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INSTRUMENTATION AND CONTROL SYSTEM FOR AN F-15 STALL/SPIN MODEL

By Felix L. Pitts, David C. E. Holmes,
and Klaus P. Zaepfel

December 1974

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16. Abstract

This report describes an instrumentation and control system used for radio-controlled F-15 airplane model stall/spin research at the NASA-Langley Research Center. This stall/spin research technique, using scale model aircraft, provides information on the post-stall and spin-entry characteristics of full-scale aircraft.

The instrumentation described provides measurements of flight parameters such as angle of attack and sideslip, airspeed, control-surface position, and three-axis rotation rates; these data are recorded on an onboard magnetic tape recorder. The proportional radio control system, which utilizes analog potentiometric signals generated from ground-based pilot inputs, and the ground-based system used in the flight operation are described.

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LIST OF SYMBOLS

PPM	Pulse Position Modulation
UHF	Ultra High Frequency
FM	Frequency Modulation
H_L	Left Horizontal Stabilizer
H_R	Right Horizontal Stabilizer
A	Aileron
R	Rudder
K	Denotes X1000
Hz	Hertz
SCO	Sub-carrier Oscillator
%	Percent
^oC	Degrees Centigrade
^{o}	Degree (Angular Measure)
VCO	Voltage-Controlled Oscillator
dc	Direct Current
R	Resistors or Potentiometers
A1, 2, 3	Amplifier
D	Diode
CPT	Control-Position Transducer
V	Volt
mA	Milliampere (Ampere x 10^{-3})
G	Acceleration of Gravity
ips	Inches Per Second
——	Denotes Logic Not
K	Relay
LS	Lanyard Switch
PDM	Pulse Duration Modulation
RF	Radio Frequency
RTL	Resistor Transistor Logic
NOR	Abbreviation for Not OR
IC	Integrated Circuit
CW	Clockwise
CCW	Counter Clockwise
DVM	Digital Volt Meter

ms	Millisecond (second X 10^{-3})
XMTR	Transmitter
MPH	Miles Per Hour
Comp	Digital Comparator
A/D	Analog to Digital Converter
MUX	Multiplexer
Sync.	Synchronization
Ref.	Reference
Reg.	Regulated, Register
μ	Micro denotes $X10^{-6}$
Ω	Ohms
AM	Amplitude Modulation
NC	Normally Closed

LIST OF FIGURES

INSTRUMENTATION AND CONTROL SYSTEM
FOR AN F-15 STALL/SPIN
MODEL

INSTRUMENTATION AND CONTROL SYSTEM FOR AN F-15 STALL/SPIN MODEL

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SUMMARY

This report describes an instrumentation and control system used for radio-controlled F-15 airplane model stall/spin research at the NASA Langley Research Center. This stall/spin research technique, using scale model aircraft, provides information on the post-stall and spin-entry characteristics of full-scale aircraft.

The instrumentation described provides measurements of flight parameters such as angle of attack and sideslip, airspeed, control-surface position, and three-axis rotation rates; these data are recorded on an onboard magnetic tape recorder. The proportional radio control system, which utilizes analog potentiometric signals generated from ground-based pilot inputs, and the ground-based system used in the flight operation are described.

INTRODUCTION

The techniques employed at NASA Langley Research Center for aircraft stall/spin research include testing in the spin-tunnel and wind-tunnels, and outdoor flight tests utilizing radio-controlled drop models. The three techniques are used to provide information on aircraft motions during three stall/spin regimes. The wind-tunnel technique is utilized to study characteristics up to and including stall; the outdoor radio-controlled model technique is used to study post-stall and spin-entry characteristics; and the spin-tunnel technique is used to study developed spin and spin-recovery characteristics.

The radio-controlled model technique, which utilizes the instrumentation and control systems described herein, consists of launching unpowered, scaled aircraft models weighing up to 250 pounds from helicopters, controlling the model's flight from the ground while measuring various flight parameters, and then deploying a parachute prior to impact to terminate the flight. A typical flight profile consists of allowing the model to dive for about 5 seconds, then causing the model to stall by use of the horizontal tails, then moving the lateral/directional controls in a direction to encourage any divergence to develop into a spin. The models are launched from a helicopter at approximately 5,000 feet altitude, and the parachute is deployed via a ground-based command signal when the model is at about 500 feet altitude. A photograph of the F-15 stall/spin model is shown in figure 1. The wing span of this model is approximately 5.5 feet, and the length is approximately 8 feet.

A block diagram of the airborne and ground-based systems is shown in figure 2. The ground-based portion of the proportional control system utilizes voltage-excited potentiometers for the pilot-actuated control inputs so that the control signals can be processed by analog circuitry in an aircraft control system simulator prior to transmission to the model. This provides the capability to simulate the nonlinear cross-coupled control system of the F-15 aircraft. Telemetered measurements of yaw rate are used to modify the control system characteristics to improve the simulation of the control augmentation system in the F-15 aircraft. After processing in the aircraft control system simulator, the control signals are formated into a pulse-position modulation (PPM) format for transmission to the model. This control signal is frequency multiplexed with time correlation and parachute deploy signals and transmitted to the model on a UHF radio-frequency carrier. The control signal is received on the model, discriminated, decoded, and amplified to drive servo motors which position the control surfaces.

The model onboard instrumentation system provides for sensing, conditioning, and onboard recording of various parametric flight data. This information generally consists of angle of attack and sideslip, airspeed, roll, pitch and yaw rates, control-surface positions, and time; these data are wideband FM recorded on an onboard tape recorder using voltage-controlled oscillators. After a test, the onboard recorded data are processed automatically and examined, using "quick-look" displays, for editing purposes and to obtain preliminary test results. Subsequent automated data reduction provides tabular values and plots in engineering units versus time. The following briefly describes the instrumentation and control system design concepts, the system performance, and the data processing technique. Details of the airborne instrumentation and ground support equipments are presented in the appendices.

INSTRUMENTATION SYSTEM

In the F-15 aircraft model stall/spin research program, measurements are made of three-axis rotation rates, angle of attack and sideslip, airspeed, and control-surface position. In addition, one data channel is used for a combined yaw rate exceedance event and a time correlation event, one channel is used for time, and one data channel is used to record a reference frequency for tape speed compensation. The wide-band FM recording technique provides recording system accuracy on the order of one percent of full scale which is commensurate with the research requirements. An automatic calibration correction process is provided which, in conjunction with automated data reduction, can be used to correct for oscillator frequency variation which may occur between the time of laboratory calibration and the flight test.

The block diagram of figure 3 shows the signal flow of the instrumentation system from the sensors to tape recorder. The sensors used are (1) a commercially available rate gyroscope for measuring angular rates, (2) potentiometers for obtaining angular position measurements of control surfaces and flow vanes, and (3) an airspeed sensor which basically consists of a propeller-driven magnetic device whose output is converted to a dc signal.

The nominal 0 to 5 volt data signals are routed to the voltage-controlled oscillators through a calibrate system which automatically interrupts the data channels and introduces 0.0, 2.5, and 5.0 volt calibration signals to the voltage-controlled oscillators and tape recorder for 10 seconds prior to the drop. These calibrate voltages, along with other calibration information, are used subsequently in the automatic data reduction after the flight.

The yaw-rate detector is a double-ended limit detector which senses the exceedance of $\pm 97^{0}$ per second yaw rate and provides an input to a VHF transmitter which transmits the occurrence of this event to the ground. Upon reception, this event is used as an input to the control system simulator to change the operating mode of the control system to simulate the command augmentation system of the full-scale aircraft. The yaw rate bound exceedance event is combined onboard the model with a pilot-actuated event transmitted over the command link. This provides a time correlation between the onboard tape recorded and the ground-based oscillograph data, which provides a record of the test inputs. This multi-level formated analog signal from the analog combiner, along with a 36-bit time-code signal and the various data signals frequency modulate the voltage-controlled oscillators whose outputs are recorded in parallel tracks on the tape recorder.

Table I presents a detailed list of the parameters measured and the maximum allowable error for each. Appendix A gives a detailed description of the instrumentation components.

CONTROL SYSTEM

A detailed description of the airborne control system components is given in Appendix B; the following discussion briefly describes the control system design concept.

The ground-based portion of the control system is shown in the block diagram of figure 4. The pilot inputs are supplied through voltage-excited potentiometers for pitch, roll, and yaw control. The pitch, roll, and yaw signals are applied to the control system simulator which is a special-purpose analog processor which non-linearizes and cross couples the pilot inputs and which provides output signals used to simulate the full-scale aircraft's control system.

The control-surface position output signals from the control system simulator are denoted H_L, H_R, A, and R, corresponding to positions of the left and right horizontal tails, the ailerons, and the rudder, respectively. The control-position signals are encoded into a modified pulse-position modulation format as shown in figure 4, where the information is contained in the time between the pulses. For example, the H_L information is contained in the time between the reference pulse and the H_L pulse, the H_R information is contained in the time between the H_L and the H_R pulse, etc. The nominal pulse width is 200 microseconds and the pulse spacing is a function of control-position information and is 1.5 milliseconds ±0.5 milli-seconds.

Encoding of the control signals is accomplished as follows. Counter A divides the crystal oscillator frequency so that a reference pulse is generated each 20 milliseconds; the reference pulse is routed to the multiplexer through the OR gate and one-shot multi-vibrator and causes the multiplexer to advance and sample H_L. The H_L signal is converted to an eight-bit natural binary digital word in the analog to digital converter, and counter B begins counting with its count continuously compared to the eight-bit digital word in the comparator. When there is agreement between the counter B count and the digitized H_L, an H_L signal is generated by the comparator which causes the H_L pulse to be generated by the one-shot multivibrator. The H_L pulse then causes the multiplexer to advance to H_R, counter B is reset, and the process begins again for generation of the H_R signal, etc. (A detailed description of the encoder can be found in Reference 1). The pulse train thus generated is used to frequency modulate a 40 kHz, $\pm$15 percent subcarrier oscillator (SCO). The 40 kHz subcarrier is mixed with a 7.50 kHz chute deploy tone and a 17.43 kHz time correlation events tone for transmission to the model via the UHF command link.

The airborne portion of the control system is shown in the block diagram of figure 5. The UHF command signal is received and the pulse train shown on the top line of the timing diagram is recovered by the control signal discriminator. Decoding of the control signals is accomplished as follows. The pulse train is applied to a synchronization timer which provides an input to the shift register after occurrence of all of the pulses in one frame as shown by the second line of the timing diagram. The first pulse on the shift line (reference pulse) then drives the H_L output of the shift register high (1 state) as shown on the third line of the timing diagram. The next pulse on the shift line (H_L) drives the H_L output low (0 state) and shifts the (1) to the H_R output. The H_R pulse then shifts the (1) to the A output, etc. In this manner, the pulse lengths of the signals on shift register output lines H_L, H_R, A, and R are proportional to the desired positions of the left and right horizontal tails, ailerons, and rudder, respectively.

Since the servomechanism electronics are similar for all the surfaces, only the one for the left horizontal tail is shown in figure 5. The H_L signal, which is used to control the surface motion, is a pulse train with a frame rate of nominally 20 milliseconds and a pulse width of from 1 to 2 milliseconds which is dependent on the desired control position. The actual position of the drive motor gear shaft is sensed by a variable resistor which determines the duty cycle or "on" time of a multivibrator which is triggered by the H_L pulse. The duration of the H_L and the one-shot multivibrator pulses are compared and a clockwise or counter-clockwise drive pulse is generated depending upon whether the H_L pulse is longer or shorter than the one-shot pulse. The drive pulse is then stretched and used to drive a power amplifier which drives the motor.

SYSTEM PERFORMANCE

The overall accuracy of the instrumentation system over a range of environmental conditions is on the order of 2 percent of full scale. Laboratory performance data for a typical channel of the data system are shown in Table II. This table for the angle-of-attack sensor shows data which were processed from angular input at the sensor to tabular output from the computerized data reduction. This table shows a maximum error of 0.8 degrees out of a total range of 200 degrees.

Figure 6 shows an overall static transfer function of a typical control surface which was obtained on an X-Y plotter; the abcissa is the pitch control voltage from the pitch-control potentiometer, and the ordinate is the voltage corresponding to the position of the horizontal tail as obtained from the potentiometer used to measure the tail position. This plot shows hysteresis on the order of one degree and the linearity-hysteresis combination yields an error of about 1.25 percent. Figure 7 shows the slewing response to a square wave input of a typical channel of the control system. The input on the top trace is an electronic simulation of the control-stick potentiometer output and the signal shown on the bottom trace was obtained from a potentiometer attached to the servo shaft. The lower trace indicates a slew rate of approximately 125 degrees per second.

A typical servomechanism electronics temperature performance curve is shown in figure 8. Total variation is less than 0.7 percent of full-scale over the temperature range of operation, -20° C to $+50^{\circ}$ C. This corresponds to an angular servo error of $1/2^{\circ}$. The uncompensated curve is shown for reference and illustrates the nearly linear drift characteristic of the amplifier which permits accurate compensation with a single positive temperature coefficient thermistor.

A summary of control system performance characteristics is shown in Table III. It should be noted that the performance is a direct function of testing, compensation, and attention to mechanical detail. Performance limits at present are primarily a function of the feedback potentiometer and gear train mechanical backlash. The numbers listed are measured at the output shaft of the servo. The actual deviations at the control surface will be less depending on the mechanical step-down ratio in the linkage system which varies between 2.25:1 for the ailerons and 1.1:1 for the rudder.

SYSTEM CALIBRATION AND DATA PROCESSING

The instrumentation system calibration for each channel is obtained by one of the two following methods and may consist of as many as 25 points per channel.

1. A known input is applied to the sensor and the VCO frequency is recorded.

2. A voltage point obtained from the sensor calibration and representing an input is applied to the VCO, and the output frequency is recorded. This method is used whenever it is impractical to apply the sensor calibration stimulus to the sensor while it is connected to the data system.

During calibration, three reference voltage steps are applied by the calibration system to the VCO inputs. The respective outputs, corresponding closely to the center frequency and to the bandedges, are included in the calibrations to be used for post-flight data processing. These three reference voltages are also applied to the VCOs immediately before the flight test by an automatic calibration sequencer, thereby allowing compensation for VCO drift between the time of laboratory calibration and the time the data are taken during a flight.

