detectors respond identically to both polarities of input current. The input impedance of each current detector depends upon its sensitivity; however, the total series impedance of the two used here is approximately 40 K ohms.

The characteristics of the current measuring system can be visualized by using the probe system to measure the volt-ampere characteristics of a resistor placed across the hemispherical collectors in lieu of a plasma such as the ionosphere.

Figure 13 shows the circuit block diagram. Since the resistor is a constant impedance the current which flows, Fig. 14b, is identical in waveform with the δV waveform, Fig. 14a. As noted earlier, the detector is magnitude-sensitive only, so the output waveform, which will be telemetered and recorded, is rectified as shown in Fig. 14c.



R_1 - 1 K	R_9 - 2.2 K	R_{17} - 47 K	C_3 - .03 μf	C_{13} - .082 μf	D_{10} - IN 98	Q_7 - 2N213A
R_2 - 1 K	R_{10} - 47 K	R_{18} - 100 Ω	C_4 - .01 μf	D_1 - SV-24	D_{11} - IN 98	
R_3 - 82 K	R_{11} - 2.2 K	R_{19} - 68 K	C_5 - 500 $\mu\mu$f	D_2 - SV-24	D_{12} - IN 98	T_1 - DO-T24
R_4 - 82 K	R_{12} - 2.2 K	R_{20} - 10 K	C_6 - 500 $\mu\mu$f	D_3 - IN 98	D_{13} - IN 98	T_2 - DO-T24
R_5 - 18 K	R_{13} - 680 Ω		C_7 - .03 μf	D_4 - FD-300	L_1 - DI-T8	T_3 - DI-T22
R_6 - 47 K	R_{14} - 47 K		C_8 - 12 μf	D_5 - FD-300	Q_1 - 2N492	
R_7 - 15 K	R_{15} - 47 K	C_1 - 8 μf	C_9 - .005 μf	D_6 - FD-300	Q_2 - CK67A	
R_8 - 47 K	R_{16} - 2.2 K	C_2 - 8 μf	C_{10} - .5 μf	D_7 - FD-300	Q_3 - CK67A	
			C_{11} - 6 μf	D_8 - SV-11	Q_4 - CK67A	
			C_{12} - .082 μf	D_9 - SV-5	Q_5 - CK67A	
					Q_6 - CK67A	

Fig. 11a. Schematic of ring modulator type of current detector.

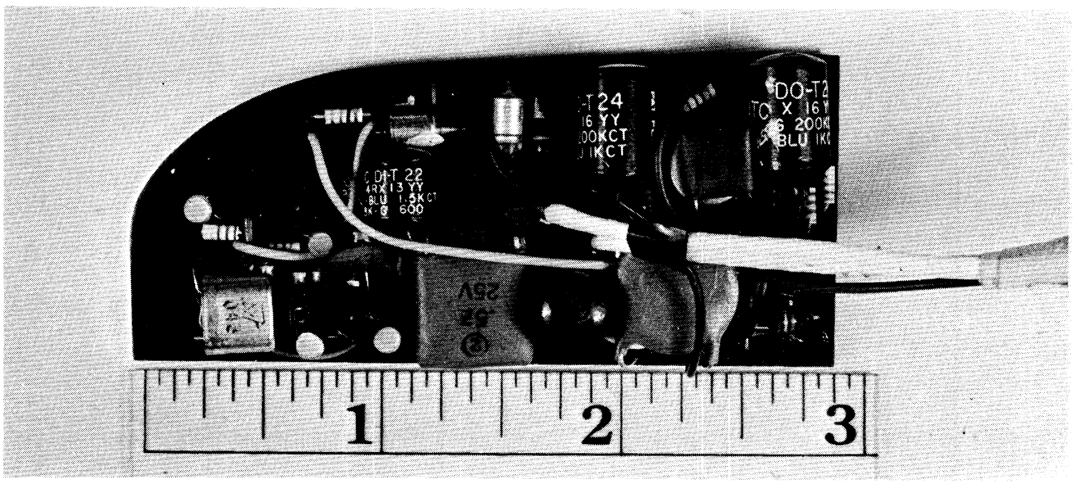


Fig. 11b. Current detector.

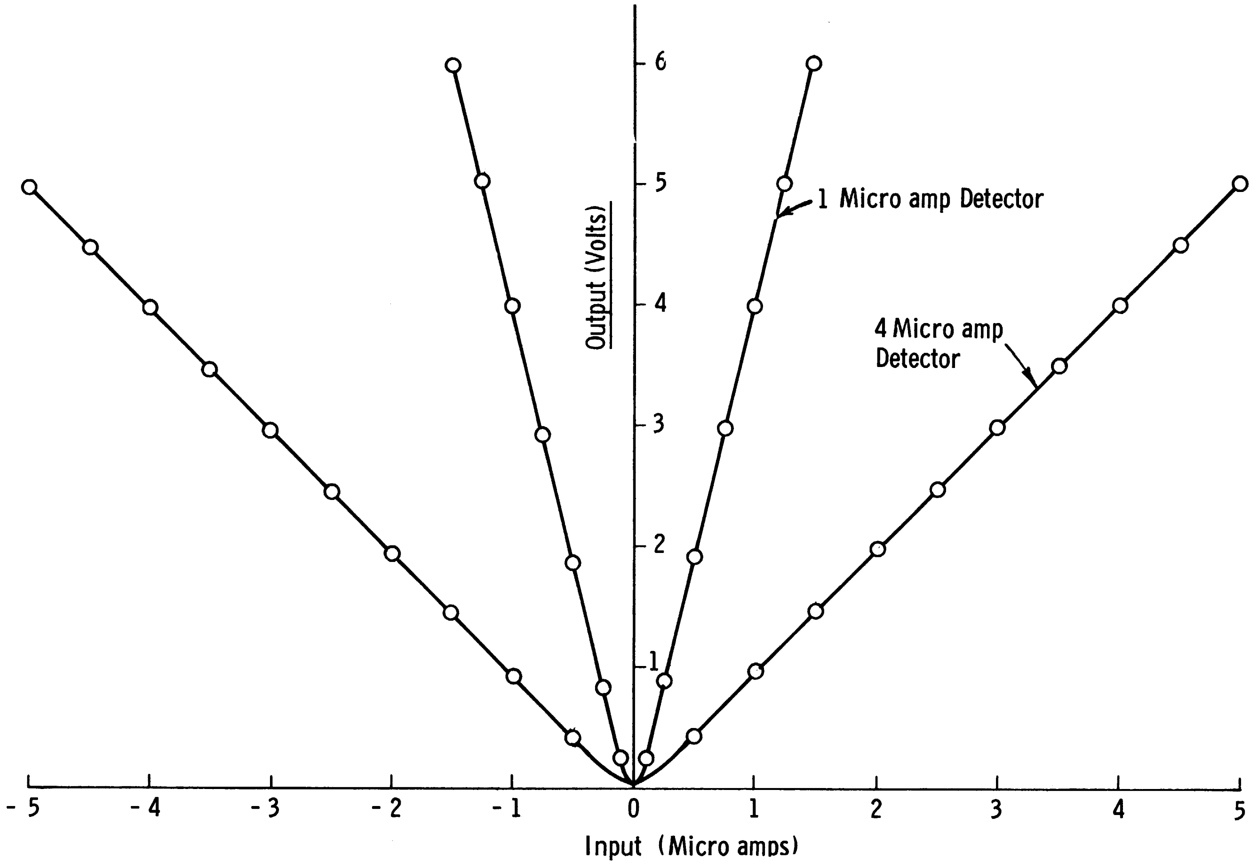


Fig. 12. Typical input-output curves of the 1- and 4-μamp detectors.

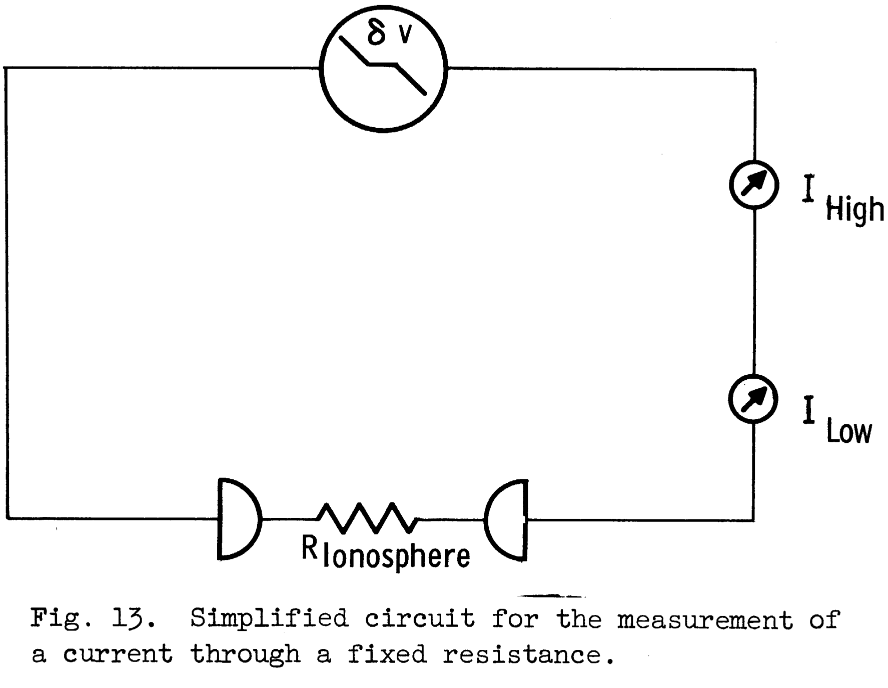


Fig. 13. Simplified circuit for the measurement of a current through a fixed resistance.

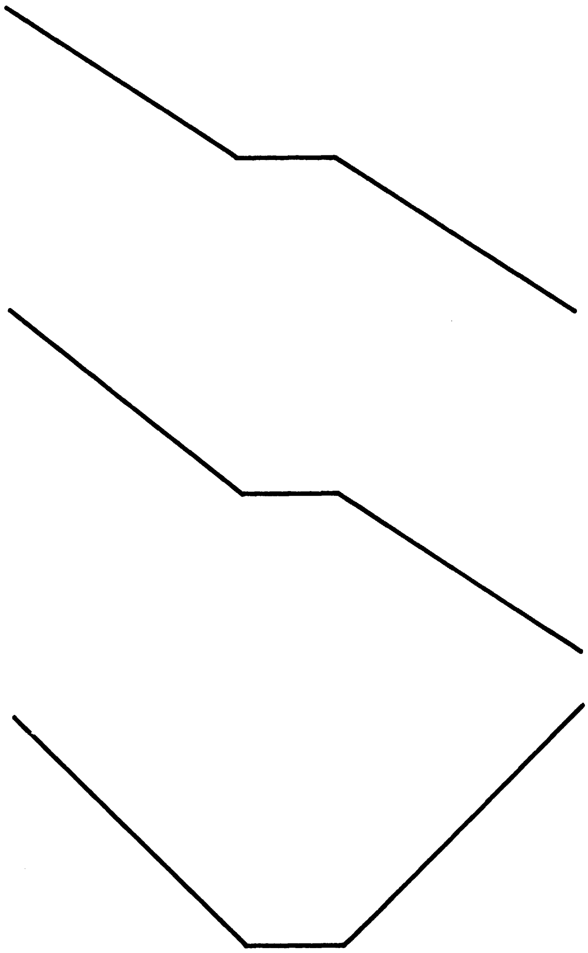


Fig. 14. Plot of δV, loop current and detector output vs. time.

2.42 Inflight Calibration

To improve the accuracy of the measurement, an inflight current calibration is employed. Periodically, the current path to the hemisphere electrodes is interrupted, and a fixed resistor of a known value, R calibrate, is substituted as shown in the simplified diagram in Fig. 15. This is accomplished by a relay, operated by an electronic timer, which switches in R calibrate for one second in every 30 seconds. Since the magnitude of the δV and the value of R calibrate are accurately known, a calibration of current vs. subcarrier frequency or deflection on paper recordings exists for use in data reduction. Figure 16 shows an inflight calibration from a section of

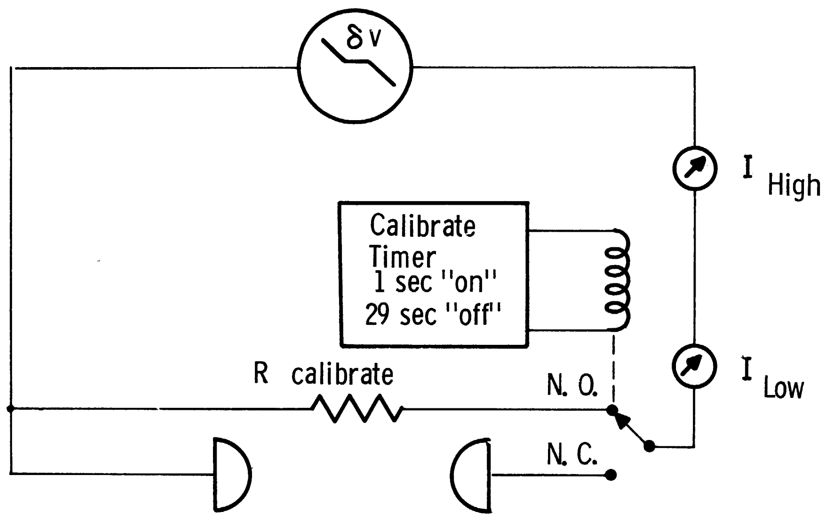


Fig. 15. Simplifed diagram of in-flight calibration system.