A flow chart of the data processing procedure is shown in figure 9. After the model is recovered from the field following a test flight, the onboard tape recorder is returned to the data processing station shown in figure 10; since the tape recorder is not designed for tape removal, the information on the tape is transcribed and this copy is used in further data processing steps. "Quick-look" oscillograph recordings to assure instrumentation integrity are obtained by discriminating the frequency-modulated data.

The tape copy is then sent to the computer center for analog to digital conversion and computer processing. The computer program includes the calibration information of the data channels and the scale factors for the model. The computer generates both model scale and full-scale tabulations and plots of the data versus time corrected for sensor nonlinearity and VCO drift.

CONCLUDING REMARKS

An instrumentation and control system for stall/spin tests of a scale model F-15 aircraft has been developed and successfully utilized in 41 flight tests. The performance characteristics of the developed instrumentation and control system are satisfactory for stall/spin tests of scale model aircraft. The overall accuracy of the instrumentation system is on the order of 2 percent of full scale over the environment; demonstrated performance in the laboratory indicated a maximum error of 0.4 percent of full scale for a typical channel. The accuracy of the control electronics is about 0.7 percent of full scale over the temperature range; surface positioning accuracy obtained in the laboratory, including linearity, hysteresis, etc., is on the order of 1.25 percent. The flight performance of the data and control systems has been excellent with no significant data losses or control system malfunctions in 41 flight tests.

REFERENCE

1. Meissner, Charles W., Jr.: A Roll-Pitch Interaction Simulator and a Control Position Command Encoder for Remote Piloting of Spin-Entry Research Models. NASA TN D-7361, November 1973.

APPENDIX A

INSTRUMENTATION SYSTEM COMPONENTS

The airborne instrumentation system can be functionally grouped according to the following systems:

1. Sensors and signal conditioning
2. Timing
3. Data recording
4. Calibration
5. Power distribution

The assemblies that make up these systems are shown in figure A1.

Sensors and Signal Conditioning

The airflow sensor measures three parameters: angle of attack, angle of sideslip, and airspeed. Both angles are defined to be measured with respect to the longitudinal axis of the model. The airflow sensor is free to rotate 360 degrees in pitch, and ±60 degrees in yaw. The airflow sensor consists of an aerovane which is attached to a sting by a shaft allowed to continuously rotate in pitch. The sensor is mounted about 20 inches in front of the model on a hollow removable boom that houses wires connecting the sensor to the data system as shown in figure A2.

The angles of attack and sideslip are measured by using film-type potentiometers located inside the sensor housings. The potentiometers are excited by a 5-volt dc regulated supply and have the following characteristics: ±1 percent nonlinearity, 0.2 percent hysteresis, and 0.2 percent noise. The output signals pass through the slip rings in the sensor housing and wires in the boom to the calibration and data recording systems as shown in figure A3.

The airspeed is measured by a propeller-driven alternating current generator mounted in the nose of the aerovane. The frequency output of the generator is proportional to propeller spin rate. The output frequency is converted to an airspeed-variable voltage by the temperature-compensated signal conditioning system, shown in figure A3, whose output is introduced through the calibration system to the data recording system.

The angular rates are measured with a commercially available three-axis rate gyroscope whose rate-proportional output for each axis varies from 0 to + 5 V dc. The rate gyro power is derived from the unregulated 28-volt dc supply. The gyroscope is mounted in the model in such a way that it measures the three orthogonal rotational rates of the model. The outputs are directly routed through the calibration system to the data recording system; however, the yaw rate output is also used as an input to the control augmentation system.

The switching points for the control augmentation system are at the yaw rates of $\pm 97^{\circ}$/second. The yaw rate is derived from the yaw-axis output of the rate gyro and fed to the yaw rate boundary detector in the model. This detector circuit functions to give a high output for yaw rates greater than $|97^{\circ}/\mathrm{sec}|$, and a low output for yaw rates less than $|97^{\circ}/\mathrm{sec}|$, as shown in figure A4. Figure A5 is the schematic diagram of the yaw rate bound detector. The potentiometers, R1 and R2, set the threshold levels corresponding to the yaw rate thresholds. If the input fed directly to amplifier A1 is greater than the upper threshold, i.e., the voltage corresponding to $+97^{\circ}$/second, the output goes high. For this condition, the inversion and offset produced by the circuit of A3 causes the output of A2 to be blocked by D2. If the input voltage becomes less than the lower threshold, i.e., the voltage corresponding to -97°/second, the inversion and offset voltage produced by A3 results in a voltage at the input of A2 that is greater than the lower threshold set by R2, and the output goes high. The output of A1 is now low, but it is blocked by D1. Two outputs are available from the yaw rate bound detector; a high-level output which is connected to the data recording system, and a low-level output which is connected to the onboard transmitter.

The position of each control surface is measured by a control-position transducer (CPT) that is linked mechanically to the surface. A direct CPT linkage is used on four of the five control surfaces as shown in figure A6a and A6b; on the other, the CPT is linked to the servo output shaft as shown in figure A6c. Each transducer is a precision rotary potentiometer 0.5-inch in diameter with a plastic film resistance element that provides approximately 330° of electrical rotation. However, the maximum deflection encountered on the surface is only 60°, and the inputs to the recording system must be within 0 V to +5 V. In order to maximize sensitivity, yet allow some degree of rotational misalinement, a +18-volt regulated voltage is applied across the fixed terminals of the CPTs. Consequently, the full-scale output voltage ranges are approximately 4 V for the full-scale deflections of the surfaces.

Timing

Two of the 14 tracks on the flight recorder are used for time correlation of events. One track records the onboard time, the other track records a four-level combination of two on/off events: ground-record time correlation and yaw-bound exceedance. The onboard timer is the time reference for all recorded data; it generates a 36-bit time code that is recorded simultaneously with the data. The timer and the tape recorder are started several seconds before release of the model from the helicopter and run continuously until power is shut off during parachute deployment. The output of the timer is a 1 kHz carrier which is amplitude-modulated by the internally-generated, 36-bit time code which increments in 1-second intervals and marks 0.1-second intervals. It counts from 000 to 999 and resets itself whenever power is interrupted. The 1 kHz carrier can be used for 1-millisecond resolution. The normalized frequency stability of the crystal-stabilized clock is 1.5 x 10^{-6} per degree Centigrade. A block diagram of the timer is shown in figure A7. The unit will operate from about +10 V dc to +35 V dc. At +28 V dc, the running current is 50 mA; starting current is 200 mA. Its dimensions are 3.5 inches long x 2.4 inches wide x 1.6 inches high, and it weighs 206 grams. Figure A8 is a photograph of the timer.

Data Recording

The data recording is accomplished by using an onboard tape recorder and voltage-controlled oscillator (VCO) assembly. Each of the frequency modulated VCO output signals is recorded on a separate track of the flight tape recorder. Two channels of the recorder are used for the timer and the tape-speed compensation reference. Figure A9 is a photo of the tape recorder, timer, and VCO assembly.

The tape recorder is 4 inches in diameter by 4 inches high, and weighs 2.8 pounds. The tape recorder power requirement is approximately 8 watts. Tape flutter is less than 2 percent under bench conditions and less than 5 percent during ±10 G peak vibration. Recording and playback are achieved by using a single 14-track in-line head. The tape speed is 15 ips providing 90 seconds of recording time on 1-inch wide instrumentation tape. The recorder contains end-of-tape sensors that stop the tape and also provide end-of-tape or beginning-of-tape indications.

A separate voltage-controlled oscillator drives each of the 14 tracks of the tape recorder head with a 20 mA peak-to-peak square wave. The oscillator input ranges are either 0 to 5 V dc or ±2.5 V dc; the oscillator input impedance is greater than 1 Megohm. The VCO linearity is such that deviation from the best straight line is less than ±1 percent of design bandwidth. The power requirement of the VCO assembly is 11.7 watts.

Calibration and Automatic Sequencing System

The calibration system permits multi-point data system calibrations taken under laboratory conditions to be corrected in the data reduction process for VCO drift. The calibration system simultaneously switches the 12 data channel VCO inputs from sensor outputs to the output of a circuit that produces any of three stable reference voltages.

The output frequencies corresponding to 0 V, 2.5 V, and 5.0 V inputs to the VCOs are recorded during the laboratory multi-point calibration for each data channel and are also recorded on the tape recorder just prior to the test flight. The difference between the VCO frequencies measured in the laboratory and those obtained immediately before the test flight are applied as corrections to the multi-point calibration during the data reduction process.

Figure A10 is a simplified diagram of the calibration system. Miniature relays are used to provide the switching functions. When the calibration bus command is applied, relay K1 switches the VCO input from the sensor outputs to the calibration circuit. In the absence of any other command, 0 V is applied to the VCOs due to the states of K2 and K3. The calibration bus has to remain on while the other two calibration steps are applied: the 2.5 V step by K2, and the 5.0 V step by K3.

The automatic calibration and launch sequencer used in the helicopter and shown in the photograph of figure A11 initiates each flight test by automatically giving successive commands that start the tape recorder and timer, apply the three reference calibration steps, and launch the model. Figure A12 shows a sample of the calibration portion of a flight record for several channels. The calibration sequencer also serves as a switching and monitoring panel for certain non-automatic functions within the model. Prior to launch, it is electrically connected to the model by two umbilical cables and receives power from batteries in the model and in the helicopter. During the launch operation, the automatic sequencer is hand-held aboard the helicopter by the person who performs the manual functions and initiates the automatic functions of the launch sequence. A series of lights are used to monitor these functions; the lights for the automatic sequence also serve as a countdown. As shown in figure A13, the automatic sequence is generated by digital logic that is clocked by the unijunction transistor circuit which pulses at approximately 1 Hz. When the "calibrate" pushbutton on the box remains depressed, the commands, as indicated in Table A1 by 1s are applied at one-half the clock-pulse rate. Although step eight turns off all commands, during flight operations power is supplied to the recorder and timer through a Lanyard-operated switch. This switch is activated just prior to umbilical separation. However, if the pushbutton is released at any time, either during the automatic sequence or thereafter, the sequencer resets itself and inhibits the clock.

The automatic sequencer also serves as a control panel for (1) manually switching the data system power between the external battery pack in the helicopter and the internal pack in the model, (2) for turning the servo power on and off, and (3) for turning the onboard transmitter on and off. Panel lights monitor these switching functions.

Power Distribution

An unregulated +28 V supply, a regulated +18 V (nominal) supply, and a regulated +5 V (nominal) supply are available for the data system. The 28 V dc supply, from which all onboard instrumentation derives its power, may be obtained from either the internal batteries during flight or, in order to conserve battery life, from an external source during pre-flight preparations. The battery packs are made of 24 nickel-cadmium D-size cells having a 4-ampere-hour capacity. The 18-volt dc regulated supply, shown on the schematic diagram of figure A14(a), is used for excitation of the control-position transducers. It operates over a voltage range of 24 V to 32V and over a temperature range of 0^{o}F to 125^{o}F with less than 40 mV drift. The 5-volt dc regulated supply, shown in figure A14(b), excites the potentiometers in the airflow sensor, applies voltage to the voltage divider network that produces the three stable reference levels in the calibration system, and provides the trip-level reference voltage in the yaw-bound exceedance system. The voltage regulation is such that over the ranges of 24 V to 32 V and 0^{o} F to 125^{o} F the regulator drift is less than 50 mV.

The power distribution system, shown in the schematic diagram of figure A15, contains circuitry that receives power from the 28 V dc supply and distributes it to the other components in the data system. Remote switching of the 28 V bus between internal and external sources is accomplished by the latching relay K2 which energizes non-latching power relay K1. The internal source is disconnected at the end of a flight by LS1 when a Lanyard pin is pulled by the ejecting parachute. If in the laboratory an external supply is connected to the model, the pulling of the Lanyard pin will merely cause K1 to drop to the external source. A diode D1 in series with the 28 V bus is used for reverse-bias protection. Pulling the tape recorder Lanyard pin closes switch LS2, which causes the non-latching relay K3 to be energized and to supply power to both the tape recorder and to the timer. This action assures that the tape recorder and the timer will continue to run during the flight after the model has dropped away from the umbilicals.

APPENDIX B

CONTROL SYSTEM COMPONENTS

The airborne control system can be functionally grouped according to the following systems:

1. Receiver
2. Control signal discriminator
3. Decoder
4. Servo amplifier
5. Power distribution
6. Servo motor assemblies

Receiver

The UHF command receiver is a commercially available 10-channel FM receiver with a sensitivity of 1 microvolt; two channels are required for this aircraft. The modulation acceptance is 60 kHz deviation per channel with a maximum of five simultaneous channels. The outputs from the command channels are in the form of relay closures. Additionally, the 40 kHz subcarrier containing the control signal is taken from the receiver discriminator for processing in the control system.

Control Signal Discriminator

The control signal discriminator is a commercially available 40 kHz ±15 percent proportional bandwidth airborne unit designed to operate from a 28 V dc supply. The discriminator recovers the pulse position modulation (PPM) control signal from the 40 kHz subcarrier oscillator. A linear phase filter is used on the output to prevent ringing of the pulse train.

Decoder

The PPM pulse train from the discriminator is input to a one-shot multivibrator for signal regeneration as shown on the schematic diagram of figure B1. The output of the one-shot is a pulse train with suitable rise times for driving the remaining logic. This output is applied to both a sync timer and the shift line of two shift registers. The sync timer is a retriggerable multivibrator which places a high (1 state) at the input to the shift register when the first pulse (reference pulse) is received and a low (0 state) for all subsequent pulses until a minimum of three missing pulses have been detected. This allows the sync timer to reset to the 1 state for the next frame. The shift line receives every pulse in the incoming frame and shifts the 1 state bit placed in the input throughout the shift register. This in turn drives each output to a 1 state for a period equal to the time between pulses in the input pulse train. Each PDM output is individually buffered and input to the servo amplifiers. Provision is made for up to eight channels of proportional data. Four channels are used on the F-15 aircraft.

An auxiliary or test input, used for system checkout, allows a PPM pulse train to be coupled directly to the decoder input without using the RF link.

Servomechanism Electronics

The servomechanism shown in figure B2 is composed of five major subassemblies each of which is briefly described in the following paragraphs.

The comparator consists of two RTL NOR gates I_{c1} and I_{c3}. The PDM input signal is applied directly to one input of the clockwise NOR gate and inverted for application to one input of the counter-clockwise NOR gate. These data are compared with the pulse duration from the reference generator and a clockwise or counter-clockwise error pulse is generated.