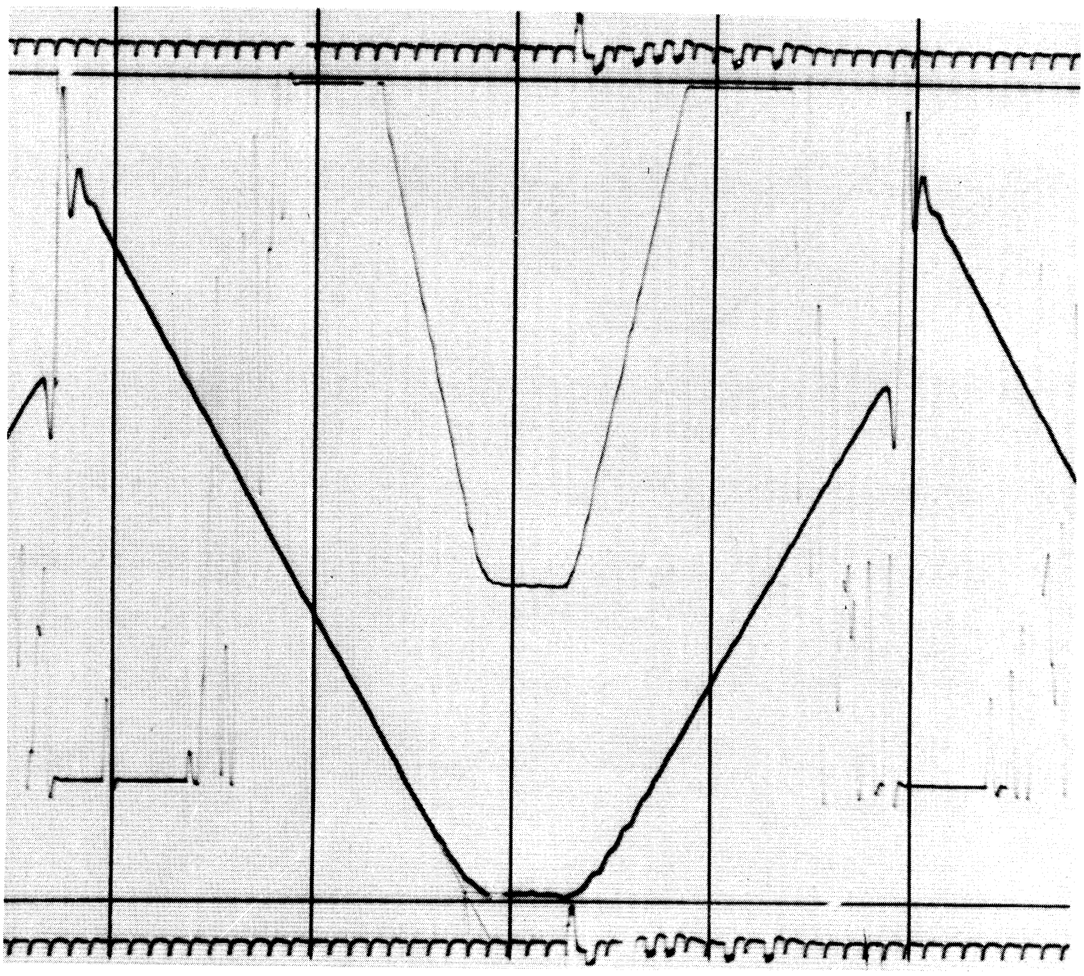


Fig. 16. Telemetry record showing in-flight calibration.

actual flight records. A schematic diagram and photograph of the electronic timer are shown in Figs. 17a and 17b, respectively. A discussion of the op-

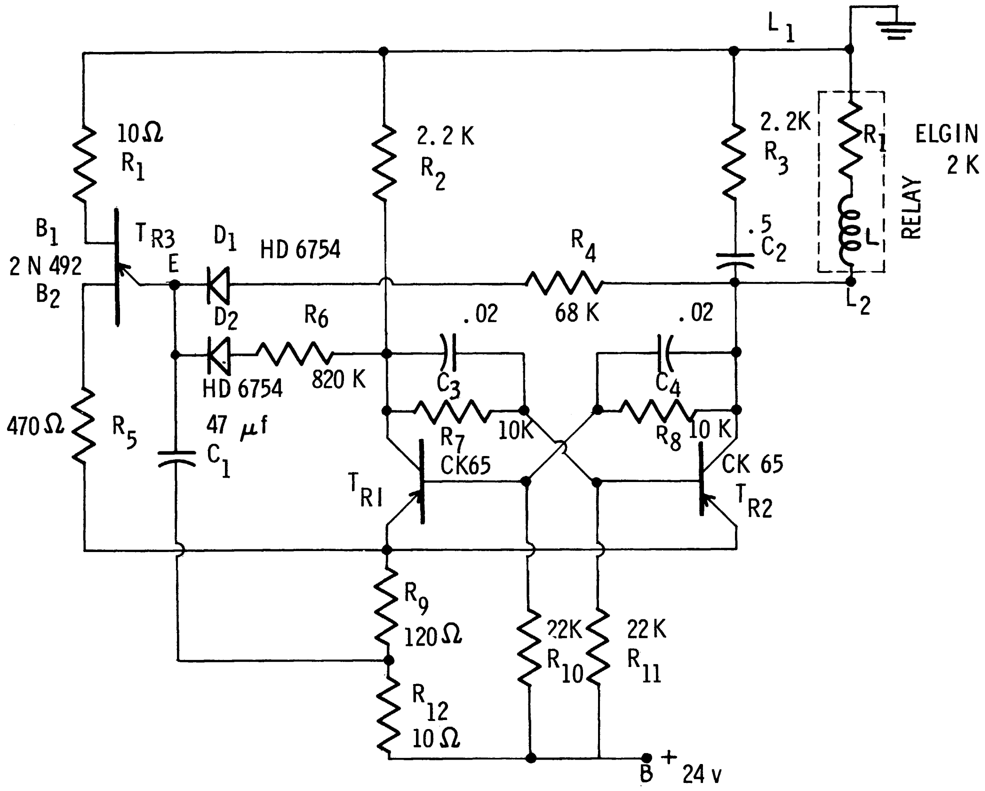


Fig. 17a. Schematic of the calibration timer.

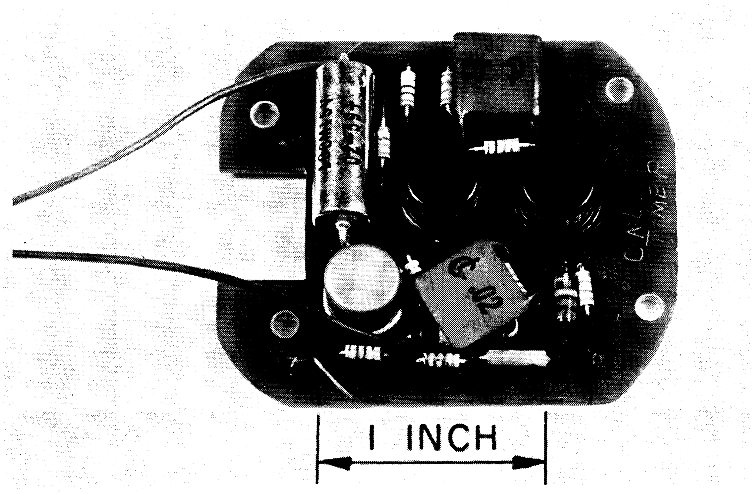


Fig. 17b. Timer circuit.

eration of the timer can be found in Refs. 2 and 4. The calibration time of approximately one second is chosen to allow time for three cycles of δV. A calibration every 30 seconds provides adequate information to evaluate variations, if any, in instrument behavior. In actual flights, the calibrations have not varied significantly. The calibrate system is designed to be "fail-safe" in that the most likely failures would leave the system in the normal measurement mode.

2.43 Aspect Magnetometers

Since the current collected at each hemisphere is in part a function of Dumbbell orienation, it is necessary to provide aspect data throughout the flight. A pair of mutually perpendicular magnetic aspect sensors, used in conjunction with r-f signal strength and collected current variations, make possible the determination of Dumbbell orientation. One sensor is aligned with the Dumbbell axis, and the second is mounted radially, or perpendicular to the axis. The pair is an especially packaged unit purchased from Schonstedt Engineering Company, Silver Spring, Maryland. The units operate from 6 volts input and provide an output of from 0-5 volts as each sensor is rotated into and out of the direction of the earth's magnetic field (approximately 600 milligauss). Basically, each sensor responds to the component of the field which lies in the direction of the sensor. Since the Dumbbell motion is cyclic, 100% monitoring of both magnetometer output is not necessary; thus the two magnetometers time-share a single telemetry channel (VCO). Figure 18 is a functional diagram of the system. The time-sharing is accomplished by an electronic timer similar to the calibration timer discussed

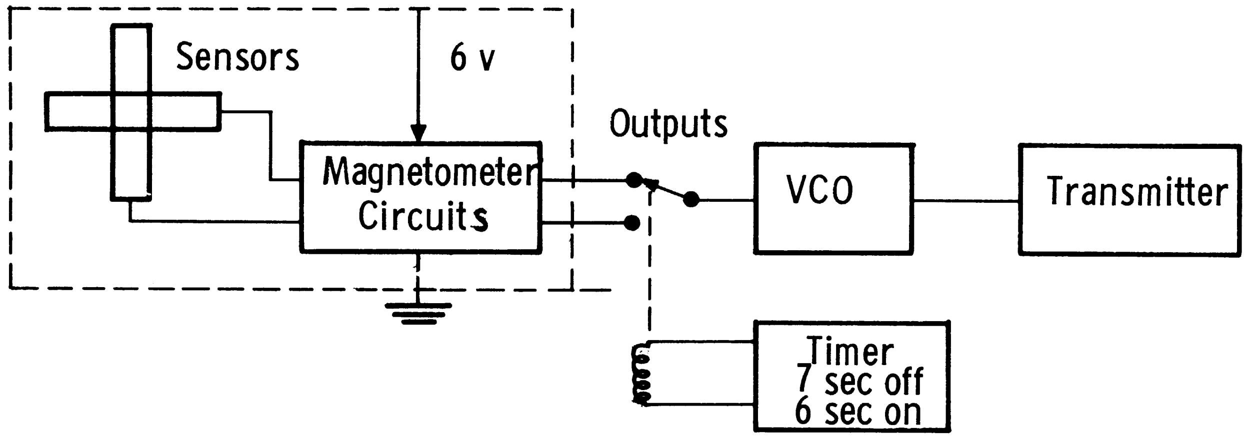


Fig. 18. Aspect magnetometer system.

above and shown in Fig. 17, but using somewhat different values for the time-determining components. The times of 6 and 7 seconds are chosen to indicate best the expected motion periods and are slightly different from each other to allow positive identification, although the tumble period (approximately 5 seconds) and the spin period (approximately 1 second) are sufficiently different to be easily recognized if the ejection of the probe occurs normally.

Figure 19 is a photograph of the telemetry record during an actual flight, showing the magnetometer data.

2.44 Power Supply

Primary power is furnished by 2 sets of Yardney type HR-1 Silver Cells, one a single pack of 4 to supply 6 volts, and the other, in two packs of 4 and 12, to supply 24 volts. The 6-volt supply is used to power the transmitter filaments and the magnetometer package. It is also used in a voltage divider for remote control position monitoring discussed in Section 2.45.

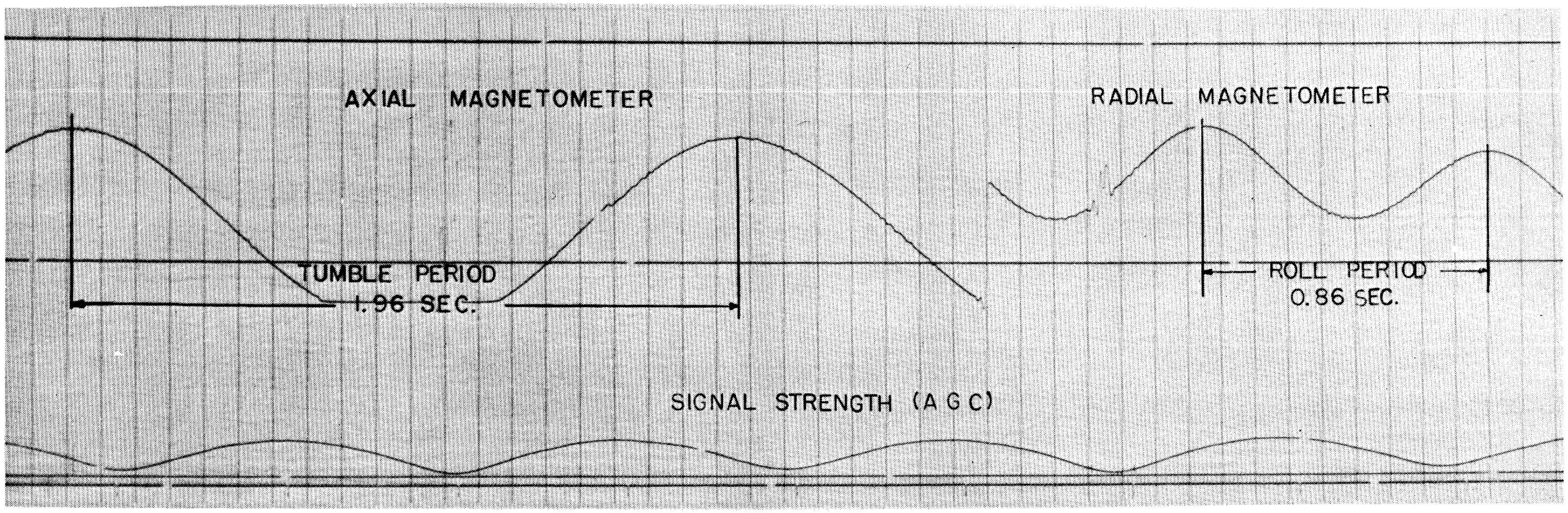


Fig. 19. Telemetry record magnetometer data.

The 24-volt supply is used in the primary of a d-c—d-c converter which furnishes regulated plus and minus 28 v for instrumentation circuitry and 180 v for transmitter B+. The 24 volts are also used directly for the 8V motor and for the operation of several relays. Figure 20 is a power diagram. The d-c—d-c converter employs a common collector configuration with a toroid transformer. The 180-v output is obtained from a full-wave bridge rectifier with an RC filter and is not regulated; the plus and minus 28-v outputs are regulated with a transistor and zener diode from a 40-volt half-wave, RC

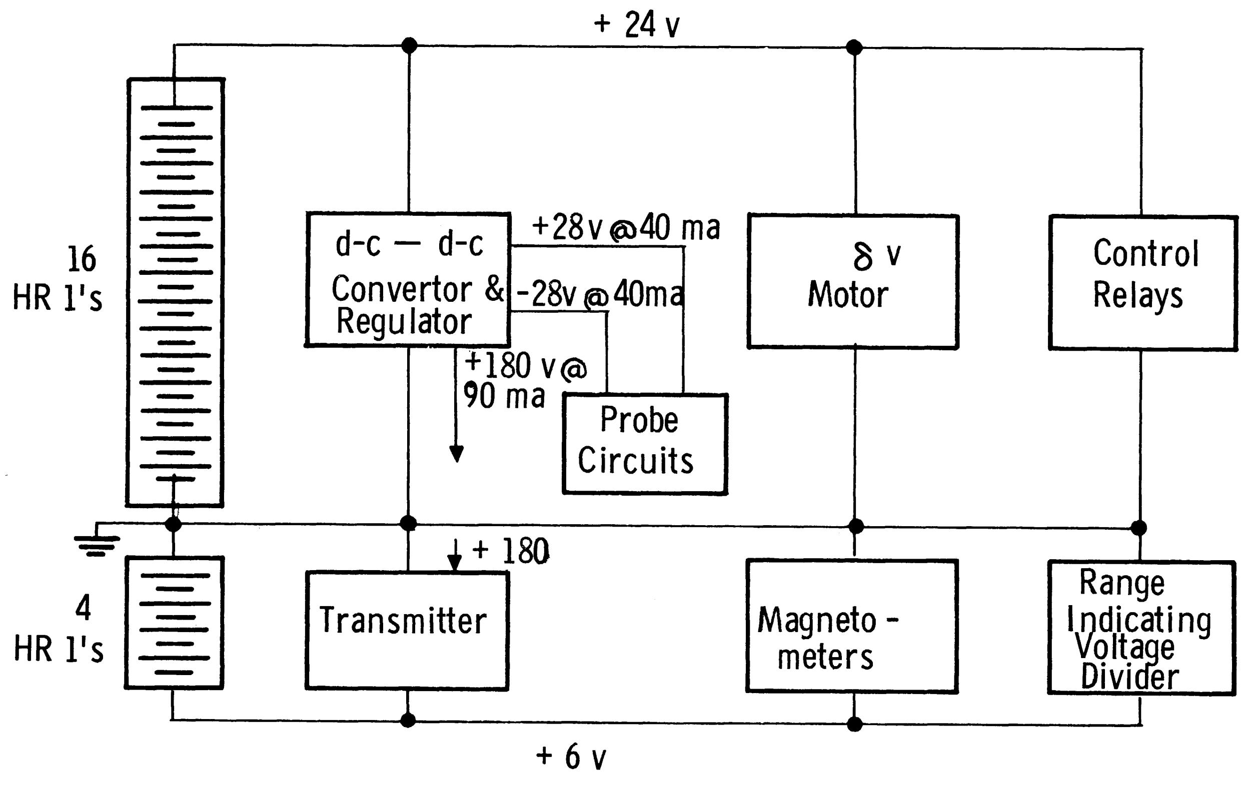


Fig. 20. Dumbbell power diagram.

filtered output. Figure 21 is a schematic of the converter and regulator. The two converter power transistors are case-mounted to a large heat sink as shown in Fig. 22. Other photographs of the power supply are Figs. 6, 7, and 23. Approximately 1 amp is drawn from each set of batteries. The HR-1s are rated at 1 ampere-hour, so that energy is available for an hour of operation. However, the dissipation of heat, mentioned earlier, particularly in the vacuum of space, limits the continuous use of the instrument to about 30 minutes. The additional half hour of life is available for preflight instrumentation checks and other "ON" times prior to firing.