The reference generator is a temperature-compensated, voltage-variable, one-shot multivibrator composed of two cross-coupled NOR gates. Position feedback is accomplished by use of a shaft-mounted potentiometer. Sensitivity and zero adjustments (potentiometers R_2 and R_3) are provided to allow a variation of ±20 percent about the nominal ±45^{o} of servo rotation. The reference generators are individually temperature-compensated by a positive temperature coefficient thermistor (R_4) in the timing circuit.

A portion of the motor drive signal is fed back to the reference generator through resistor R9 to advance the generator in the direction of rotation of the output shaft to provide damping. In order to insure adequate stability of the reference generator supply voltage, a series voltage regulator is used.

The error pulses from the comparator are relatively narrow and do not contain sufficient energy for driving the motors, therefore, the pulse is stretched by use of an expander gate and an RC timing circuit

(R_5, C_3, and R_6, C_4). The time constant of the RC network is adjusted so the minimum resolvable error pulse is expanded over 50 percent of the 20 millisecond frame.

The buffer driver section performs a dual role of isolating the logic circuits from the output power amplifier circuitry and of preventing a random trigger pulse from driving both output stages simultaneously. When the clockwise drive circuit is activated a logic one level from the clockwise buffer section is applied to the counter-clockwise (CCW) buffer thus inhibiting its output via the action of the CCW NOR gate IC_8. The output complementary circuits are thus prevented from simultaneously conducting.

Amplification of the logic level currents to the level required by the servo motors is achieved in a complementary Darlington connected power amplifier stage. Resistors R_7 and R_8 provide surge current limiting and high frequency noise damping.

Power Distribution

Unregulated, +28 V, +12 V, -12 V supplies and a regulated +4.8 V supply are provided for the control system. The internal 28 V supply provided for the data system is used to power the command receiver and discriminator. The +12 V and -12 V dc supplies are internal battery packs within the model. Each battery pack consists of 10 nickel-cadmium D-size cells of 4 ampere/hour capacity. The +4.8 V regulated power is obtained from the +12 V battery by an integrated circuit voltage regulator shown in figure B3. All control system logic functions are powered from this source.

Servo Motor Assemblies

The servo motor assemblies are shown in figure B4 and a schematic diagram is shown in figure B5. The servo amplifier electronics will drive a wide variety of dc motors, thereby allowing the selection of the motor to meet the torque requirements. The larger motor assembly has a maximum output torque of 5.4 ft lbs (at 3.5 amps) and one is used on each of the horizontal tails of the F-15 model. The smaller motor assembly has a maximum output torque of 2.0 ft lbs (at 1.5 amps) and is used to drive the rudder and aileron surfaces. The particular motors used are dc permanent magnet gear motors with speed reduction gears of 524.6 and 485 for the large and small airborne equipment.

Limit switches are provided to prevent stalling the servo mechanisms at the mechanical limits of travel due to over driving or system failure. Dynamic braking of the servo assembly (via the motor back emf) is accomplished by allowing the transistor driving the motor to short the motor when the limit has been reached. Feedback to the reference generator is obtained from a potentiometer mounted directly on the shaft of the servo. Zero adjustment of the mechanism is accomplished by rotation of the wiper assembly.

The control system is packaged in machined cases of anodized aluminum with RF gaskets and bolt-on covers. The servo amplifiers are packaged in pairs and the decoder is packaged separately. All components are mounted on printed circuit cards, as shown in figure B6, which slide into machined grooves, thereby giving good mechanical strength and rigidity while allowing ease of maintenance. Figure B7 shows typical control system components.

APPENDIX C

GROUND CHECKOUT AND CALIBRATION SYSTEM

The checkout monitor and control unit shown in figure C1 is used to command, monitor, and measure with laboratory equipment all the essential functions of the model instrumentation system and to energize the control system. Also, the functions located on the automatic sequencer are included. The reference calibration steps can be sequenced from the checkout system, either automatically as in the automatic sequencer, or manually. The checkout system is used for calibration and verifying proper system operation as follows:

Voltage-Controlled Oscillator Calibration

The Voltage-Controlled Oscillator (VCO) inputs and outputs are brought from a monitoring connector in the model to the checkout system where they can be switched on a channel-by-channel basis to a digital voltmeter (DVM), an oscilloscope, and a frequency counter. A calibration point is obtained for a selected channel by switching to that channel, placing a known sensor input into that channel, and simultaneously reading VCO input voltage on the DVM and VCO output frequency on the counter; either input or output may be selected for viewing on the oscilloscope by another selector switch. Each of the three reference calibration steps can be manually commanded for each channel and read out on the meters.

By using the calibration fixture shown in the photograph of figure C2, any angle within the range of the angle of attack and angle of sideslip sensor can be precisely set in 1-degree increments. To take readings, one of the two machined and accurately engraved protractors is clamped to and alined with the boom. The aerovane is set to a known angle by setting a pointer attached to the aerovane into an engraved line on the protractor.

Calibrations for the control surfaces are performed in essentially the same manner as those for the airflow angles. The instruments shown in figure C3 are protractors, each designed specifically for the surface it is to measure and engraved to allow a reading precision of 0.1°. In addition, these protractors are used for adjustment and calibration of the control system.

Switching Functions

The 28-Volt Supply Bus can be switched between internal and external supplies and monitored with a DVM. The tape recorder and timer can be energized and the recorder operated in the forward or reverse mode. The beginning-of-tape and end-of-tape sensors are monitored by indicator lamps.

TABLE I

Measurements List

Airborne Recorded Measurement	Range	Maximum Allowable Error
Angle-of-Attack	$\pm 100^{0}$	$\pm 3^{0}$
Angle-of-Sideslip	$\pm 55^{0}$	$\pm 2.2^{0}$
Velocity (Airspeed)	30 to 195 mph	±8.2 mph
Roll Rate	$\pm 360^{0}$/sec.	$\pm 14.4^{0}$/sec.
Pitch Rate	$\pm 180^{0}$/sec.	$\pm 7.2^{0}$/sec.
Yaw Rate	$\pm 600^{0}$/sec.	$\pm 24^{0}$/sec.
Rudder Position	$\pm 30^{0}$	$\pm 1.4^{0}$
Left Stabilator	-28^{0} to $+15^{0}$	$\pm 1.4^{0}$
Right Stabilator	-28^{0} to $+15^{0}$	$\pm 1.4^{0}$
Left Aileron	$\pm 20^{0}$	$\pm 1.0^{0}$
Right Aileron	$\pm 20^{0}$	$\pm 1.0^{0}$
Yaw Rate Exceedance Event	ON/OFF	
Time Correlation Event	ON/OFF	
Time		1 ms

TABLE I (CONT'D)

Ground Recorded Measurement	Range	Maximum Allowable Error
Pitch Stick Position	-12 to +20^o	±1.6^o
Roll Stick Position	±20^o	±2^o
Yaw Pedal Position	±20^o	±2^o
Left Stabilator Control Signal	-6 V to +10 V	±0.8 V
Right Stabilator Control Signal	-6 V to +10 V	±0.8 V
Aileron Control Signal	±10 V	±1 V
Rudder Control Signal	±10 V	±1 V
Air-Ground Time Correlation Event	ON/OFF	
Main Parachute Command	ON/OFF	
Time		1 sec.

TABLE A1

Automatic Calibration Sequence

Step No.	T/R & Timer ON	Cal. Bus ON	2.5V ON	5.0V ON	Light L5 ON	Drop
1	1	0	0	0	0	0
2	1	0	0	0	0	0
3	1	1	0	0	0	0
4	1	1	1	0	0	0
5	1	1	0	1	0	0
6	1	0	0	0	1	0
7	1	0	0	0	0	1
8	0	0	0	0	0	0

TABLE II

Data System Laboratory Static Performance: Angle of Attack Data

IN	OUT	ERROR	
		Absolute	Percent of Full Scale
-100.0^{o}	-99.5^{o}	$+.5^{o}$	.25%
-80.0	-79.6	+.4	.20
-60.0	-59.8	+.2	.10
-40.0	-39.9	+.1	.05
-20.0	-19.7	+.3	.15
-10.0	-9.6	+.4	.20
0.0	+0.3	+.3	.15
+50.0	+50.3	+.3	.15
+100.0	+100.8	+.8	.40

TABLE III

CONTROL SYSTEM PERFORMANCE CHARACTERISTICS

Range (servo shaft rotation)	$\pm 30^{\circ}$ to $\pm 60^{\circ}$ (adjustable)
	$\pm 45^{\circ}$ nominal
Temperature stability	0.7% of full scale
Slew rate (No Load)	125°/sec
Error due to nonlinearity and hysteresis	1.25% of full scale
Output maximum torque (Large Servo)	5.4 ft lbs
Output maximum torque (Small Servo)	2.0 ft lbs

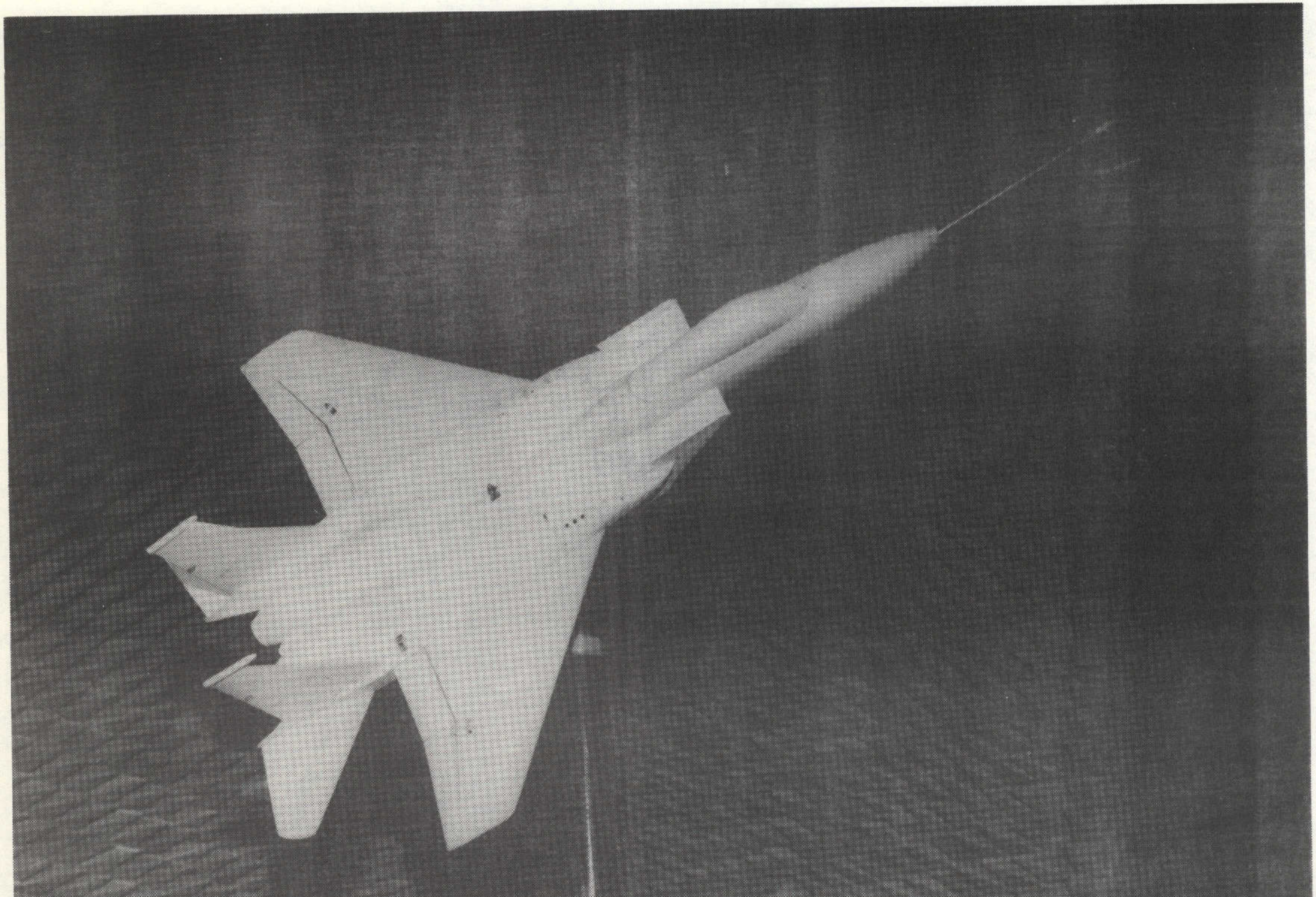

Figure 1. - Thirteen percent scale F-15 aircraft model

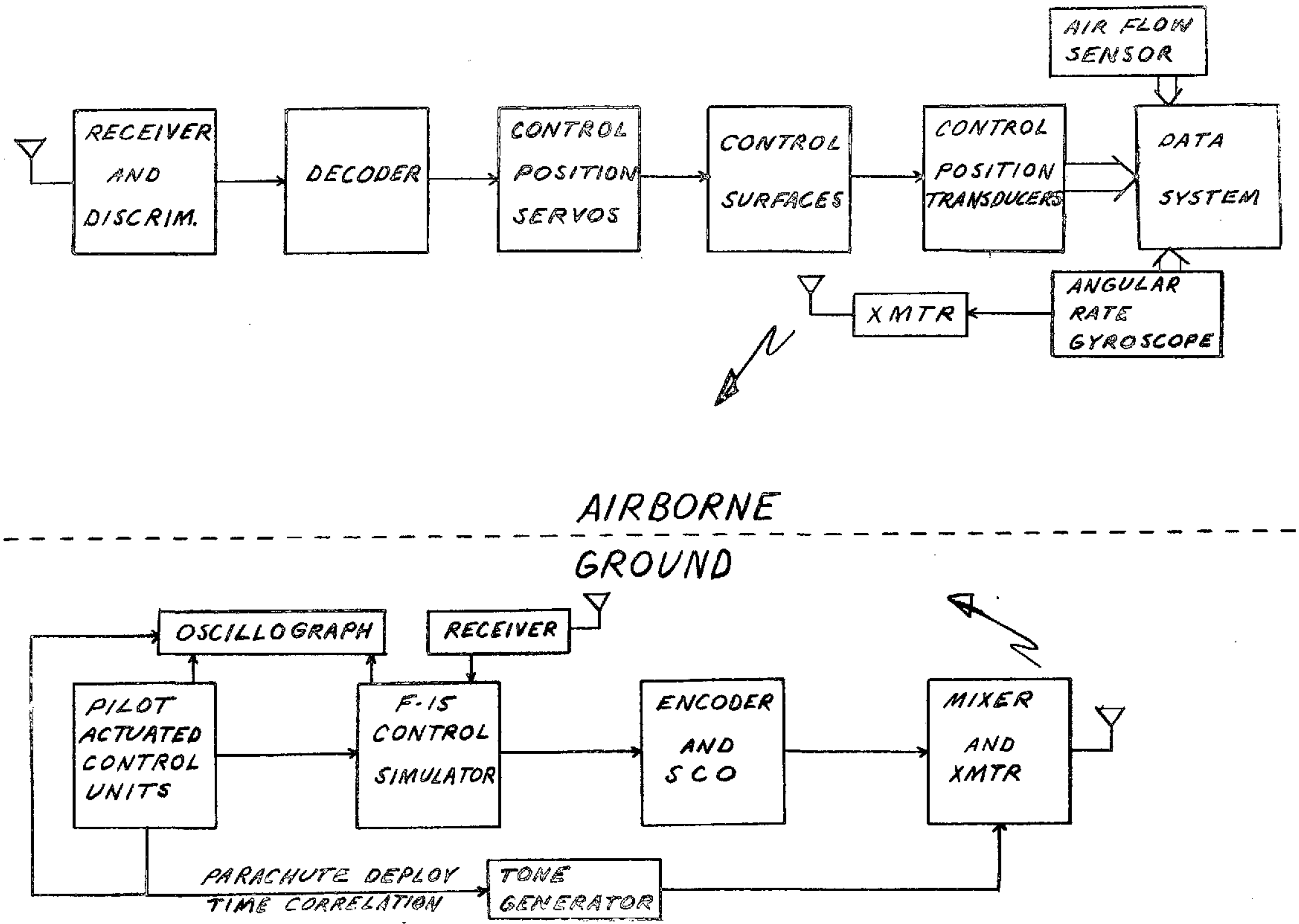

Figure 2. - System block diagram

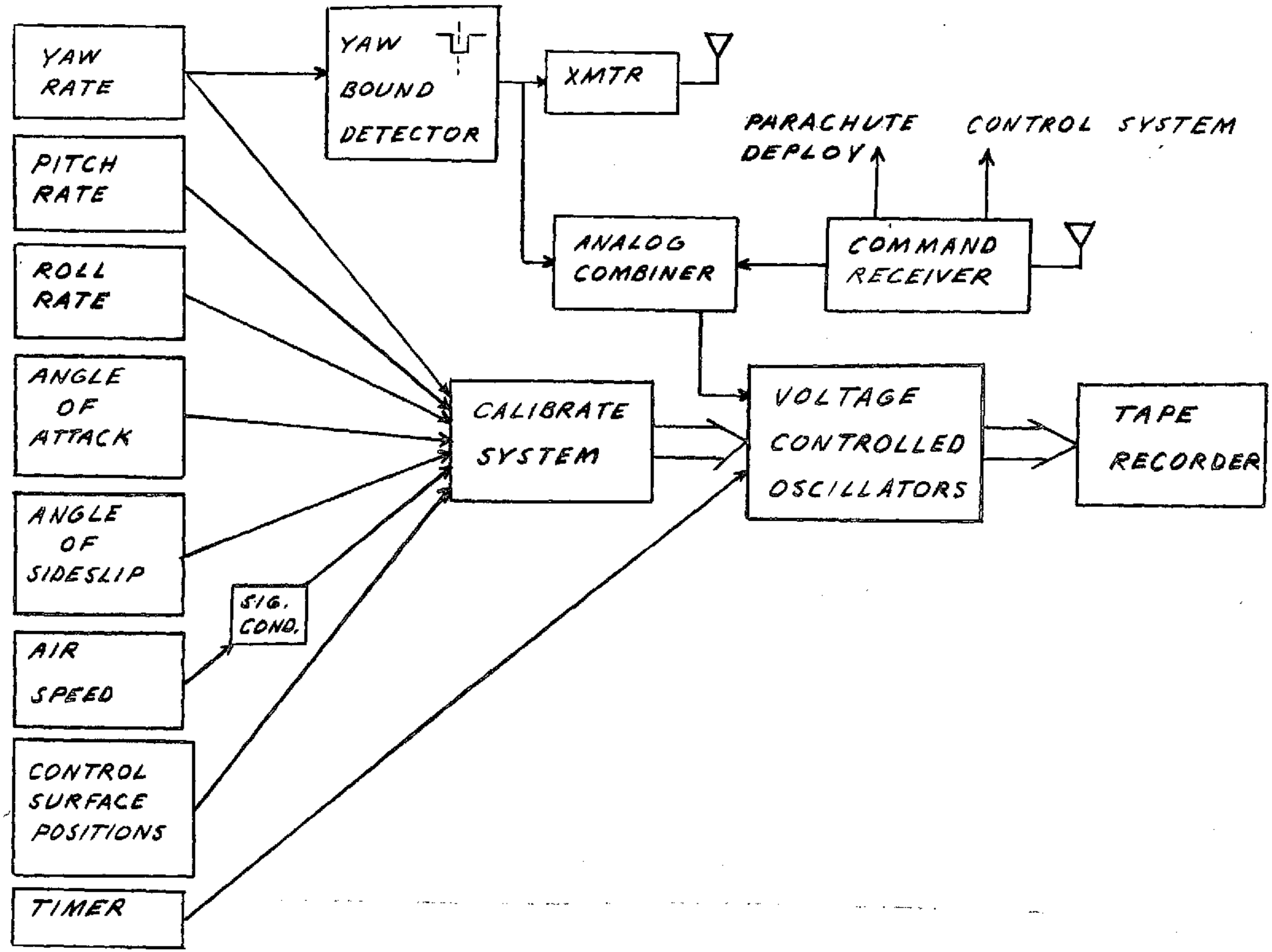

Figure 3. - Airborne Instrumentation System Block Diagram

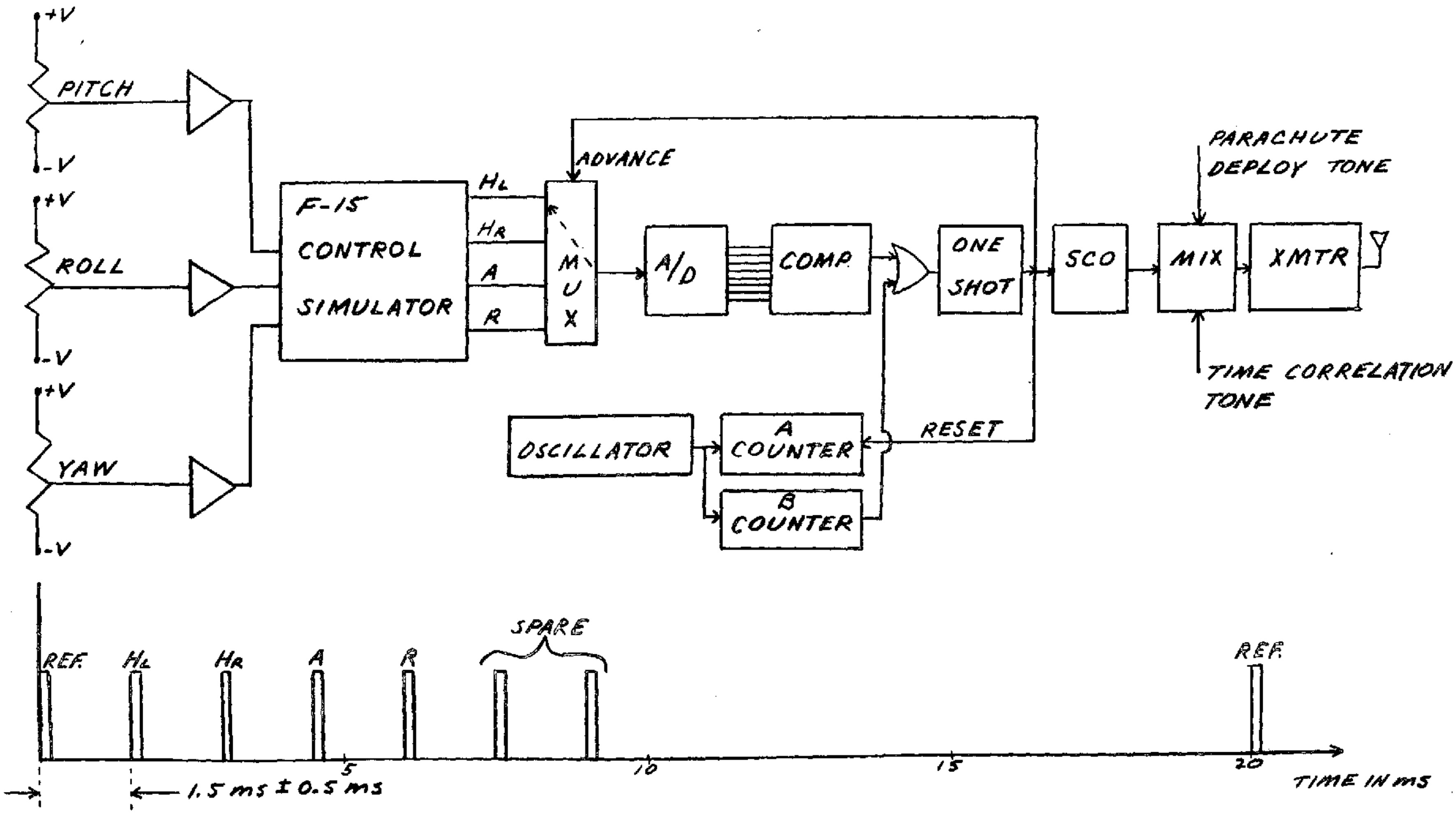

Figure 4. - Control system block diagram (ground).

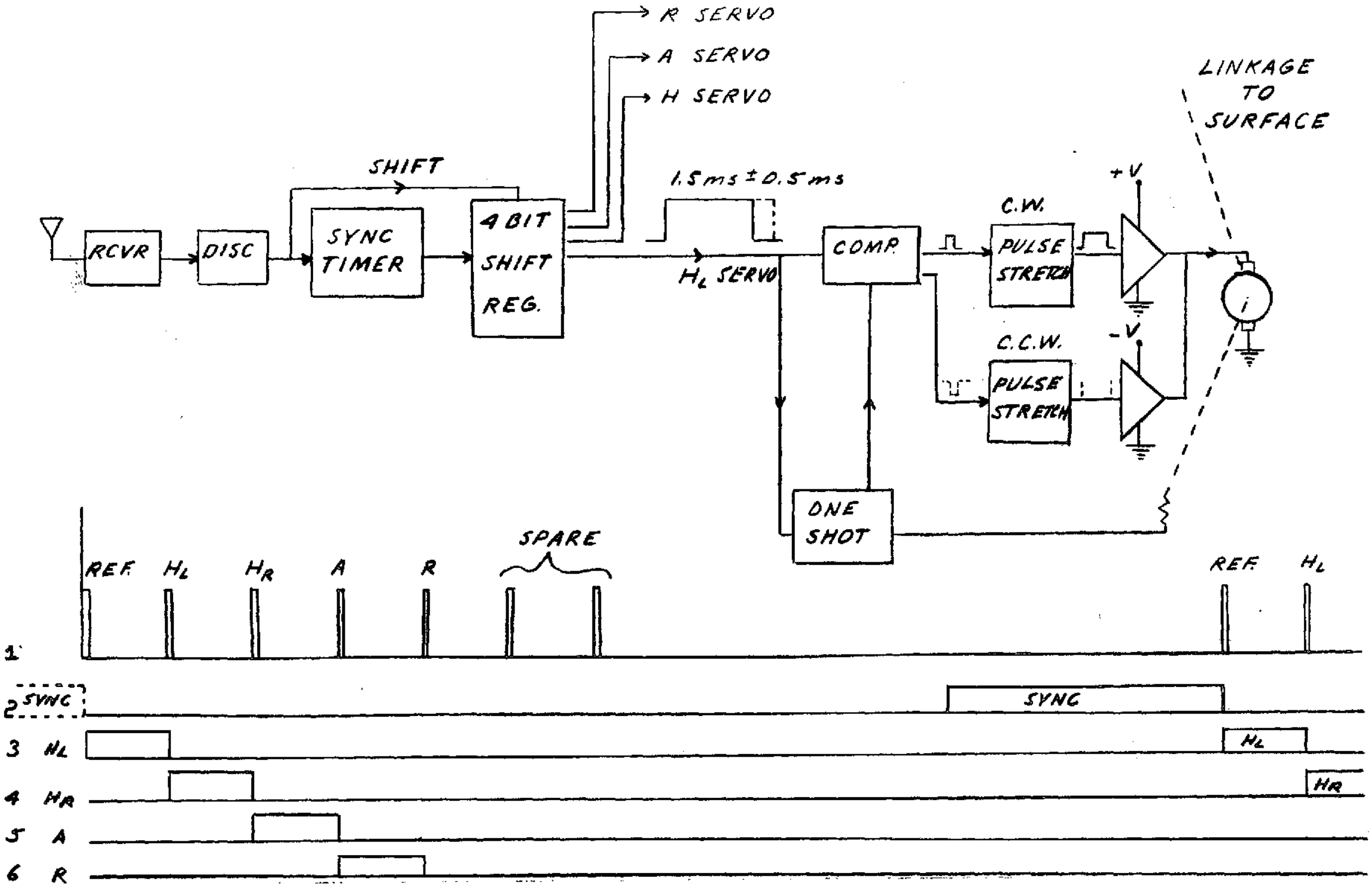

Figure 5. - Control system block diagram (air).