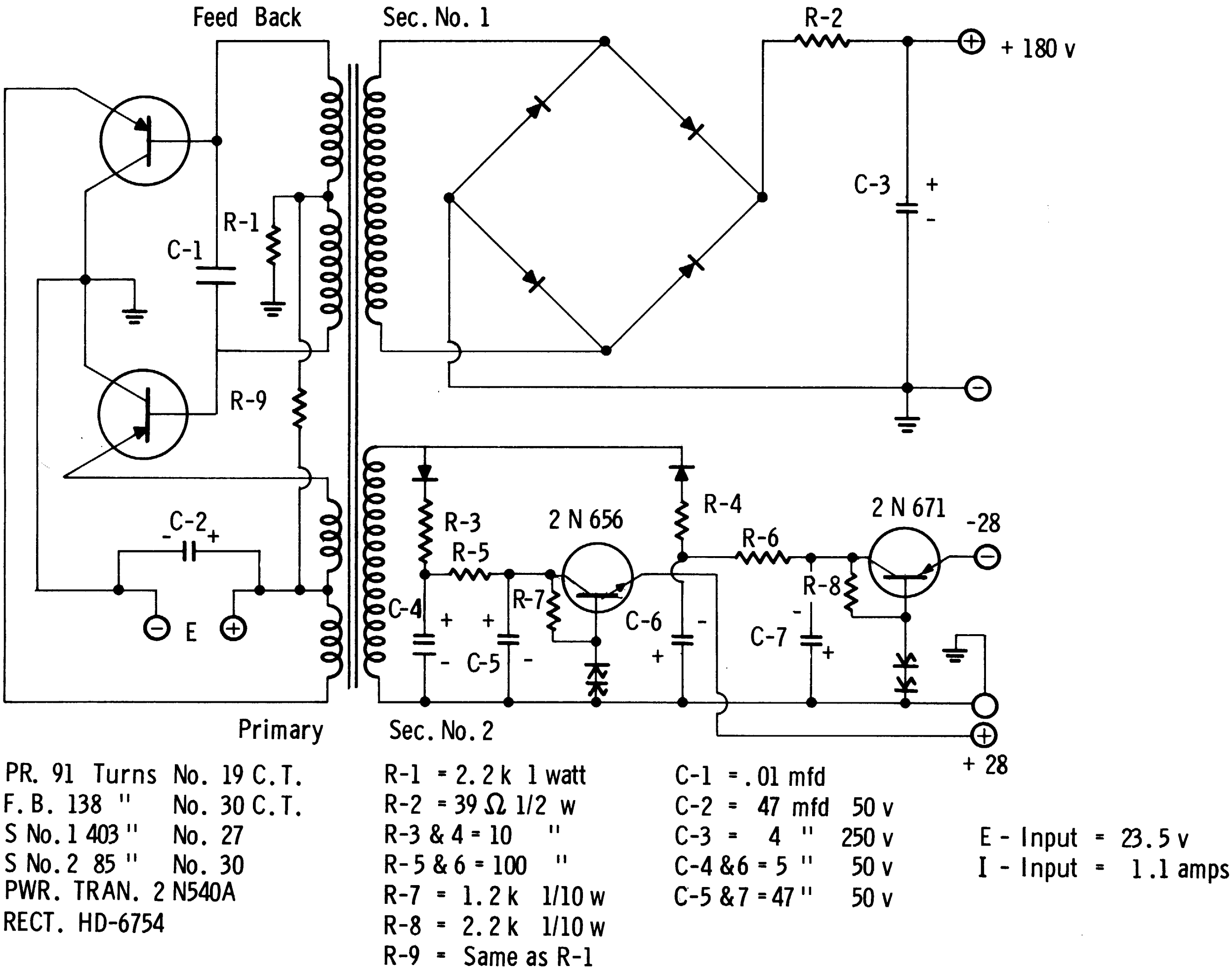


Fig. 21. Schematic of d-c—d-c converter.

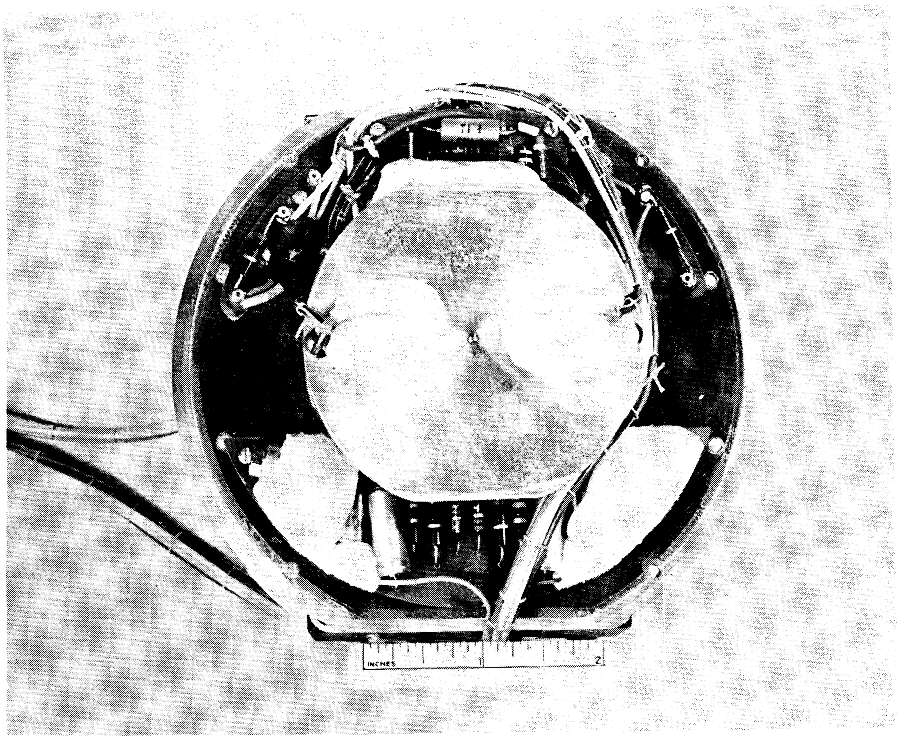


Fig. 22. Transmitter sub-assembly, bottom view.

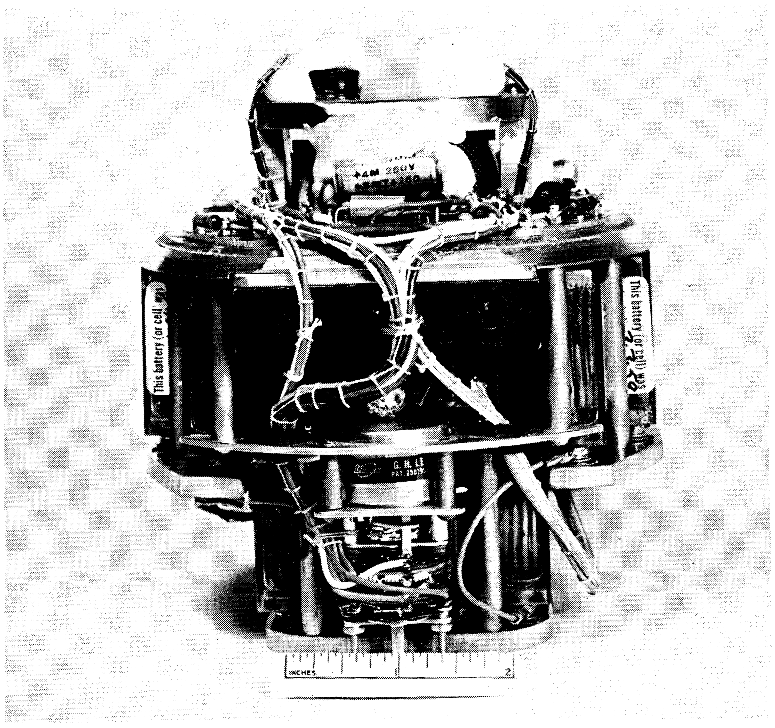


Fig. 23. Transmitter sub-assembly, side view.

2.45 Control Circuits

The control circuitry in the Dumbbell provides ability to turn power on and off, remotely, in a sequence dictated by various instrumentation circuit requirements. The "OFF" to completely "ON" sequence involves 5 steps and so, for positive operation, provision is made for a remote voltmeter indication for each sequence step. The indication of the steps of the sequence are as follows:

Position	Function	Indication Voltage (At position indication terminal on the central nylon insulator)
1	All circuits off	6
2	6-volt power applied to transmitter filaments and to aspect magnetometers 24-volt power applied to d-c—d-c converter which supplies plus and minus 28 volts to instrumentation circuits	4.5
3	180-volt power applied to transmitter	3
4	24-volt power applied to 8V motor and electronic timers	1.5
5	8V voltage sources turned "ON"	0

Two 24-volt Ledex rotary selector switches are used to perform the above sequencing. One, called the Power Ledex and so labeled in Fig. 24, is switched remotely and on command from position 1 to position 4. This Ledex is located

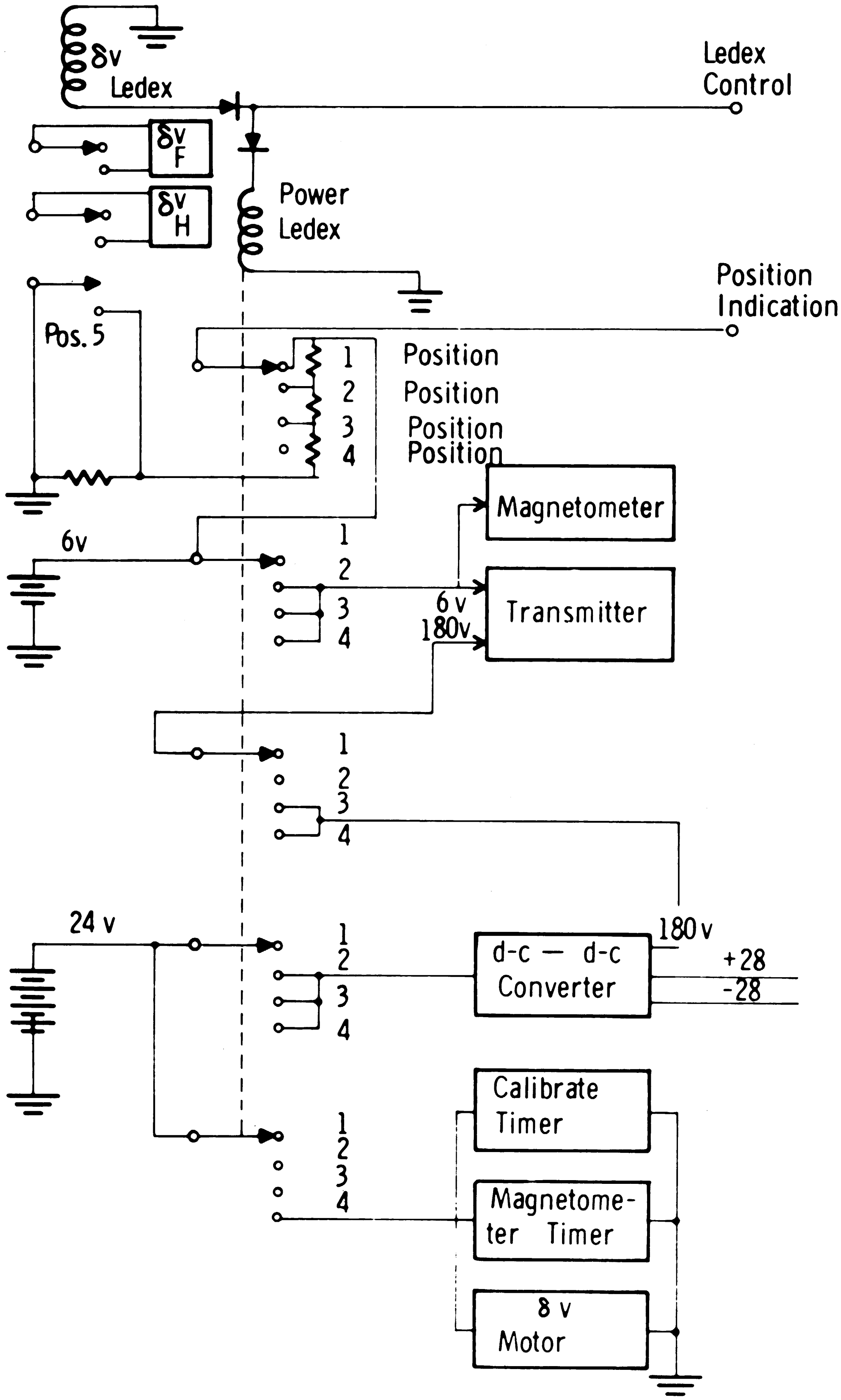


Fig. 24. Dumbbell control circuit.

in the power supply end of the instrument, and is visible in Figs. 6, 7, and 23. The other, the δV Ledex, is located in the electronic circuit end and has one function, to turn the δV sources "ON" and "OFF." Its location, shown in Figs. 6 and 8, close to the current measurement circuits, was chosen to reduce interference pick-up on leads, since any noise at this point will directly affect the probe current measurements. Both of these Ledexes are continuous rotation types which, in this application, step from the fully "ON" position directly to the "OFF" position. To minimize the number of external connections to the Dumbbell, a single lead is used to operate both rotary switches. Two diodes are used, so arranged that a plus 24-volt impulse operates the Power Ledex and a minus 24-volt impulse operates the δV Ledex. These voltages are applied remotely from a position control unit in the blockhouse. The same unit houses the position indication voltmeter. Position indication is provided by using a Ledex wafer in a voltage divider arrangement as shown in Fig. 24. In the "OFF" position, the wiper of the switch is at the 6-volt side of the divider and moves down in 1.5-volt steps to 0 at fully "ON." The probe experiment requires that there be no extraneous external voltage on the probe, so the 0 volt indication was chosen for position 5, the "fly" condition. A 1000-ohm resistor is placed in series with the position indication contact to prevent excessive drain on the 6-volt batteries if the position indication circuit were inadvertently shorted in the rocket or blockhouse wiring. The two external connections, one to the position indicator voltmeter and the other to the position control switch, are made by pressure contacts on screw heads located in the central nylon insulator. These are shown in Fig. 25.