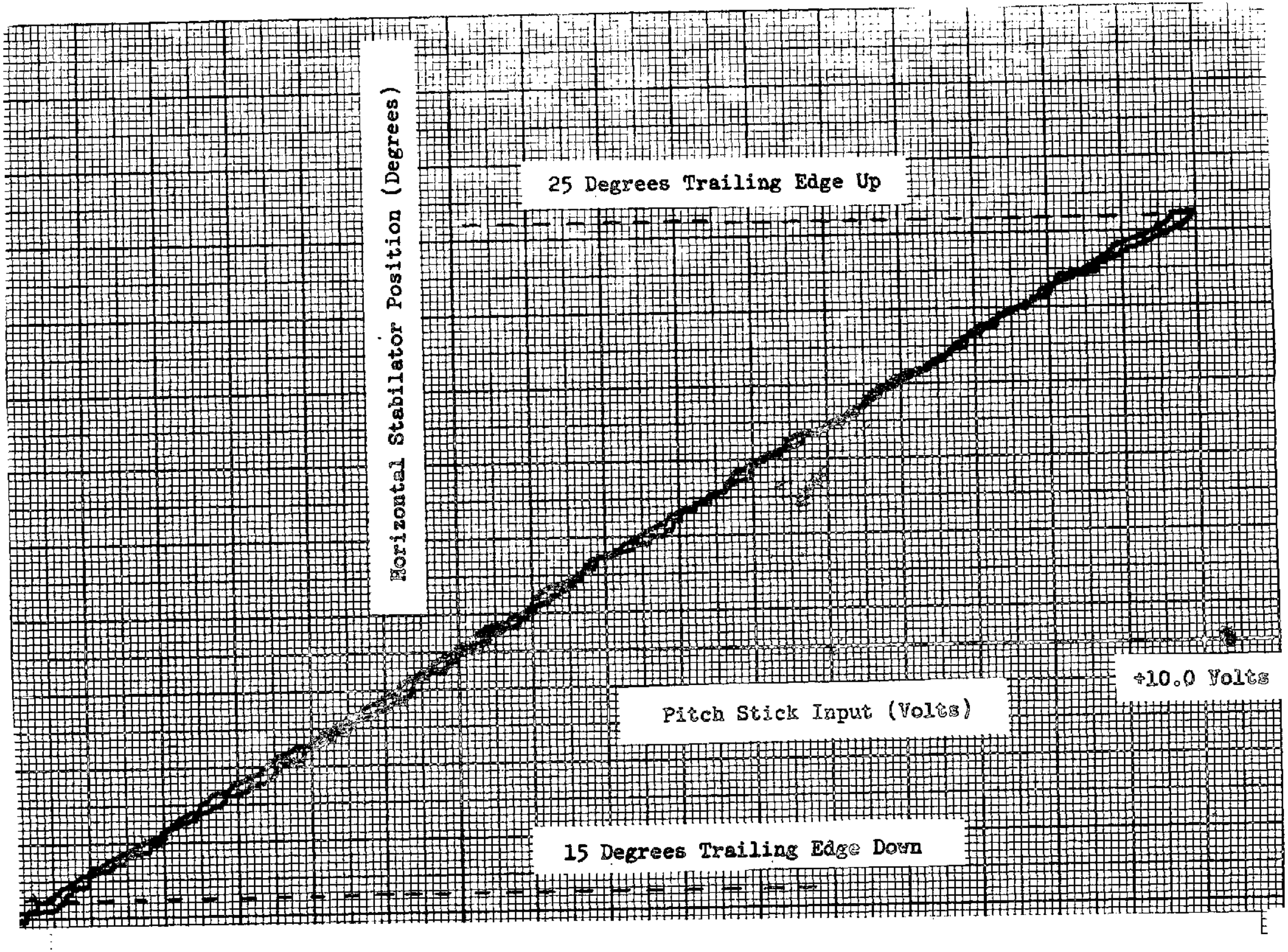

Figure 6. - Control system transfer function (stick input - surface output).

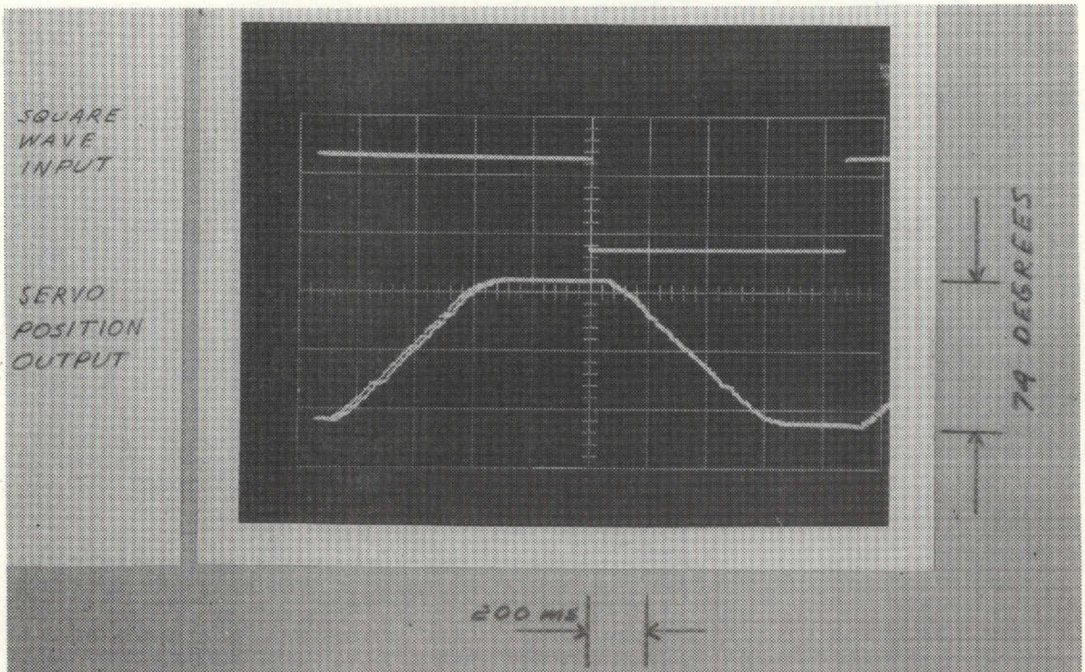

Figure 7. - Control system step response.

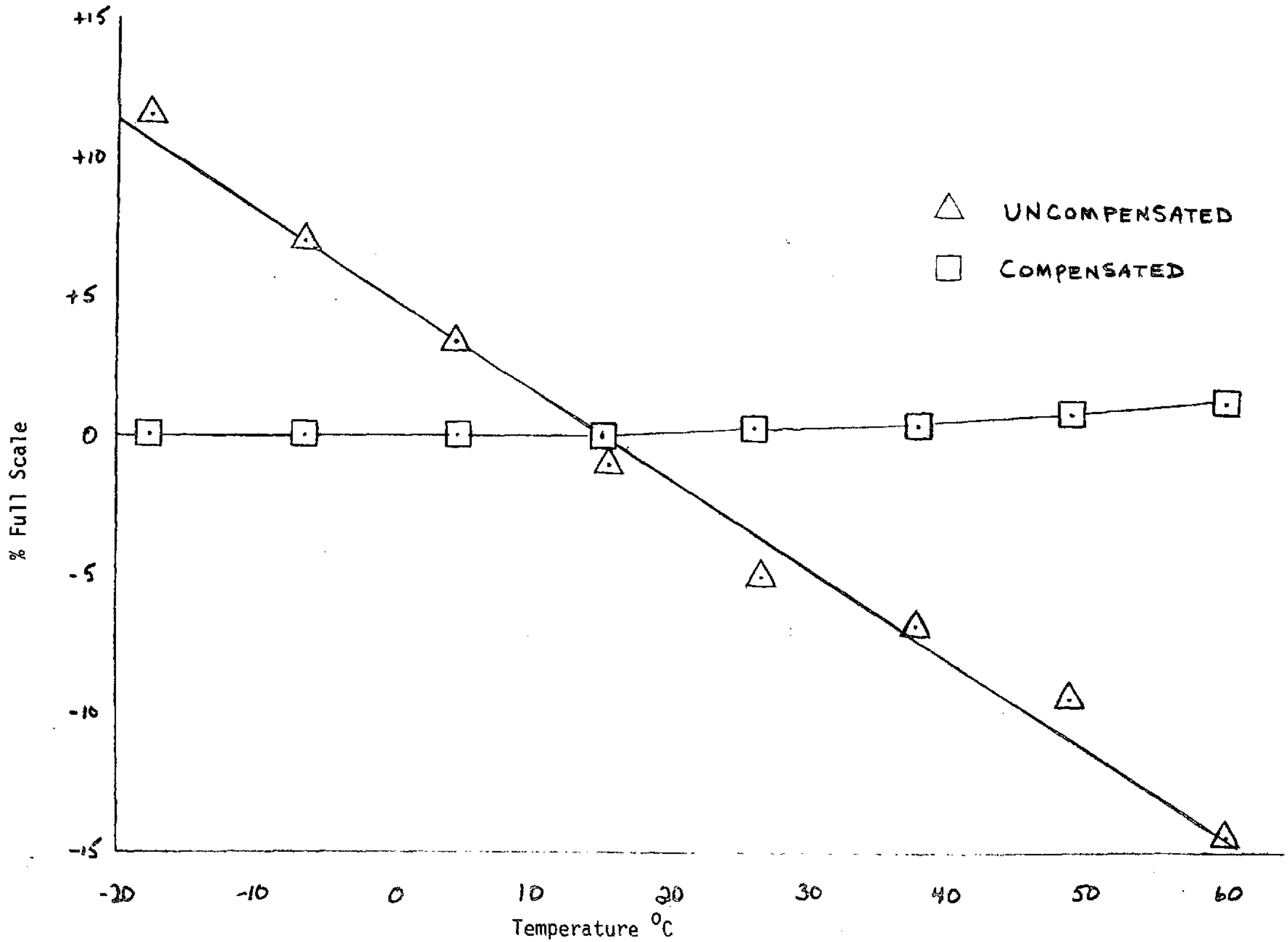

Figure 8. - Servo mechanism electronics temperature performance.

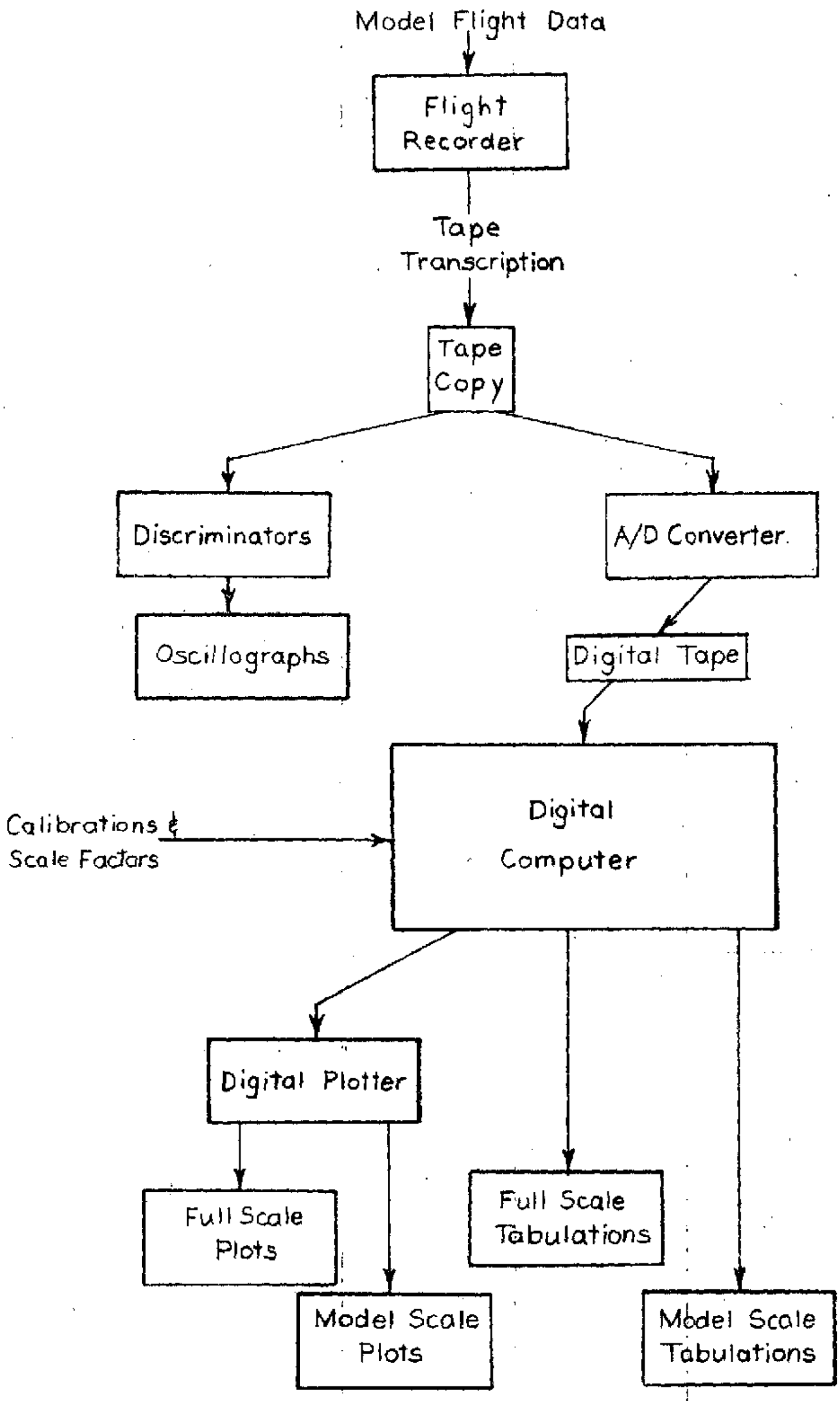

Figure 9. Data processing flow chart.