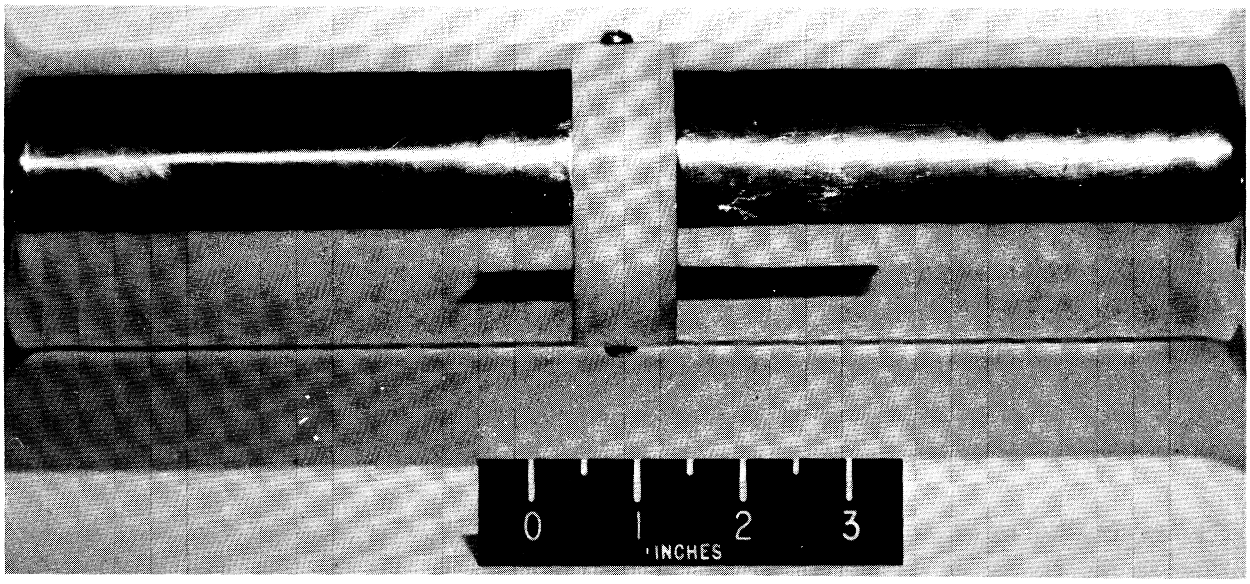


Fig. 25. The central nylon insulator showing position and control contacts.

2.46 Telemetry

The d-c outputs of the two current detectors and the aspect magnetometers are used to frequency-modulate three voltage controlled oscillators of the FM-FM telemetry system. The oscillators are transistorized multivibrators designed to oscillate at a standard IRIG FM-FM center frequency with a 2-volt input and to deviate plus and minus 7-1/2% with 4- and 0-volts input, respectively. The square wave output is filtered to provide a sine wave input to the telemetry transmitter. A schematic and photograph of the VCO are shown in Figs. 26a and 26b, respectively. The three VCO outputs

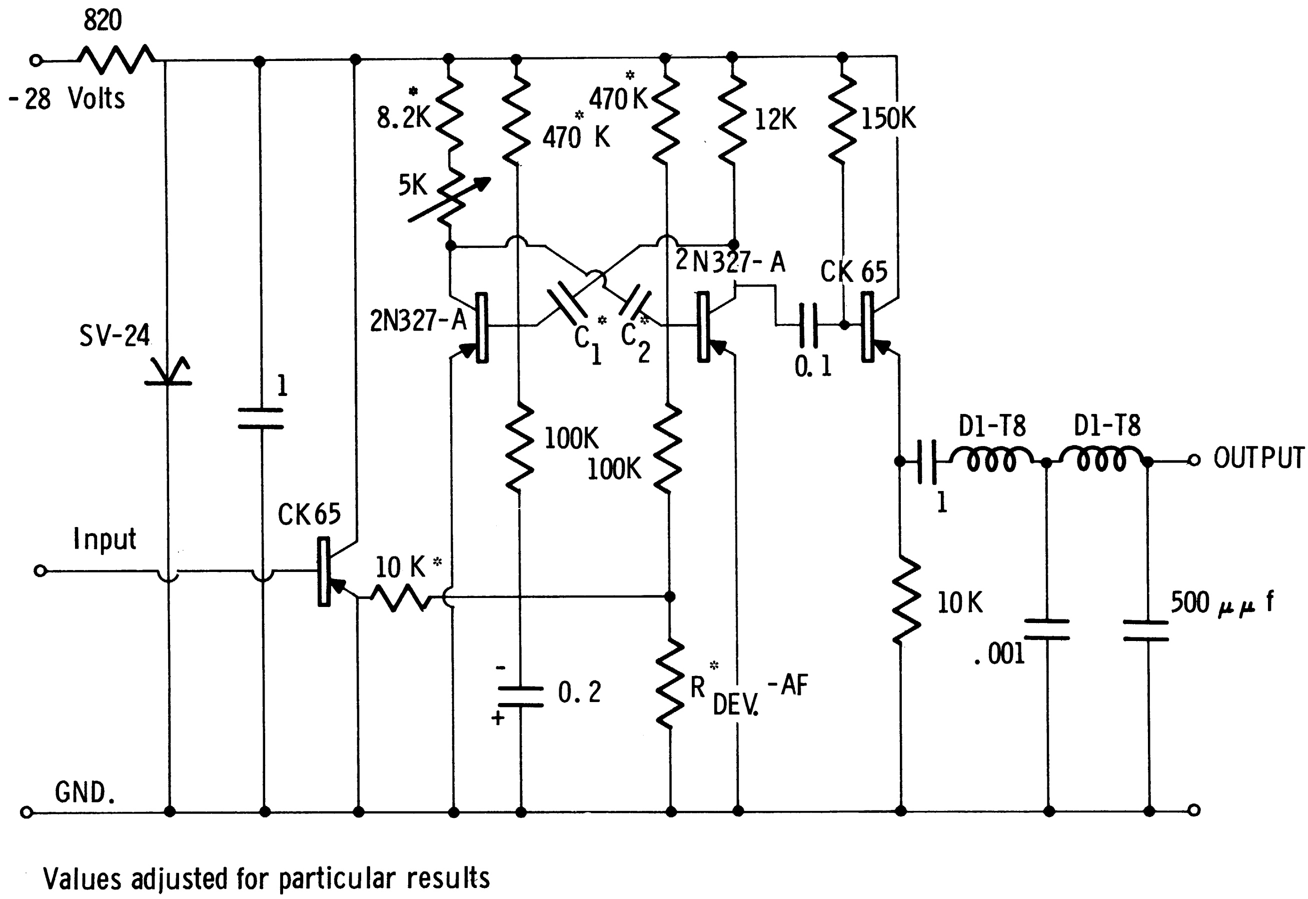


Fig. 26a. Schematic of VCO.

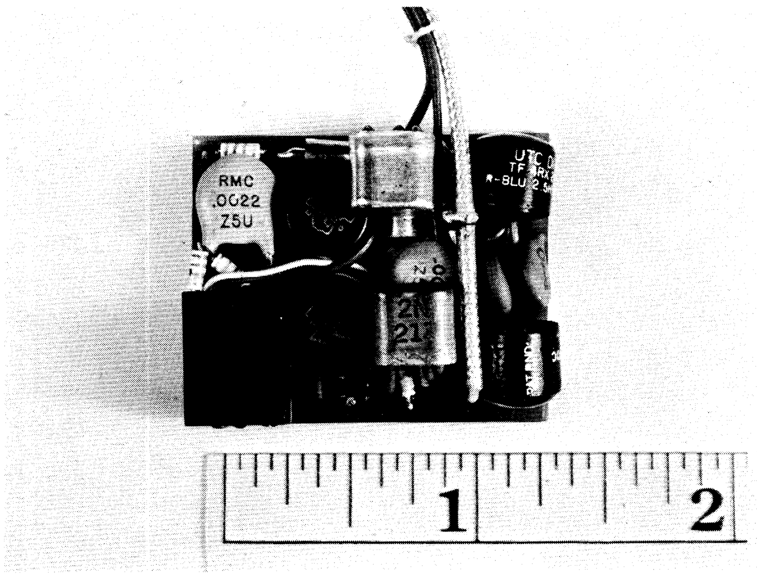


Fig. 26b. Photograph of VCO.

are connected together and their output levels are individually adjusted to produce the proper carrier deviation for a modulation index of 4, and the mixed signal is fed to the transmitter modulation input. The transmitter r-f output if connected through 50-ohm coax cable to the inner ends of the two funnels. The output impedance of the transmitter is adjusted to minimize the VSWR. Antenna patterns taken indicate that the Dumbbell is nearly an ideal dipole; this, when properly tuned, is less than one db below a theoretical dipole.

2.47 System Integration

The layout of the system was dictated in part by decisions made at the outset. In particular, it had been decided that the telemetry transmitter would be centrally located in one of the spheres and that the magnetometer package would occupy the cylindrical section of one of the funnels or guard electrodes. In addition to the volume limitation, several other layout aspects were recognized as problem areas. These were principally:

1. r-f interference in the current measuring system
2. Heat generated by the transmitter
3. Structural integrity in the extreme environmental regime
4. Component accessibility and ease of assembly

To avoid r-f interfernece resulting from proximity of the current measuring system to the transmitter, it was decided to use one sphere for the components associated with current measurement, i.e., the δV generator, the current detectors, and their VCO's and the other sphere for the transmitter, power supply, and control circuits. This decision also relieved the measuring system of the large heat output of the transmitter. The electronic components of the current measuring system are built into a plug-in can to facilitate checkout and to permit modular replacement in the event of malfunction. The can contains the two detectors, two VCO's, the calibrate timer and relay, and a terminal strip for the interconnections of these units. A ten-pin male plug is mounted to the can and mated to a deck-mounted female receptacle. Figure 27 is a functional diagram of the current measuring system, showing the circuitry in the can. The hook-up is straight-forward. The probe current path is indicated with a heavy line. During the calibrate period, the calibrate relay operates and the current path is through the calibrate resistor. All leads associated with the probe current path are shielded and are bypassed with small capacitors where they pass through the plug to minimize r-f pickup. The d-c output of each current detector is fed via an accessible connective terminal board to the appropriate VCO input. The two VCO outputs are tied together inside the plug-in can and are fed out through the plug to the transmitter. The three power inputs (+28 v, -28 v, +24 v), and ground are fed in through the plug and are r-f bypassed with chokes and capacitors.

As explained in Section 2.48 under testing, the plug-in can may be completely tested out of the system. This is of obvious value in isolating the effects of noise pickup that originates in the Dumbbell system. The other remaining components of the measuring system are mounted on the aluminum deck near the plug-in can. Principally, these components are the δV battery packs, the motor-driven potentiometers, and the Ledex which turns the δV "ON" and "OFF."

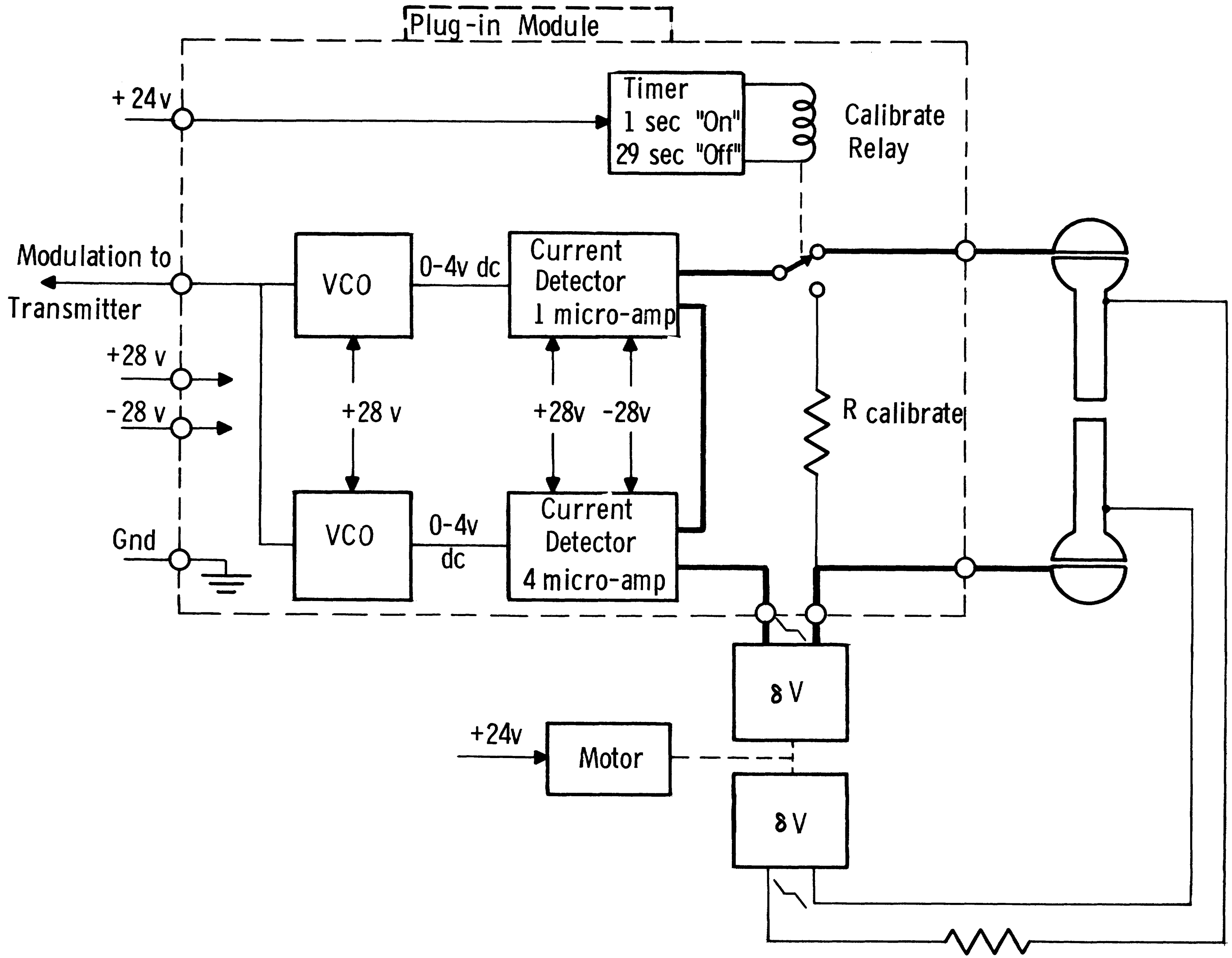


Fig. 27. Functional diagram of the measuring system.

These components, together with the plug-in can, constitute the entire measuring system. By arranging them to span the minimum distance along the Dumbbell, which is also the antenna, the r-f gradient seen by these components is minimized. The exception to this is the lead which makes connection to the hemisphere electrode on the transmitter end of the Dumbbell. Special care in filtering and shielding of this lead is taken.

The bottom of the deck on which the current measuring components are mounted is used principally to mount terminal boards for intra-system connections. These, together with the δV drive motor, utilize most of the available space on the bottom side of the deck.

The "funnel" or guard electrode system is connected as shown in Fig. 27. The series resistor shown is used to provide a voltage drop in the guard circuit which just balances that in the hemisphere circuit due to the impedance of the current detectors so that the guard voltage will closely approach the hemisphere voltage. The connection to the funnel which houses the measuring circuits is made just below the instrumentation deck. The other funnel acts as system ground so the connection to it is made on the instrumentation deck which is also grounded.

The two magnetometer sensors and their electronics are contained in the foamed package visible in Fig. 6. Connections to the input and output terminals of the package are made on a terminal board mounted on the side of the auxiliary instrumentation can which houses the timer and VCO associated with the magnetometers. The output of the VCO is connected in parallel with the two other VCO outputs to be fed to the modulation input in the transmitter.

As discussed earlier, the other end of the Dumbbell assembly houses the primary batteries, d-c—d-c converters, the transmitter, and control circuitry. A deck attached to the funnel, which is system-ground, is the basic support for all these components which, when assembled, form a single unit as shown in Fig. 23.

The integration of the components in this end posed no major problems electrically. Space limitations and heat generation of the transmitter dictated judicious choice of component location. An important feature of the layout is the location of the batteries which may be changed without disassembly of the system.

The leads interconnecting the two ends of the system are laced into a harness. A loop, to provide adequate slack for assembly and disassembly, is pulled up and tied down at final assembly. A second harness, containing the antenna feed cable from the transmitter and the two control leads to the connections at the center insulator, is likewise looped at the transmitter end.

As may be seen in various photographs of the instrumentation, plastic foam is widely used to tie down leads. When properly applied, the foam supports leads so that, under acceleration, no damaging forces are applied to terminations. Standard Teflon insulated wire is used throughout.

2.48 Testing

It is clearly essential, in the use of rocket-borne instruments, that the operational characteristics and limitations of the instrumentation be accurately known before flight. To provide this essential information about the Dumbbell system, extensive testing is done.

Each individual circuit is adequately tested in all anticipated environments prior to integration, and the system is then tested similarly. Extensive test records are kept for possible use in explaining unanticipated phenomena.

Testing of the current measurement portion of the Dumbbell begins with evaluation of the input-output characteristic of each current detector under various environmental regimes and under varying input voltage levels. The input-output characteristic is evaluated including measurements of frequency response, phase shift, input and output impedances, noise level and distortion. After completion of these tests, the detectors are mounted in the current measurement module with their associated VCO's which have been individually tested. The module is then tested using external simulation to complete the system (power supply, δV, etc.). Finally the module is mounted in the Dumbbell and after integration problems (principally r-f interference) are solved, the current measurement system is again extensively evaluated through the telemetry link. This testing includes frequent reading and recording of the important accuracy parameters, R calibrate and the δV to establish a history of their behavior.

The magnetometer instrumentation is tested by measuring its output vs. orientation before and after integration in the local geomagnetic field. This testing is repeated just prior to launch in the magnetic field at the launching site.

The power supply operation is carefully evaluated prior to integration in the specified environmental regimes and with varying input voltages and load currents, and again after integration by frequent monitoring of its operational characteristics. The flight batteries are checked by carefully monitoring the ampere-hour input and output during the initial charge-discharge cycle and again during a charge cycle prior to installation for flight.

The operation of the telemeter is continually evaluated during all system checks. Other specific testing includes measurement of transmitter output power vs. temperature and input voltage, and measuring and optimizing of the antenna VSWR and radiation pattern.

The completed Dumbbell undergoes impact and vibration testing as described in Section 2.494. All aspects of its operation are monitored during these tests. A ground ejection test of the nose cone is conducted with the operating Dumbbell. At the launch site, several instrumentation checks are made, including three formal tests—a "horizontal" check of the complete rocket system before the rocket is placed in its launching position, another called the "vertical" after rocket emplacement, and a third "Instrumentation Check" prior to final launching preparation.

Graphic records, usually from an oscillograph, and written documentation of all tests are made, and when the instrument is launched, a large file of test data is available for aid in evaluating the flight behavior.

2.49 System Performance

The performance of the completed instrument is outlined below by discussing the most important parameters of which successful data collection is a function. The evaluation is based principally on laboratory tests, but the successful operation of Dumbbells on 4 recent rocket flights and partial success on several earlier flights have also aided in evaluating the performance characteristics of the instrument.

2.491 Accuracy.—The accuracy of the current measurement is a function of the stability of the two parameters on which the in-flight calibration is based, that is, the amplitude of the δV and the value of the calibration resistor. If these variables are maintained at fixed known levels, then the resulting calibration current will be known and the entire system (including current detectors, VCO's, transmitter, ground-based receivers, discriminators, and recorders) will be calibrated. With paper oscillograph records, the calibration will be in terms of microamperes per unit of vertical deflection on the record. For the magnetic tape recordings of the VCO signals, the calibration is in terms of microamperes per cycle of change in subcarrier frequency.

As indicated earlier, the drift in calibration of the entire instrument and ground station system has been negligible in the flights to the present time. This is indicated by comparing successive calibration waveforms of the type shown in Fig. 17, which are recorded periodically throughout the flight.

The accuracy to which the dv/dt or instantaneous amplitude is known is a function of three parameters: the δV supply voltage, the linearity of the δV potentiometer, and the drive motor speed. The δV supply voltage is known at launch time to plus or minus 0.1% and is constant within the environmental regime to plus or minus 10 millivolts or plus or minus 0.3%. The potentiometer is linear within plus or minus 0.5%. The δV drive system is conservatively designed and tests have shown that, if the average rotational speed is determined for each cycle of the δV, thus eliminating long-term variations, the speed is constant to within plus or minus 0.5%.

The calibration resistor used in flight is accurately measured after installation to within plus or minus 0.5%. A low-temperature coefficient resistor is used, mounted in a region of small temperature change so that temperature effects can be considered negligible.

The resulting accuracy of the current measuring system, based on the figures above is at worst 2%, and various tests indicate that it is normally within 1%.

2.492 Frequency Response.—The ability of the current measurement system to follow variations in probe or calibration currents is ultimately limited by either the frequency response of the current detectors or by the inherent response of the telemetry system. The response of the ionosphere is instantaneous by comparison. In general the telemetry limitation is made negligible by selecting IRIG channels (subcarrier frequencies) which have more than adequate response for their particular tasks. The frequency response of the system then reduces to that of the current detectors themselves. In the ring-modulator-type detector three areas exist in which the response may be limited: the time constant of the input circuit, the time constant or cutoff frequency of the low-pass output filter, and the chopping frequency of the modulator driver.

The time constant of the detector input circuitry becomes a problem when excessive capacitive filtering of the input is necessary to bypass unwanted, interfering signals. Normally, the bypassing necessary for the suppression of r-f interference (a few hundred $\mu\mu f$) is negligibly small in its effect on the input response. Other disturbances, however, such as electrically induced motor noise, power supply pickup, various switching transients, and laboratory 60-cycle interference are not so easily disposed of. Fortunately RC and LC filtering limits these factors to a reasonable level without seriously lowering the response of the system, with the exception of 60 cycle which will not be encountered in the ionosphere, presumably. The second factor, the cutoff frequency of the LC output filter, is a variable which is arrived at by a compromise between the desired frequency response and the allowable modulation ripple on the detector d-c output. Such ripple on the output can mix with the VCO carrier to form sum and difference "beat" frequencies which may disturb other telemetry channels. To avoid this, the allowable ripple level has been set at 1% of full-scale output, or approximately 10 millivolts peak to peak. The actual cutoff frequency of the filter, then, depends on the modulator chopping frequency (or twice this value for a bridge demodulator) which is to be filtered.

As implied above, the third factor, the chopping frequency of the ring modulator, is the most basic limitation upon the response of the detection system. A rule of thumb is that the frequency response of such a system to a sine wave input is approximately 1/10 of the chopping frequency. At present the highest chopping frequency consistent with component power and volume limitation of the circuits is approximately 5 kc. Ideally this would provide a sine wave frequency response of 500 cps. However, the waveforms which the Dumbbell is expected to encounter are not sinusoidal, so it seems advisable to select a more meaningful criterion for evaluating the response of the system. One such approach is to rate the response in terms of the rise time, or fall time, of the system; that is, the time required for the output of the detector to rise or fall between 10% and 90% of full scale when a corresponding current step function is applied at the input. Typical rise and fall times are less than 5 msec, a sufficiently fast response for the 300 msec sweep period of the δV source.

2.493 Environmental Aspects.—The electronic and mechanical systems in the Dumbbell are designed to endure the wide range of environmental variability which can be encountered in rocket-borne instrumentations. The principal environmental characteristics of the instrument are discussed below.

A nominal temperature range of 0 to 50°C has been adopted and the instrument will operate normally over this range. Actually, a much wider temperature range is tolerable, but with somewhat reduced stability.

Linear accelerations of 70 G's are encountered during rocket thrust (Aerobee 300 vehicle). The mechanical systems are designed to withstand acceleration of 200 G's along the thrust axis without failure. A 90-G impact test is conducted on the completed Dumbbell. Vibration tests are conducted on the completed Dumbbell on a shake-table. A 3-sec sweep from 5 to 50 cycles at 5 to 15 G's is made in the long axis. Similar sweeps are made on two perpendicular radial axis at 5 G's maximum. No major failures have occurred during such testing.

The assembled Dumbbell is pressure-sealed, and so can operate in a vacuum. The seal is tested by pressurizing the Dumbbell to an internal pressure of 45 psi and holding it for one hour.

2.494 Reliability.—As indicated earlier, the design of the system resulted from an interplay of theoretical, volume, power, accuracy, and environmental considerations. Now added to this list are reliability considerations.

The design philosophy has been to use simple circuits which can be compensated by careful selection of components rather than complex circuits which require no compensation but are bulky and power consuming. Of great significance, in this regard, is the use of the inflight calibrate system, which detects drift in circuit characteristics and provides the necessary information for data correction (actually, seldom necessary). The use of two current detectors serves primarily to provide adequate resolution for measurements through the entire trajectory; however, they also provide back-up for each other during much of the flight. This aspect is particularly enhanced by making the more sensitive detector and its VCO linear to over twice its normal full scale (recoverable from magnetic tape data). To realize the maximum benefit from this redundancy and to increase reliability further, each electronic unit is separately regulated and employs series current limiting so that no internal failure will disable the d-c to d-c converter which would, of course, cause complete failure of the measurement. The various switching and timing circuits are made fail-safe, that is, the most likely failures will leave the system in the more desirable position for measurement purposes. The calibrate timing circuit, for example, is designed to leave the system in the ionosphere measurement mode if switching circuitry fails.

During instrument evaluation checks and pre-flight tests the system accumulates on the order of 50 hours of carefully monitored operation during which time its reliability in a laboratory environment can be assessed. These 50 hours of test, which in general are accomplished without component malfunction, indicate a good statistical probability of an additional 15 minutes of continued normal operation in flight.

2.5 AUXILIARY CIRCUITS

In addition to the function for which they were designed, the measurement of ionosphere current, some of the Dumbbell probes have carried within them several auxiliary circuits designed to provide information which is useful in evaluating such factors as:

1. The effect, if any, of the radiated r-f telemetry power upon the surrounding ionized regions.
2. The effectiveness of the guard electrode action.

The effect of the r-f has been evaluated in two ways; first, by a simple storage system in which a set of capacitors were charged sequentially from the output of one of the detectors while the r-f power was removed, and were later read out when the r-f power was restored. The resulting digitized volt-ampere characteristic was then compared with an adjacent directly measured characteristic.

The second approach has been to reduce the r-f power periodically in the flight, by causing a periodic reduction in plate supply voltage to the transmitter from the normal 180 volts to approximately 115 volts. The result is a decrease in radiated power from 2 watts to approximately 1/2 watt. In both of the above tests, no effect of the r-f upon the local ionosphere was observed.

The guard electrode action was evaluated by two means also. One method is to measure the amount by which the guard action was not ideal and the other is to establish an ideal guard action and compare.

Following the first approach, a miniaturized electrometer voltmeter was connected across a hemisphere and its associated guard electrode and the difference voltage variation during the flight was telemetered. Ideal guard action would cause the potentials of the two electrodes to vary exactly together in amplitude and phase. The actual variation was considered small but possibly not insignificant.

The second method of investigating the guard electrode action was to short a guard and hemisphere together periodically and rely upon the identical δV generators to keep the opposite guard and hemisphere together in potential as they were both driven over the appropriate range of potentials. The results of these tests are discussed thoroughly in the data report mentioned in the Introduction.

3. THE NOSE CONE AND DUMBBELL EJECTION SYSTEM

3.1 INTRODUCTION

As indicated earlier, the Dumbbell is ejected from the rocket shortly after the aerodynamic drag forces have become negligible compared to the ejection forces. This has occurred between 70 and 80 km on the Aerobee 300 flights which have carried recent Dumbbells. Several problems arise in accomplishing the ejection, some of them obvious, some more subtle. The dominant philosophy in the design and development of the nose cone was to keep the number of functions necessary for ejection to a minimum and make each function as positive as possible. Naturally, the most important function is the nose cone opening itself since the chances of the Dumbbell staying inside are very small with the nose cone opened, as can be seen in Fig. 28.

3.2 MECHANICAL DESIGN

The clamshell-type nose cone halves, Fig. 29, which provide the aerodynamic shape of the rocket during powered flight are hinged to the base of the enclosure and are held together against the force of two springs by a magnesium ring which is pyrotechnically fractured to effect opening. The Dumbbell rests on a spring-loaded plunger within the enclosure. The plunger is held depressed against the spring force by a latch mechanically linked to a nose cone half so that opening of the nose cone pulls the latch, freeing the plunger, which, operating against the compressed spring, ejects the Dumbbell from the opened enclosure.