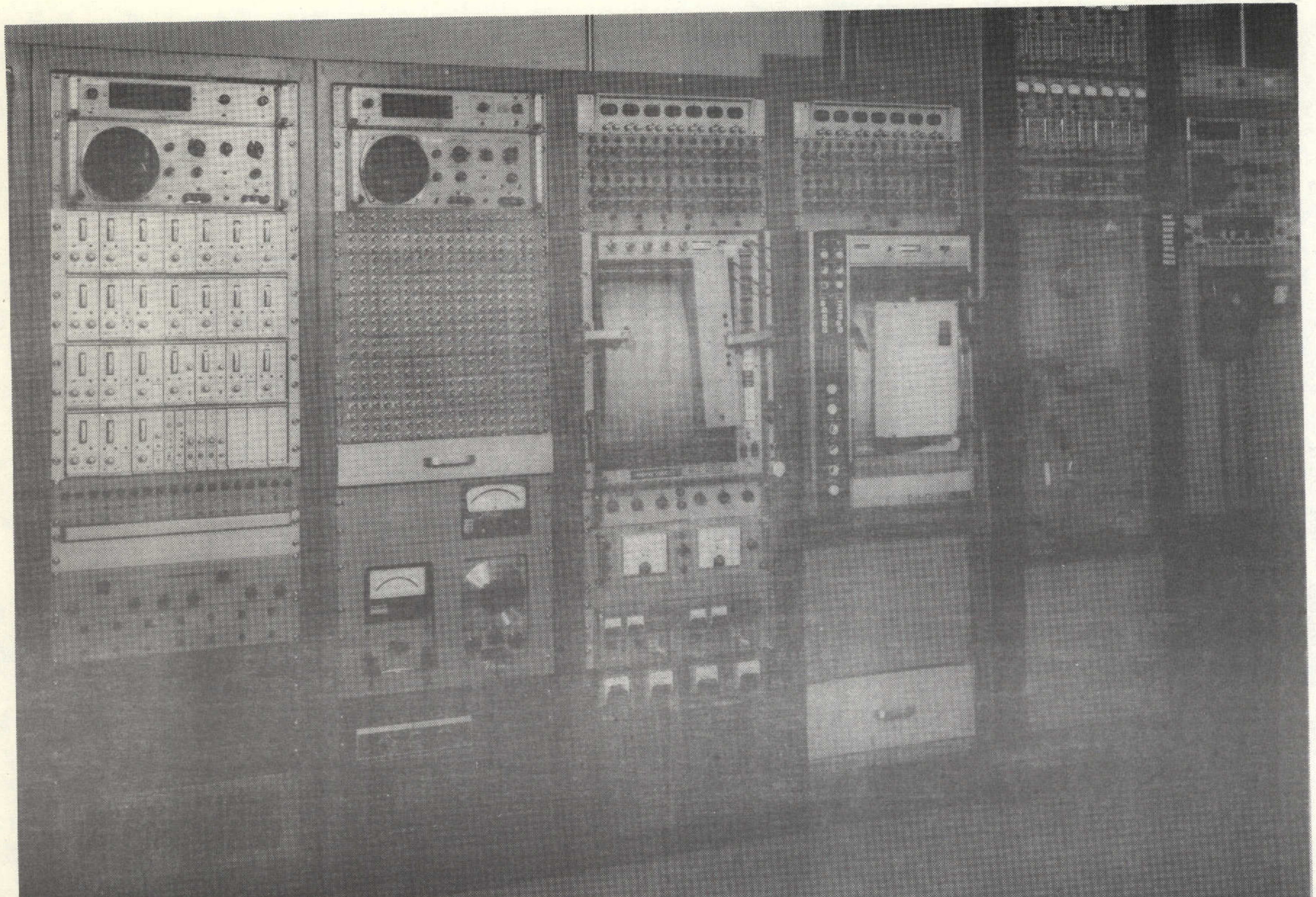

Figure 10(a). - Data processing station.

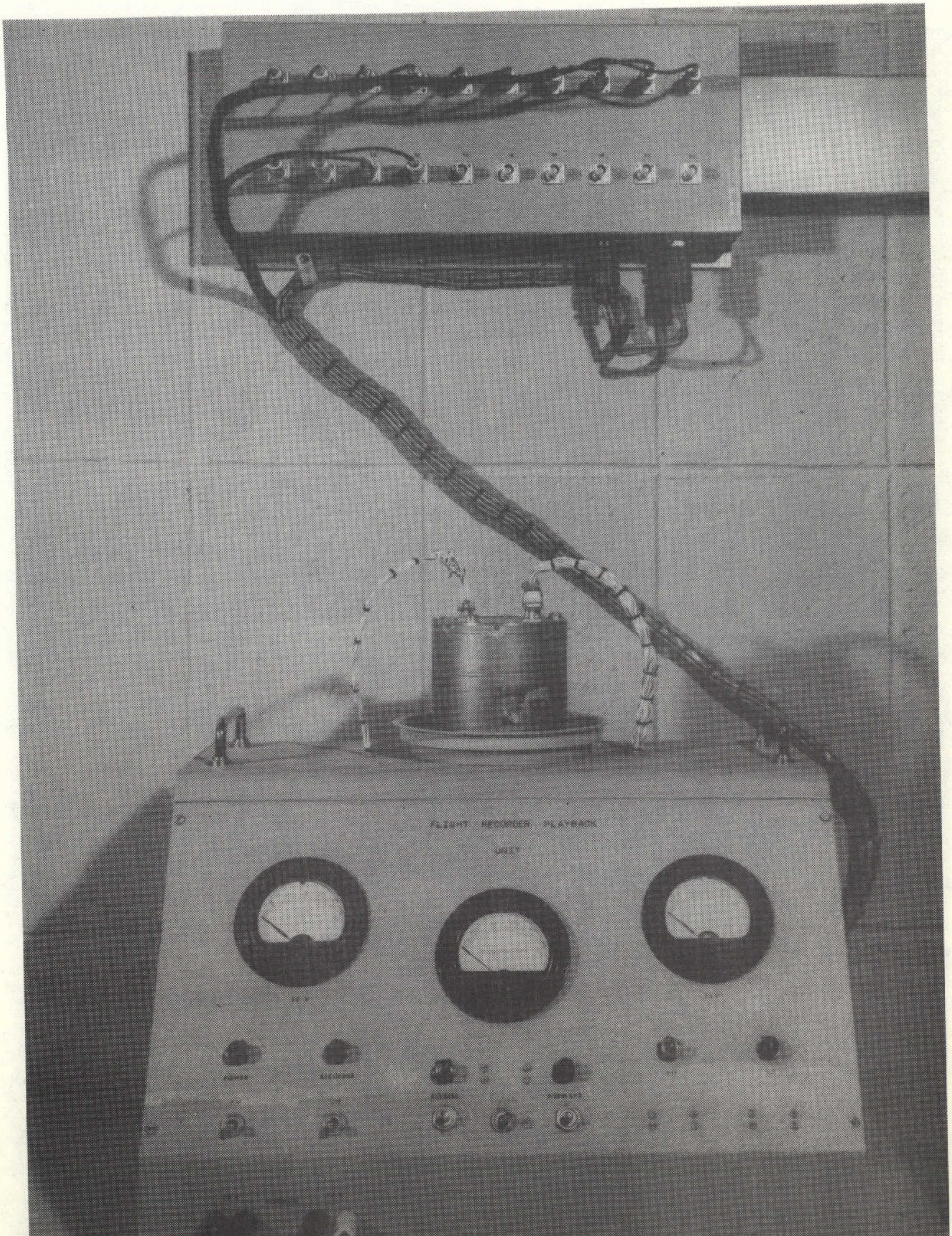

Figure 10(b). - Flight recorder interface unit.

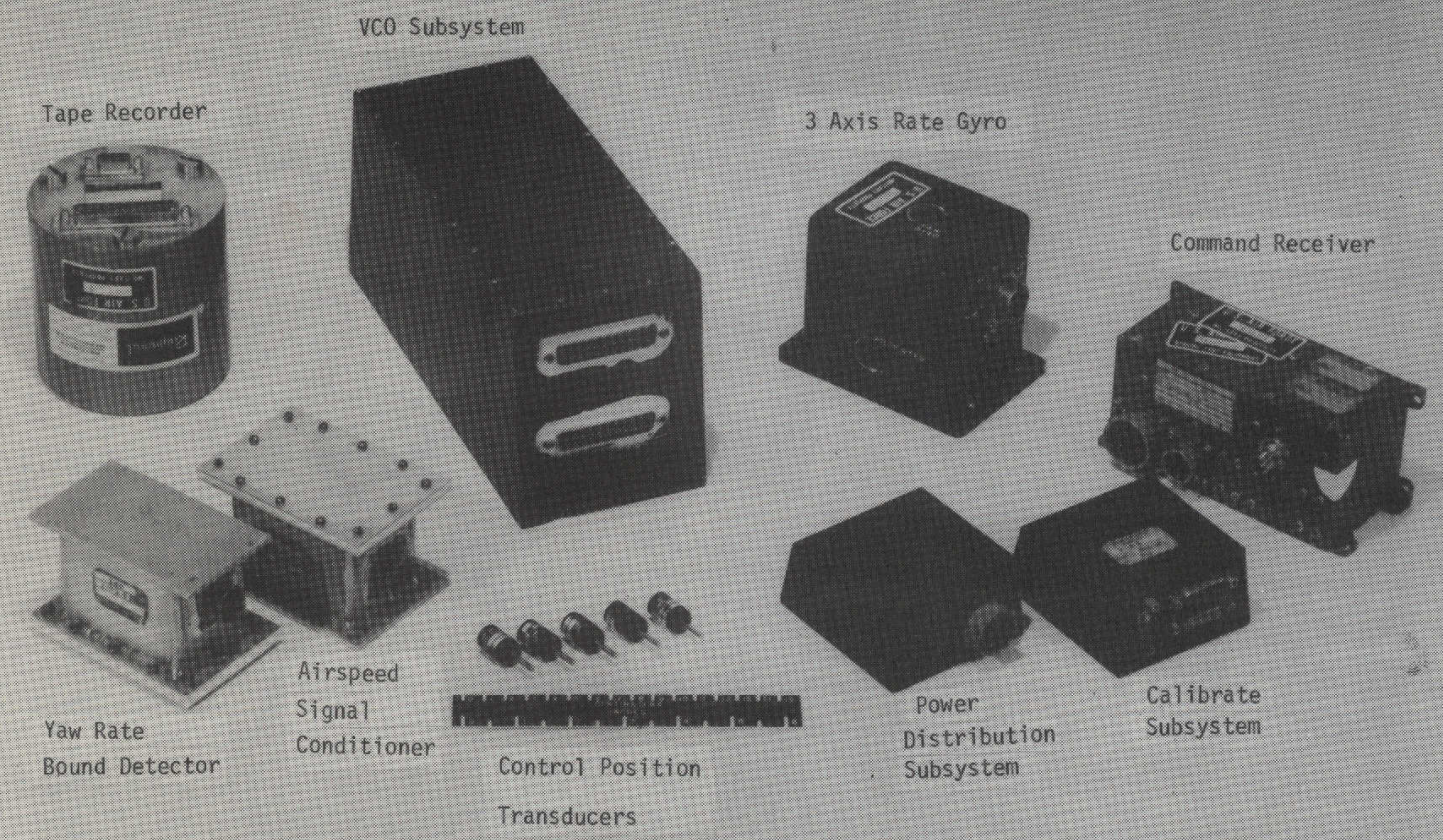

Figure A1. - Instrumentation system components.

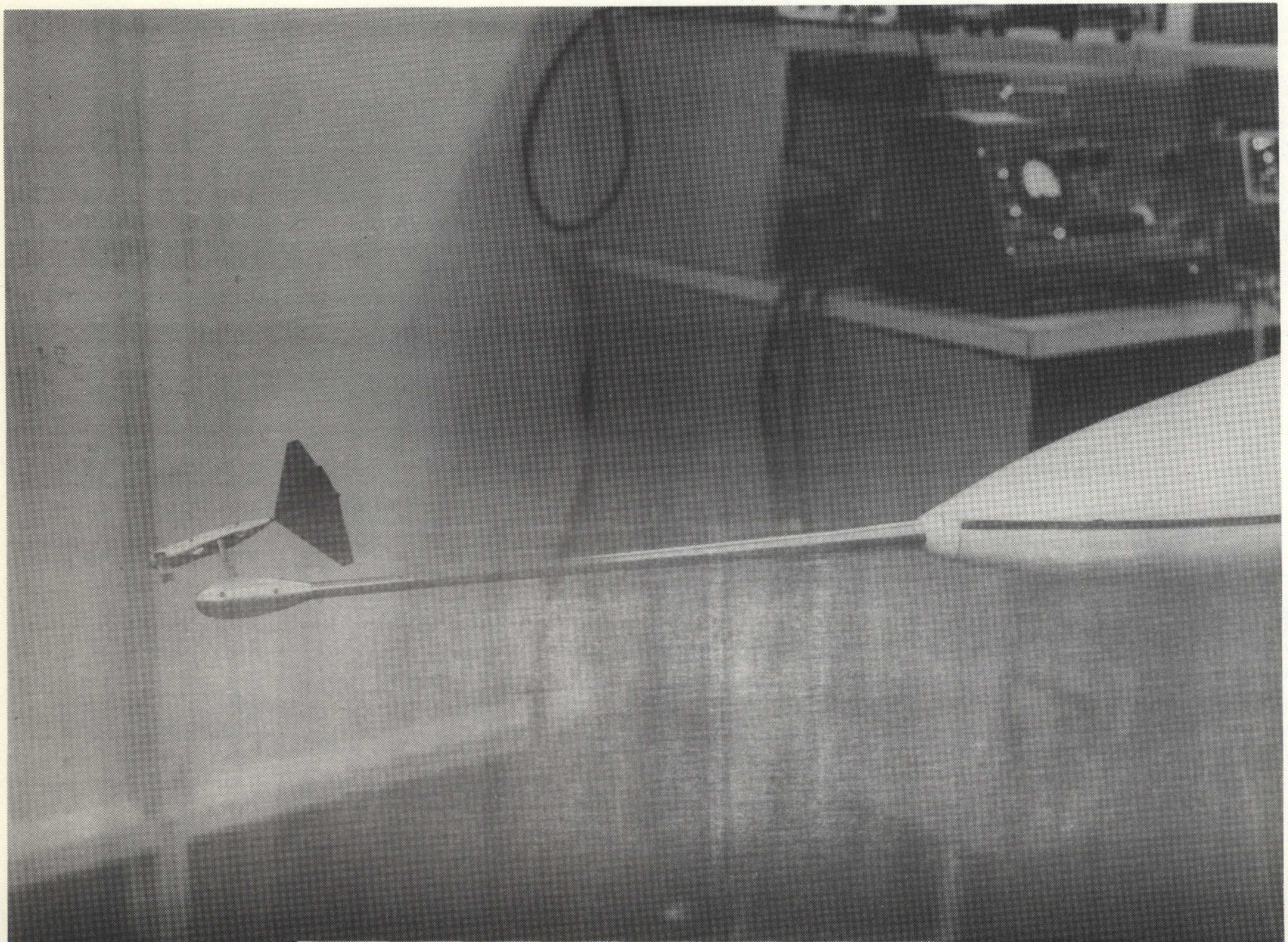

Figure A2. - Airflow sensor and boom.