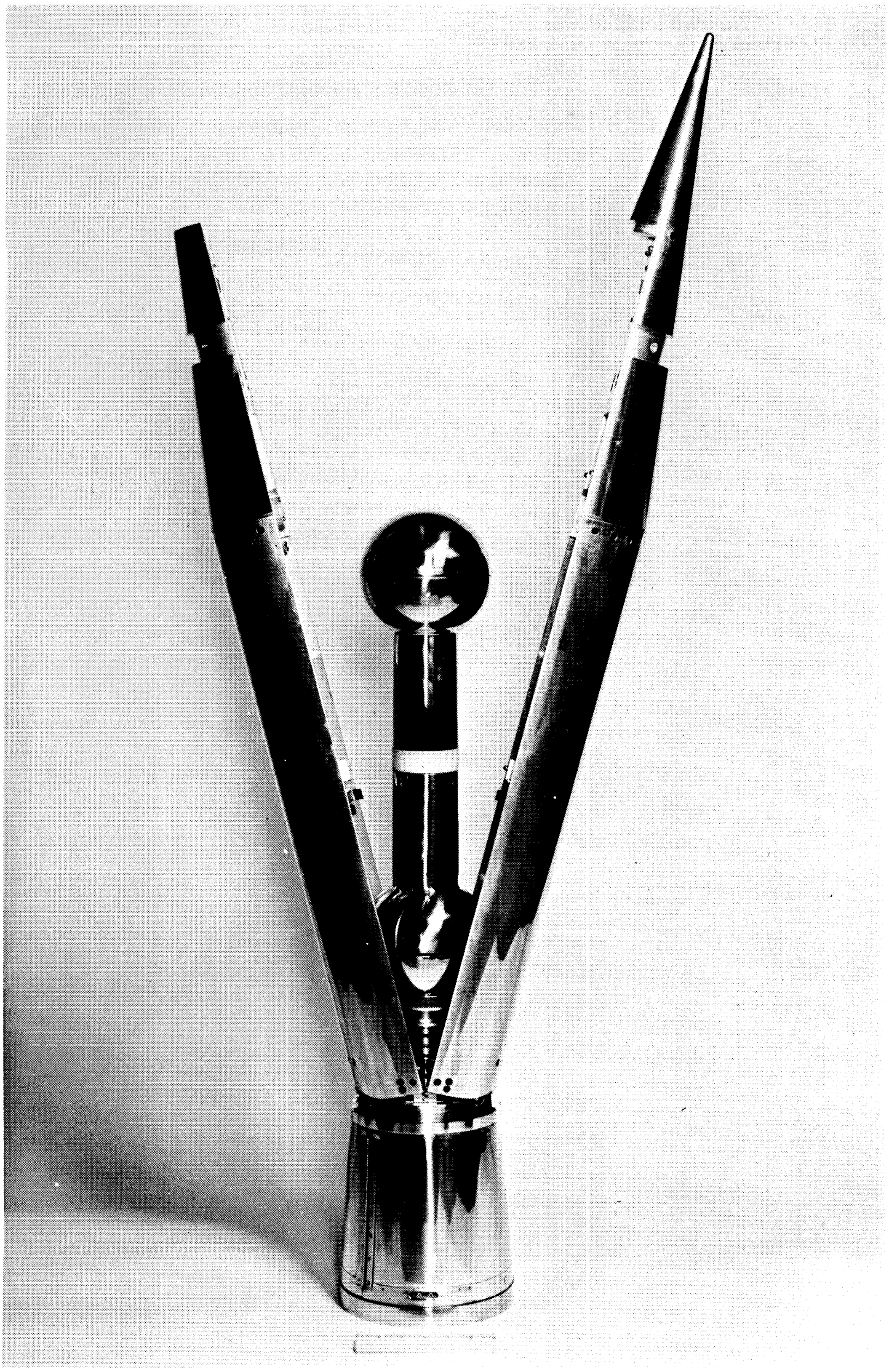


Fig. 28. Dumbbell in opened nose cone.

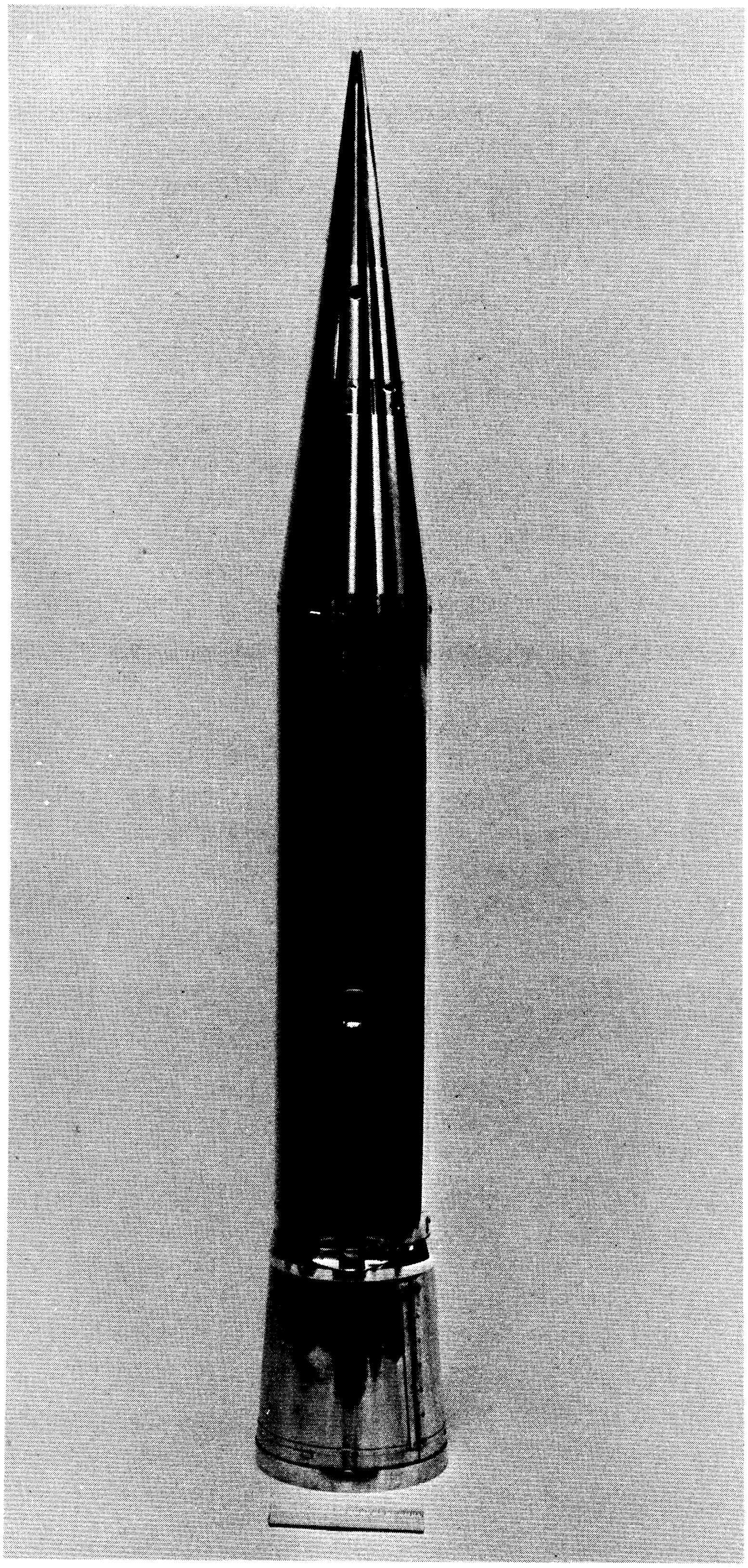


Fig. 29. Closed nose cone.

The cone section of the enclosure consists of two split halves and a solid tip, shown disassembled in Fig. 30 which are machined from aluminum castings. The flat interfaces of the split halves are machined first so that the halves may be held together for subsequent machining. A recessed channel is machined around the cone to provide for flush mounting of the magnesium frangible ring. Four cylindrical pockets equally spaced around the channel are provided to mount explosive squibs and their thermal insulators. The frangible ring is made in two parts which are fastened together with four recessed socket head cap-screws at the split. The ring is relieved slightly above each of the four squibs to control the fracture line. The ring is shown in Fig. 31.

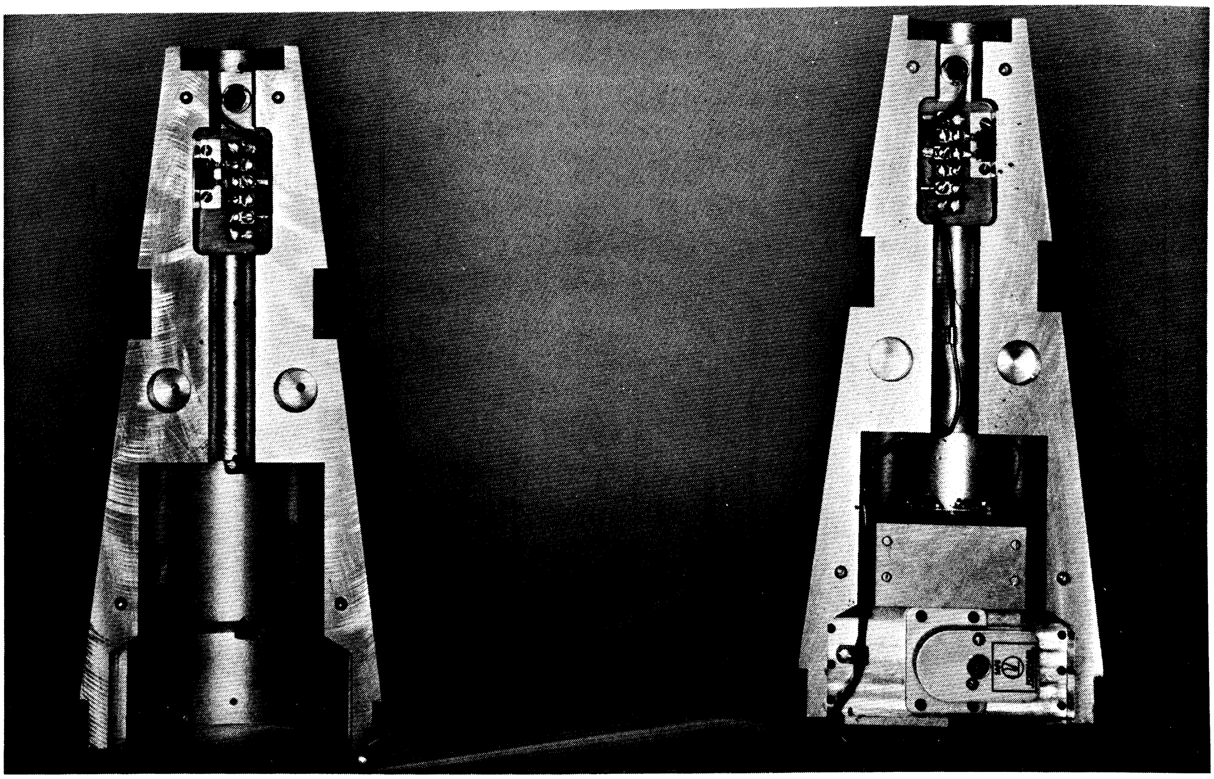


Fig. 30. Cone section disassembled.

The squibs, Hercules Type P85A0, are fitted into machined linen-base-phenalic cylinders used to provide thermal insulation. The squib-insulator assembly shown in Fig. 31, fits snugly into its recessed pocket and is held there by the frangible ring. Two small holes extend from the bottom of the pocket to the center of the cone to pass the squib leads to the firing circuitry. Except for a small central cylindrical hole, the cone in this vicinity is solid to provide strong support to direct the explosion outward and to provide heat sink for the aerodynamic heating which would raise the temperature of a smaller mass to a point where thermal ignition of the squibs could result.

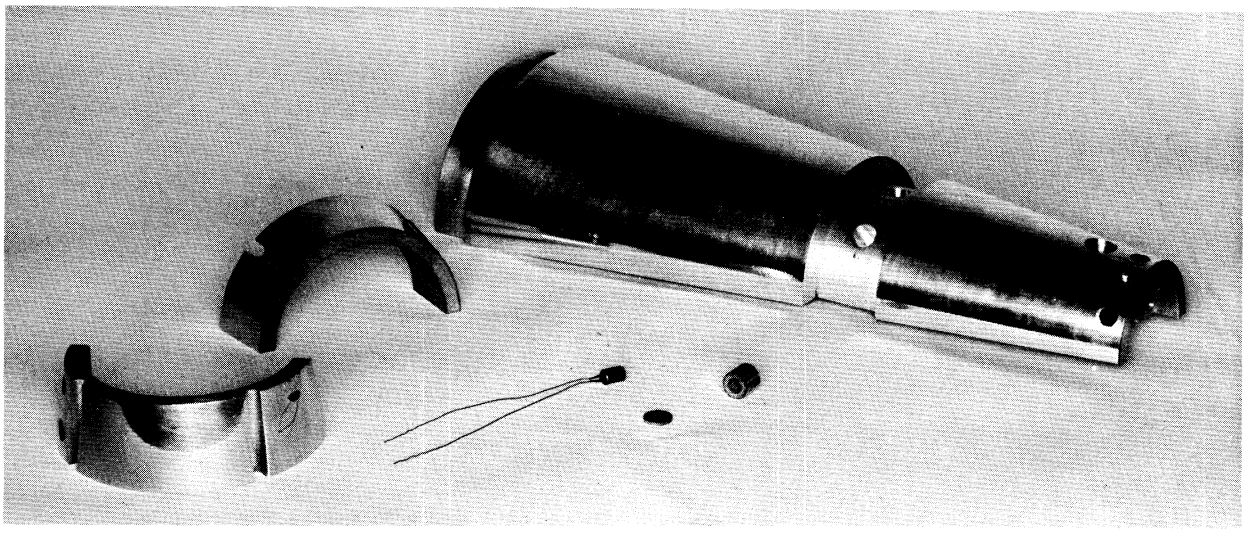


Fig. 31. Cone half with squib-insulator assembly and frangible ring.

Two round 35-lb springs are used to provide opening force and are mounted as shown in Fig. 32. In the closed, compressed position they are enclosed in their mounting holes and similar opposing holes in the opposite half. Four 1/4-in. steel dowels in one half pilot into mating holes in the other half to provide positive alignment and more importantly to eliminate strain on the frangible ring resulting from any shear forces existing between the two halves.

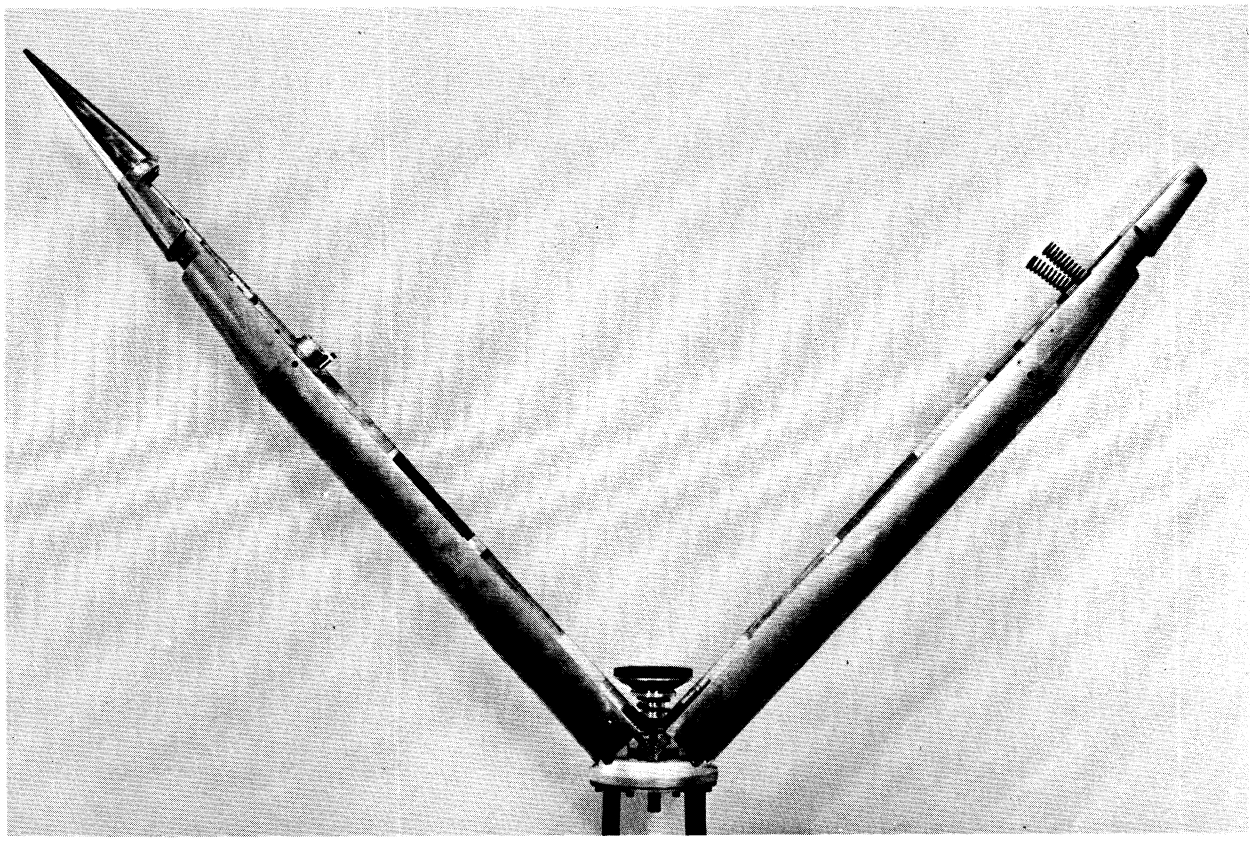


Fig. 32. Dumbbell nose cone open.

In the lower section of the cone, space and mounting faces for electrical components of the system are provided. The bottoms of the cone halves are machined for internal pilot to the cylindrical portion of the nose. The two halves of the cylindrical section of the nose are made from magnesium tubing. They are attached to the cone halves with 20 screws around the circumference. A stiffening ring is located approximately in the center of this section to strengthen the structure. The ring is also used to mount two dowels and mating holes for alignment and shear strength. Attached to the bottom of each half at 90° from the split are hinges with which the halves are attached to the base plate with 1/2-in. steel hinge pins. On one side at the split, gear segments are mounted to force the halves to open together and at the other split a base-mounted, spring-loaded piston terminated with roller bearings pushes up against the halves forcing them to the full open position. The details of the plunger and gear assemblies are shown in Figs. 33 and 34, respectively.

The Dumbbell rests in a plunger which, when depressed, is spring-loaded against the base plate to approximately 60 lb. The plunger is held in the depressed position with a strong latch bearing on a machined shoulder on the plunger assembly. When the nose cone is closed, the latch is held positively in position to prevent premature release due to vibration or radial accelerations. The mechanical linkage is so arranged that the latch does not move until the halves are open approximately 30° and then quickly unlatches, providing a positive release when the nose is sufficiently open to clear the ejecting Dumbbell.

Evaluation of Dumbbell performance before flight when it is installed in the nose cone depends on complete electrical ioslation of the Dumbbell from the rocket. To effect this, the top of the plunger on which the Dumbbell restsis made of linen-base-phenalic and insulation material is attached around the inside of the cylinder in a band at the bearing point of the Dumbbell sphere equators on the cylinder walls. Two adjustable, contoured feet are mounted on the cylinder walls, one on each half to hold the Dumbbell,

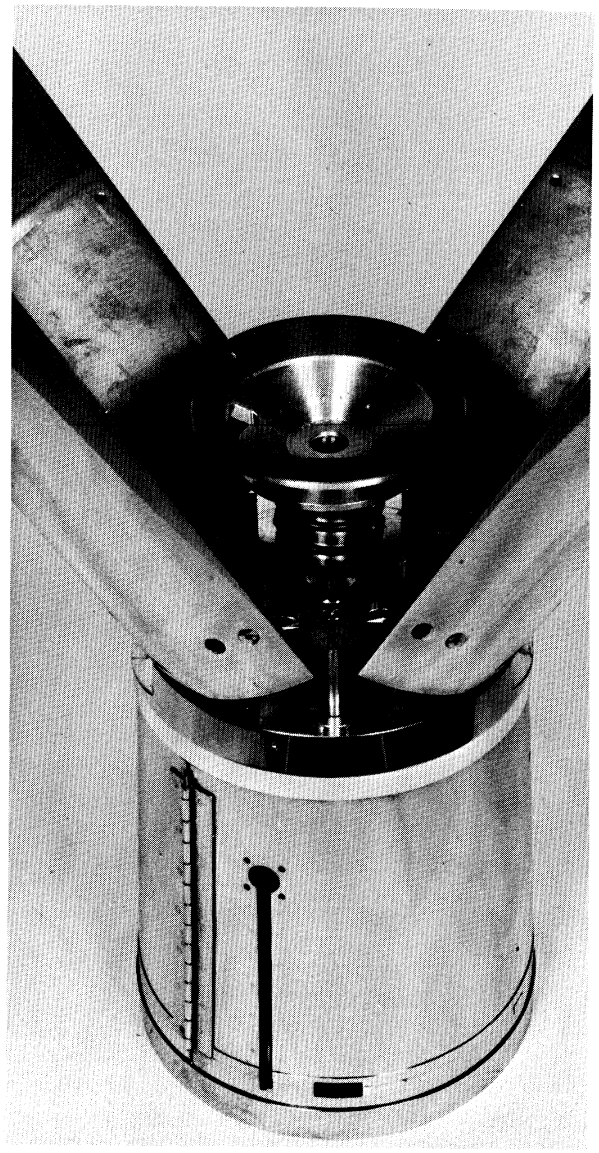


Fig. 33. Open nose cone showing plunger details.

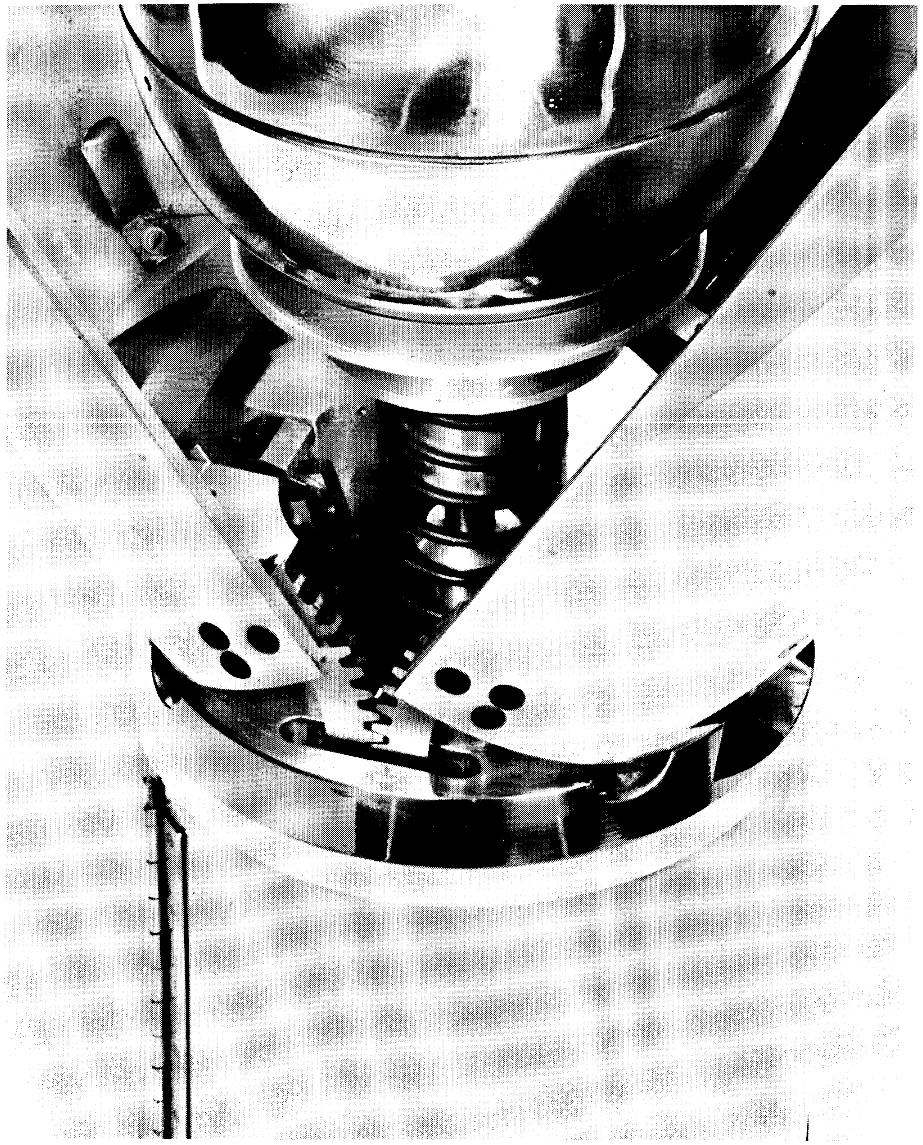


Fig. 34. Open nose cone showing latch and gear details.

firmly against the plunger until ejection. These are made from linen-base-phenalic to provide the required insulation. To provide control and monitoring of the installed Dumbbell, it is necessary to make electrical contact with the two screw heads in the center nylon insulator in the Dumbbell, and with its upper "funnel." This is accomplished by mounting phosphor bronze bands, shown in Figs. 35a and 35b, on insulating fittings from the cylinder walls to bear against the appropriate contact. These are arranged in a symmetrical manner so that no upsetting force is applied to the Dumbbell when contact is broken at nose cone opening.

An 8-pin Jones receptacle is mounted in the cylinder skin and is wired to the phosphor bronze contacts. A mating Jones plug is used to make external connections to the Dumbbell.

Figure 36 is an assembly drawing of the nose cone mounted on a uni-strut extension used to house auxiliary instrumentation.

3.3 ELECTRICAL SYSTEM

The nose cone's electrical system serves to apply detonation current to the squibs to initiate opening and ejection at a preselected time after launch. The system is entirely contained in the cone section of the nose. Its essential components are a 6-volt battery pack, a mechanical timer, the 4 squibs, and appropriate interconnections. Figure 37 is a wiring diagram of the system; the various components are shown in Figs. 38a and 38b. The battery pack, timer, and two squibs are in one half of the cone and a two-pin plug and receptacle are used to connect the two squibs in the other half to the firing circuit. The mechanical timer, which is started at launch

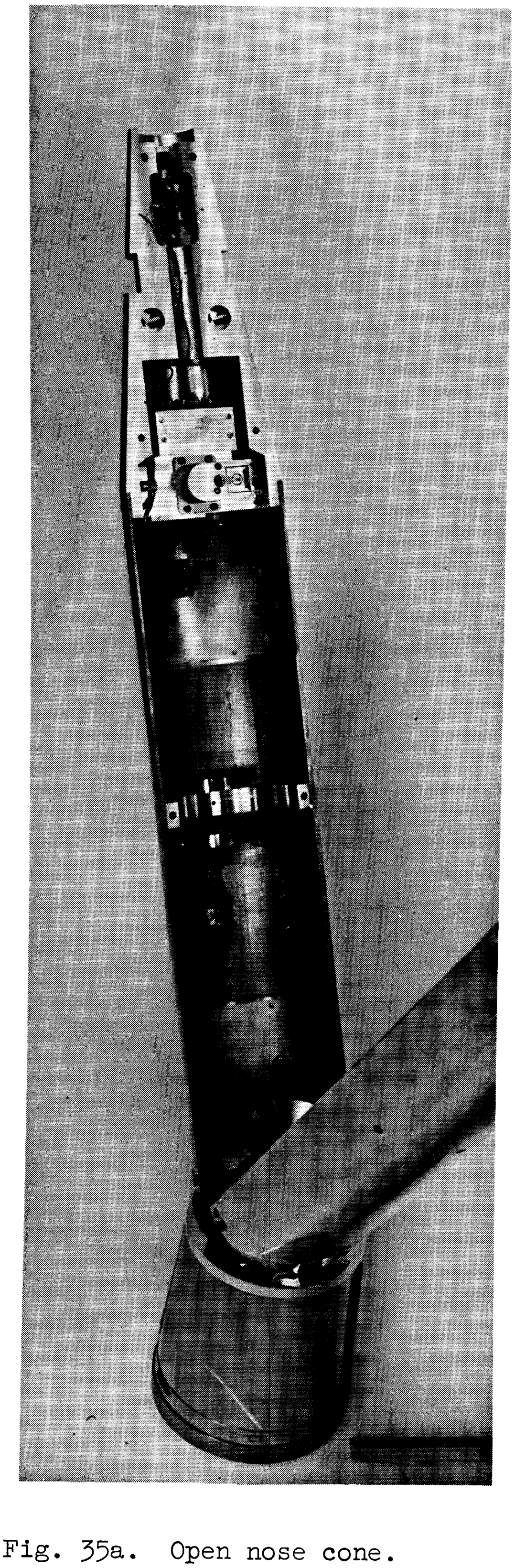


Fig. 35a. Open nose cone.
(View 1)

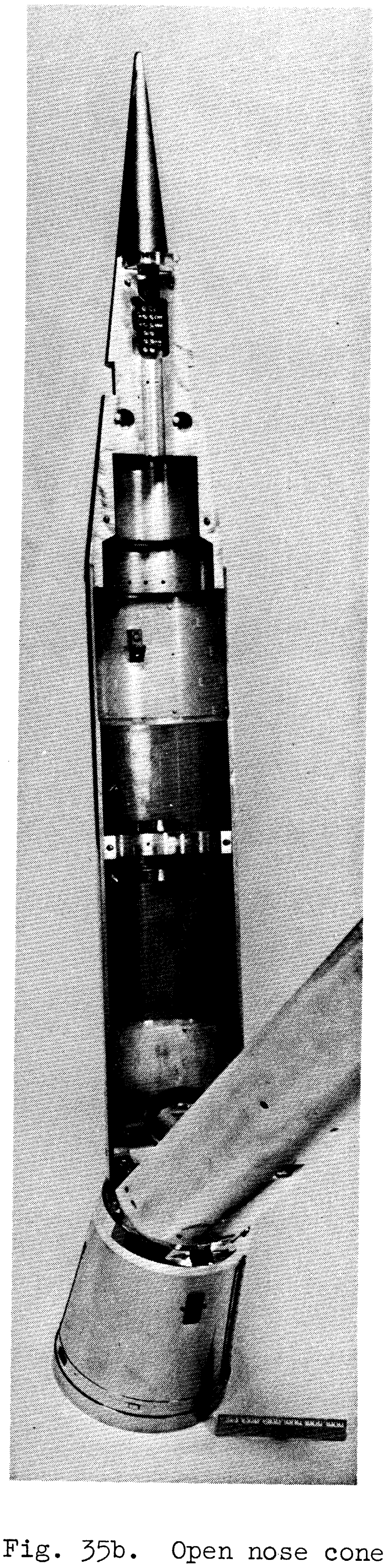


Fig. 35b. Open nose cone.
(View 2)