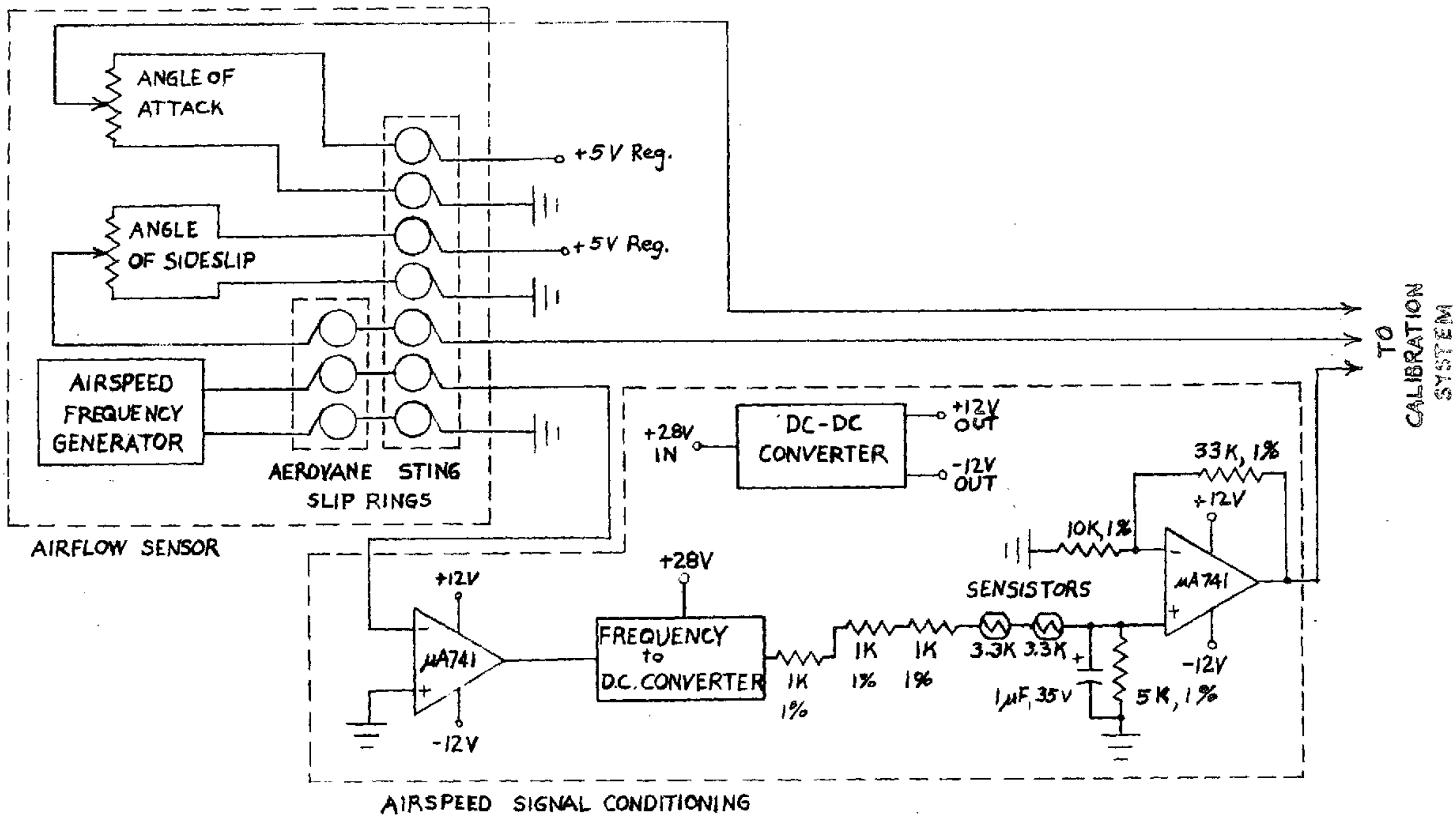

Figure A3. - Airflow sensor schematic diagram.

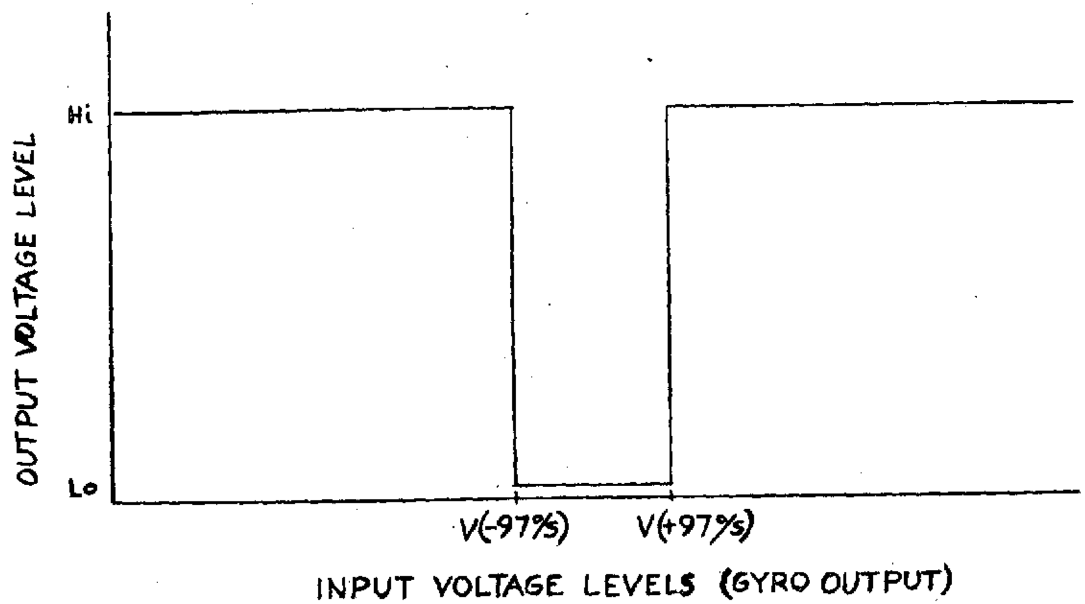

Figure A4. - Yaw rate bound detector transfer function.

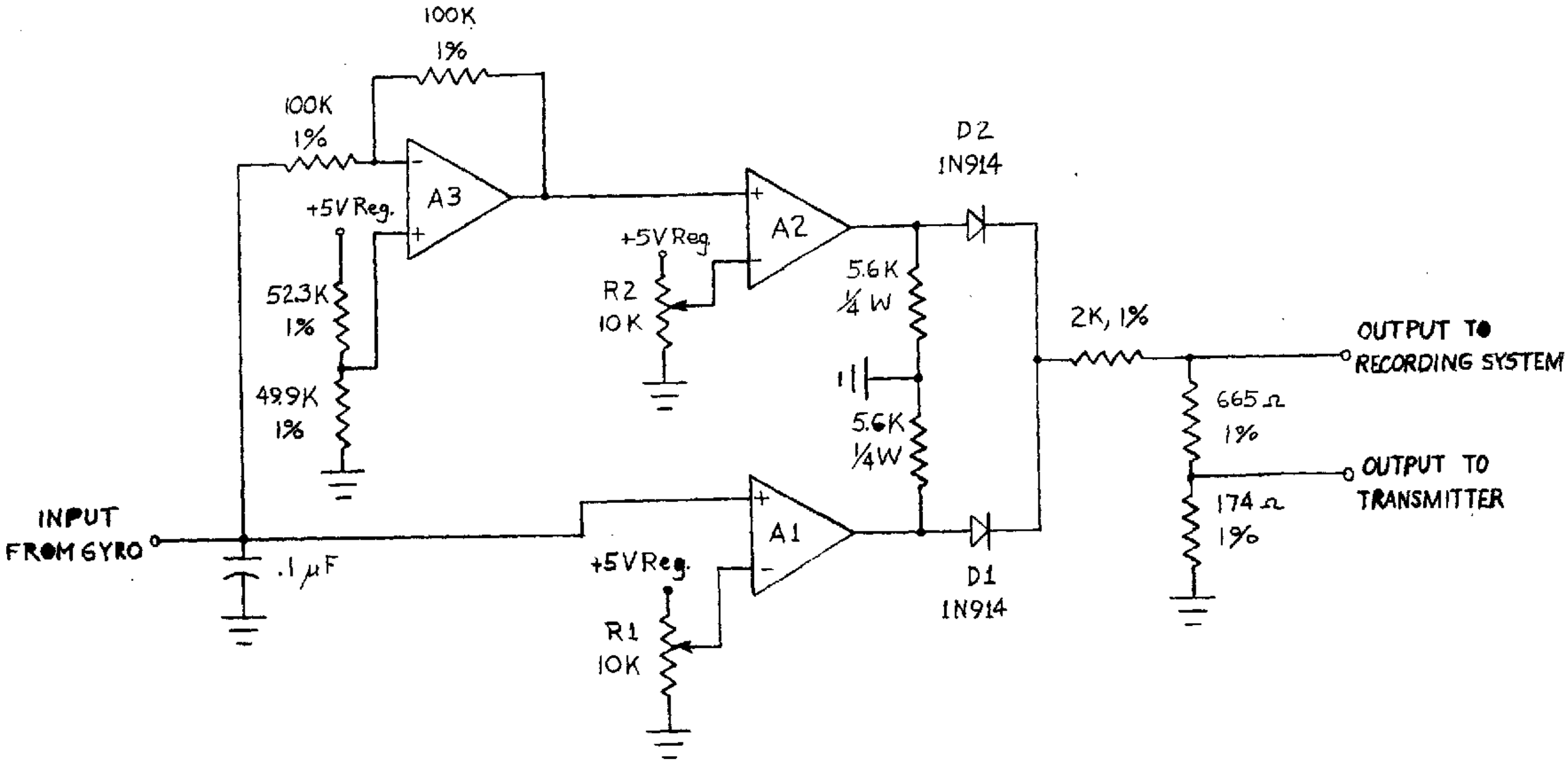

Figure A5. - Yaw rate bound detector schematic diagram.

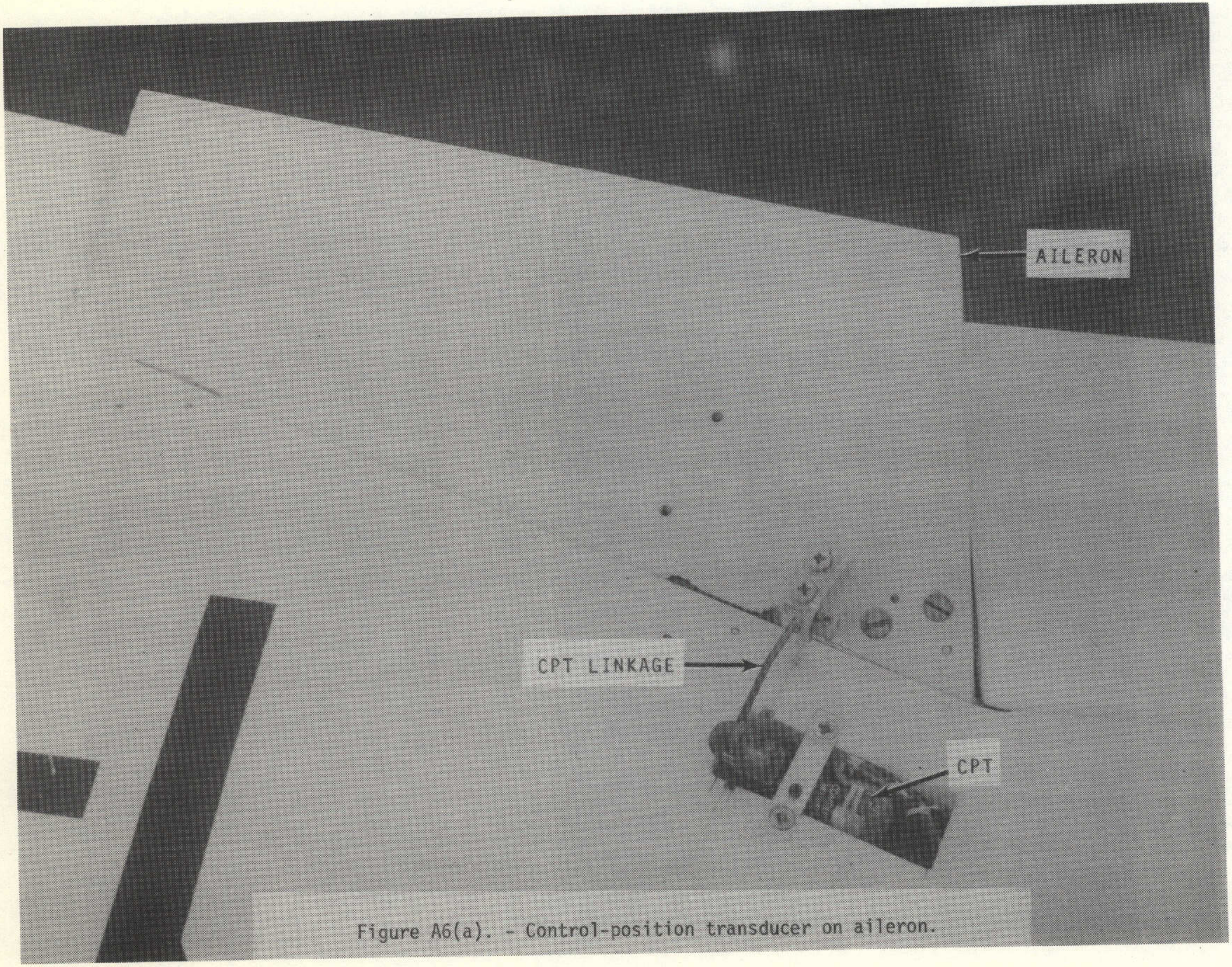

Figure A6(a). - Control-position transducer on aileron.