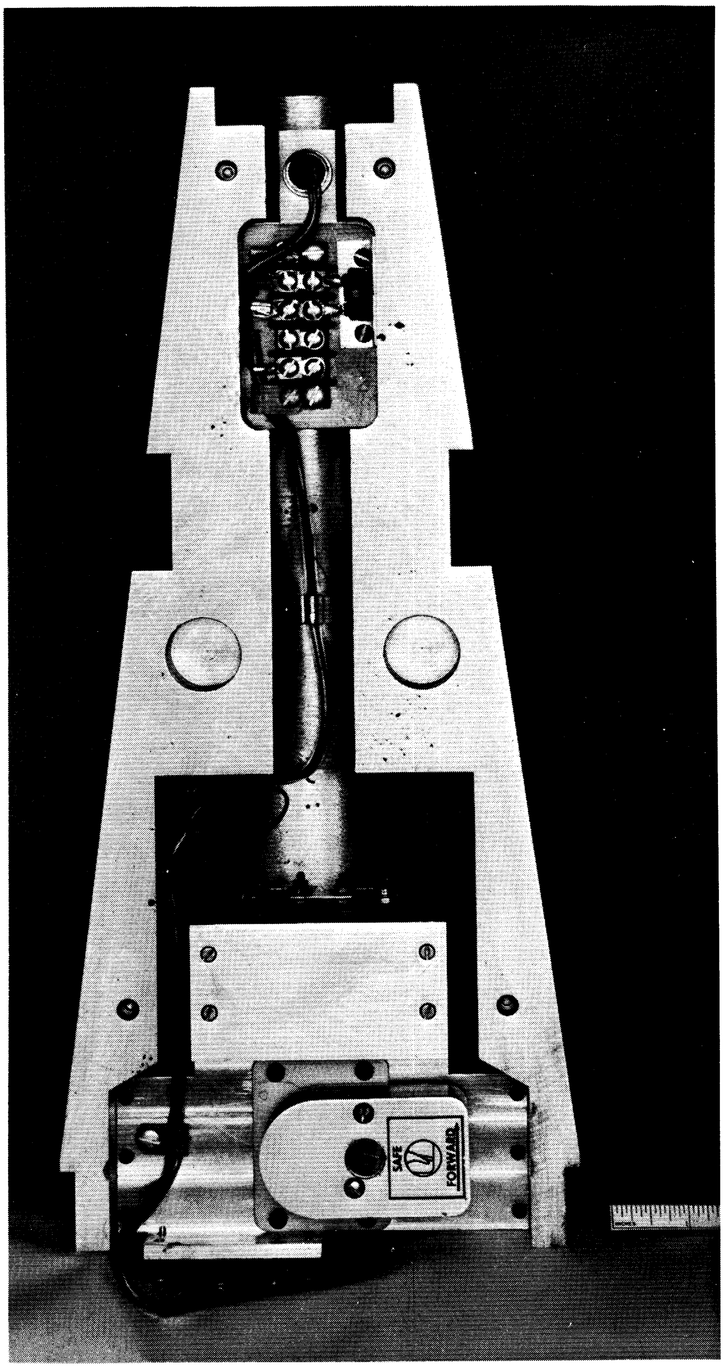


Fig. 38a. Nose cone half—
timer-battery side.

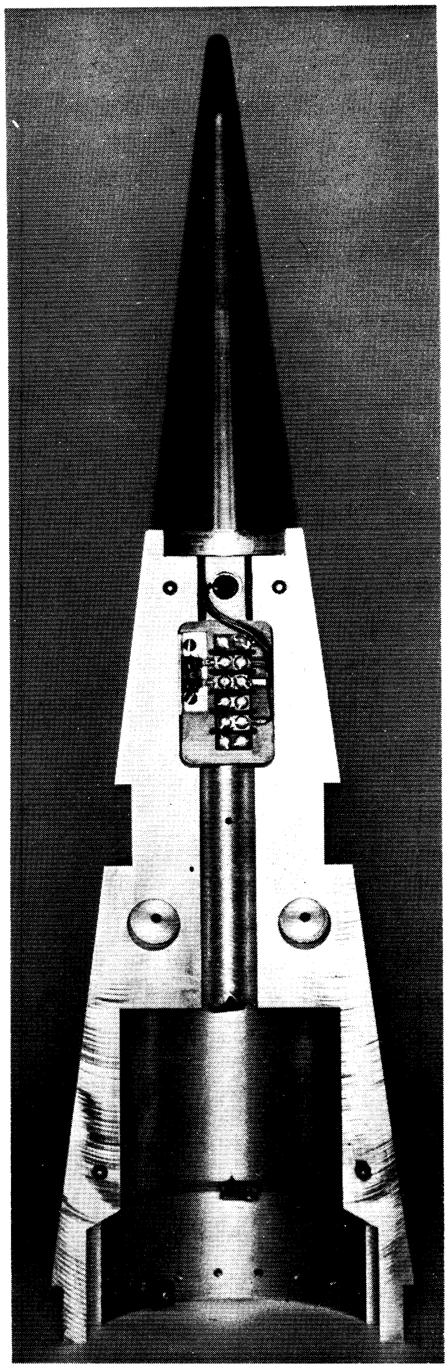


Fig. 38b. Nose cone half—
tip side.

by the acceleration, is preset to close a microswitch at some time (approximately 70 seconds, depending on the rocket vehicle) connecting the batteries to the 4 parallel connected squibs. Both sidesof the firing line are above rocket ground to permit normal operation if either side should become shorted to ground prior to ejection. The squib circuit is, however, returned to ground through a 10,000-ohm resistor to eliminate a possible hazard from a static charge buildup. Several other safety features are incorporated. A "rest" position is provided for one battery lead which disconnects the battery from the circuit until the lead is moved to the normal position prior to launch. The timer maintains a continuous short across the squibs until detonation and two external plugs, one on each cone half, provide an additional short circuit until removed just prior to launch.

3.4 PERFORMANCE

The nose-cone system described has been flown on 11 rockets to date. On 10 of these, successful ejection occurred; on the other one, the rocket broke up shortly after launch and impacted prior to ejection time and no evaluation could be made. On two of the successful operations, the ejection was about 10 seconds early; various data indicated that aerodynamic heating initiated the detonation of the squibs. The thermal insulation around the squibs was increased and subsequent ejections were normal.

Each of the nose cones flown were tested at least once in pre-flight ejection tests, which were also successful. Tests have shown that the explosion of any one of the 4 squibs applies sufficient force to fracture the ring and effect opening, thus providing a good reliability margin. Ideally, with a perfectly balanced Dumbbell, ejection would result in a straight-out motion with no end over end rotation. This is not, however, desirable from the experimental standpoint and, indeed, this does not happen. Typically the Dumbbell has tumbled with a period of between 5 and 15 seconds. The ejection spring force, 60 lb was selected to provide a rocket-Dumbbell separation velocity of approximately 4 fps, which, by the time peak altitude is reached, separates the two by about 1000 feet.

An artist's conception of the Dumbbell ejected from the carrier rocket is shown in Fig. 39 and samples of flight records of the measured volt-ampere characteristics of the ionosphere are shown in Fig. 40.

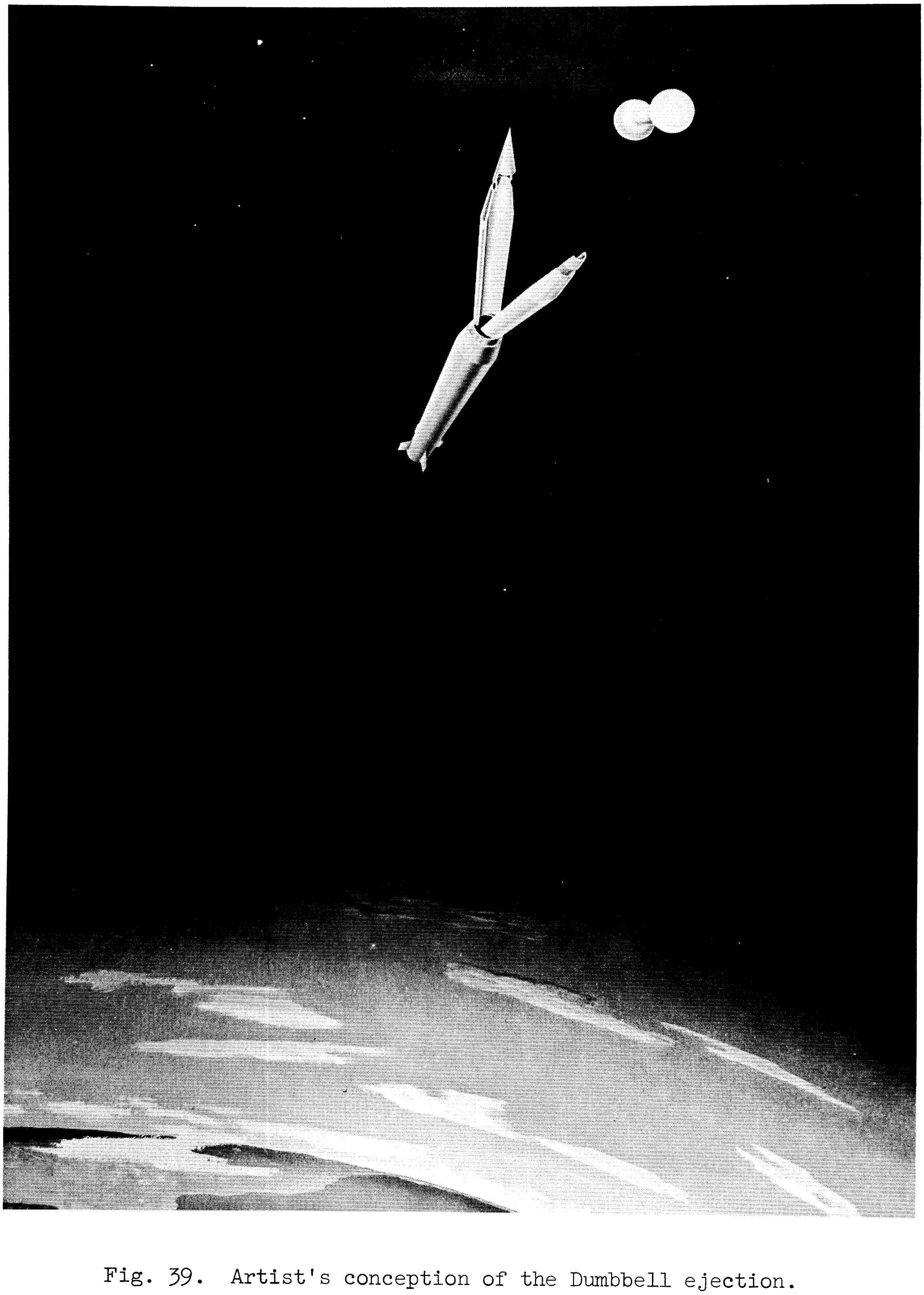


Fig. 39. Artist's conception of the Dumbbell ejection.

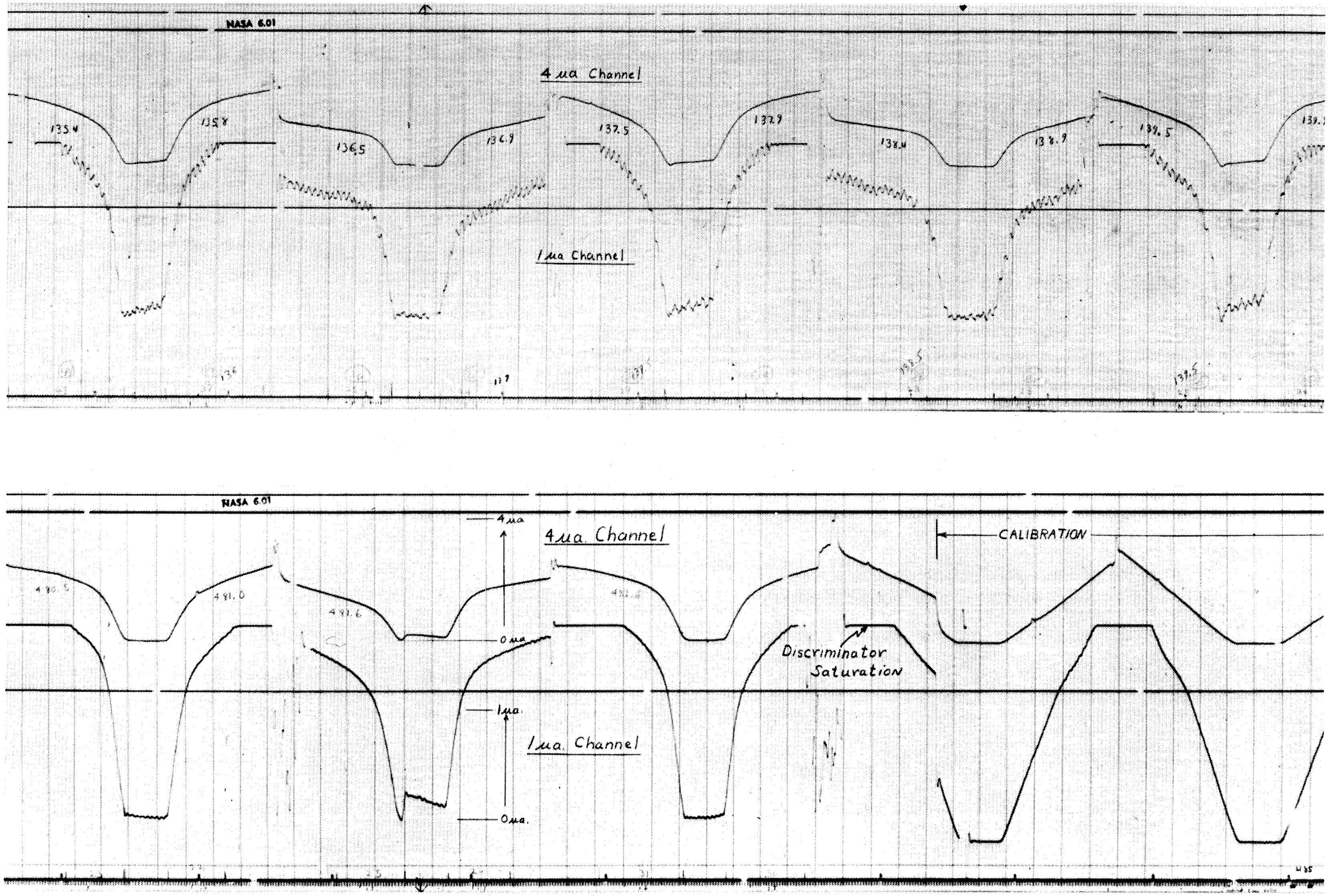


Fig. 40. Typical V-A characteristics recorded in the F1-region of the ionosphere.

4. REFERENCES

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