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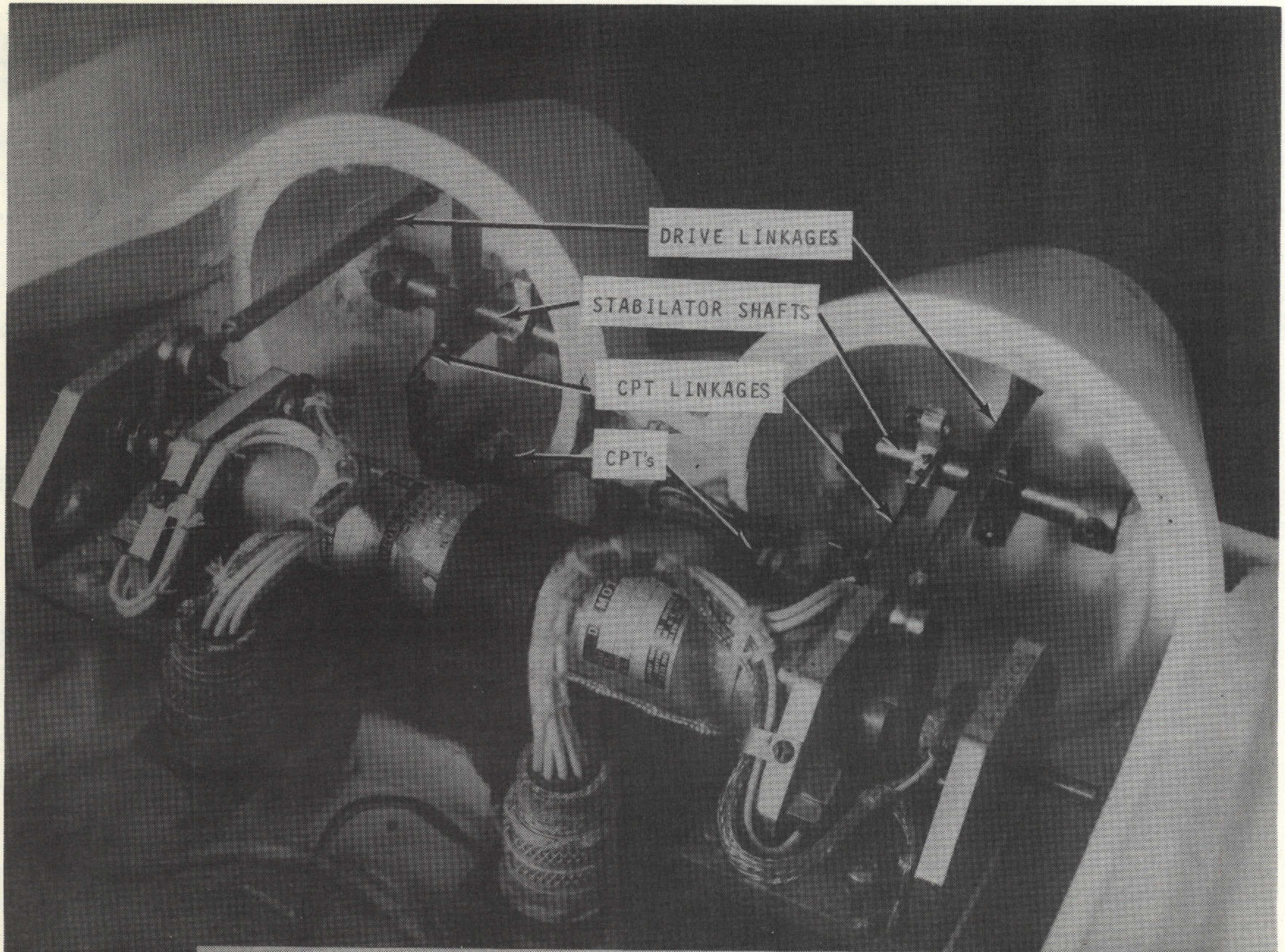


Figure A6(b). - Control-position transducer on stabilator shafts.

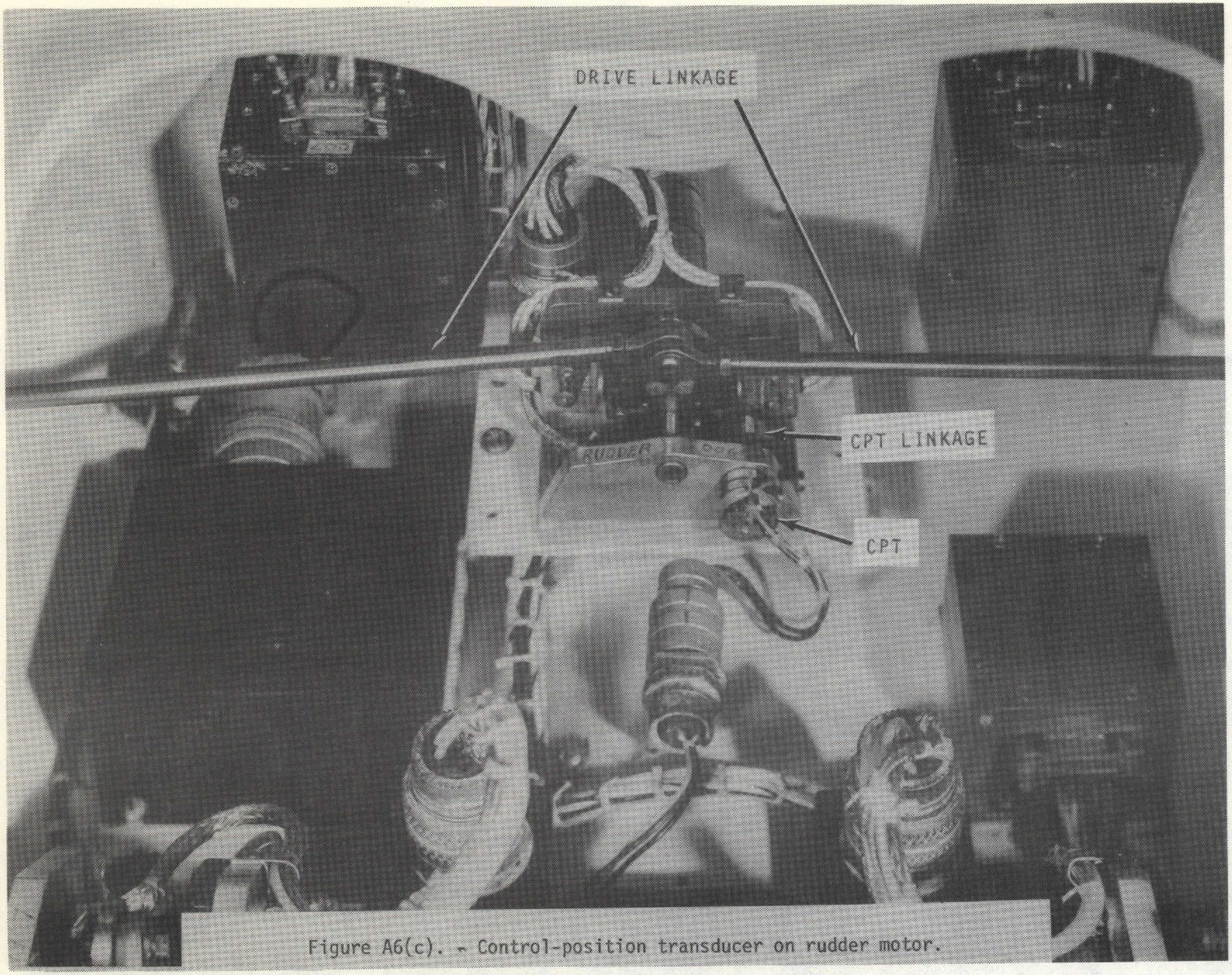


Figure A6(c). - Control-position transducer on rudder motor.

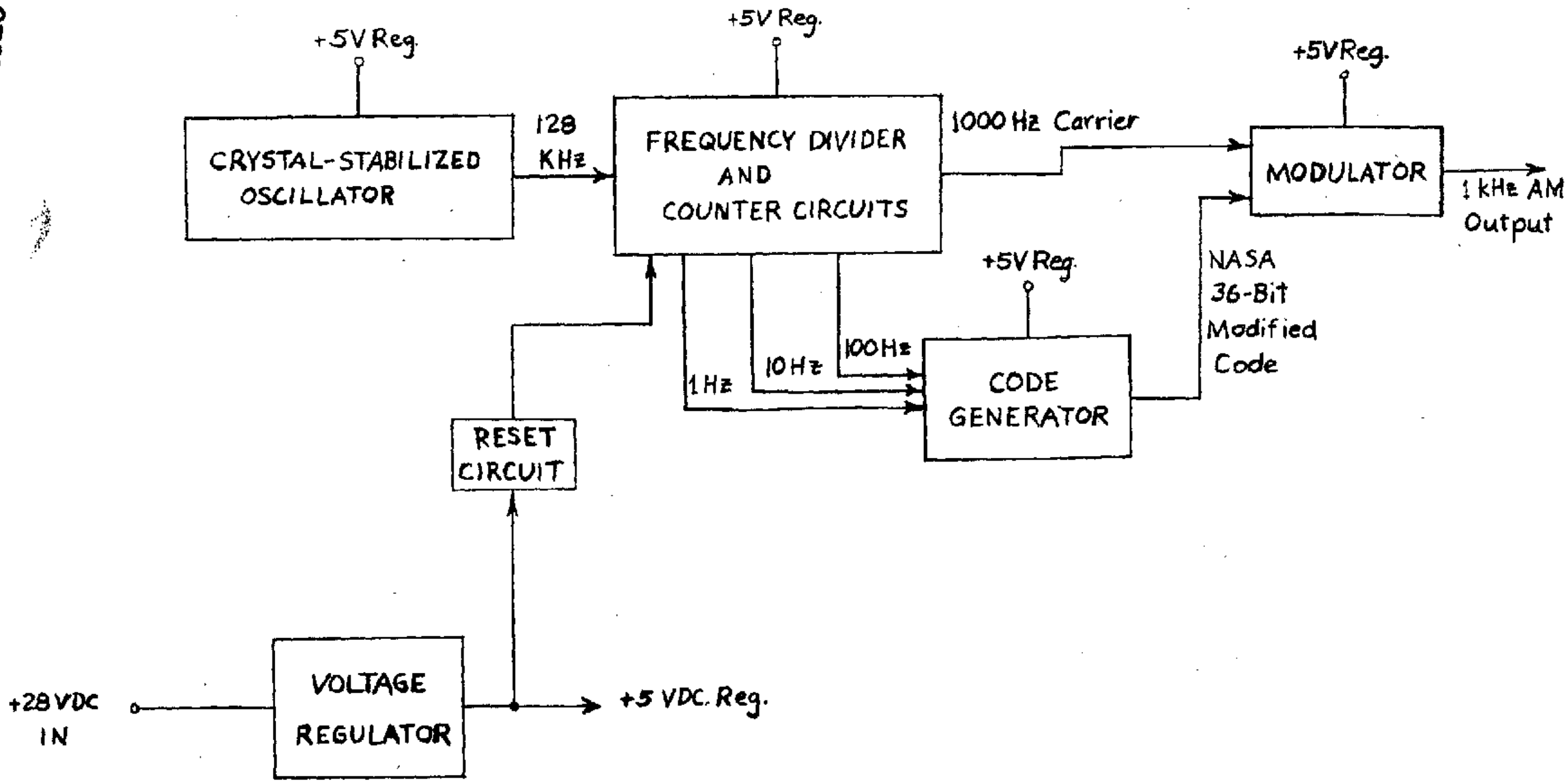


Figure A7. - Data time-code generator block diagram.

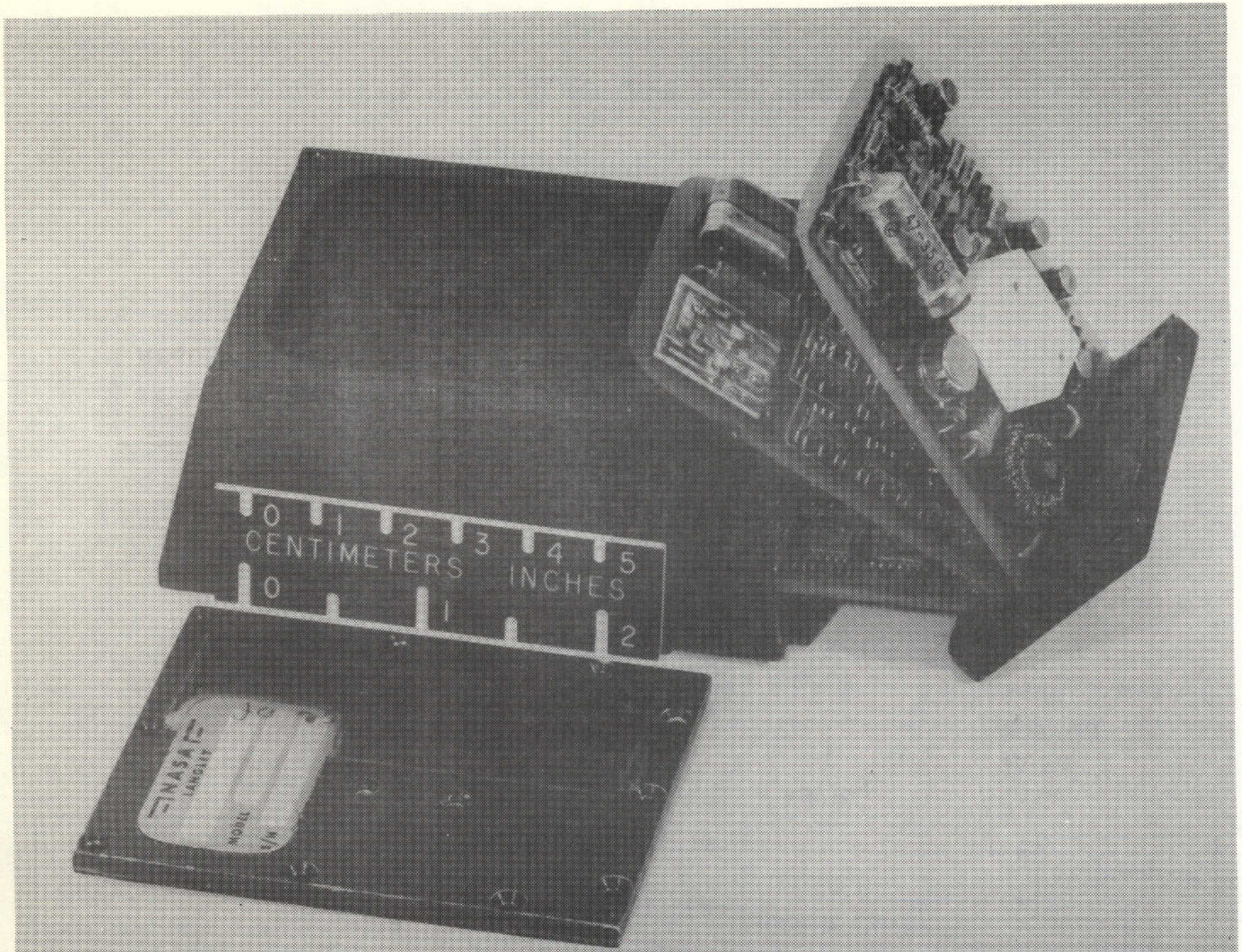


Figure A8. - Data time-code generator.

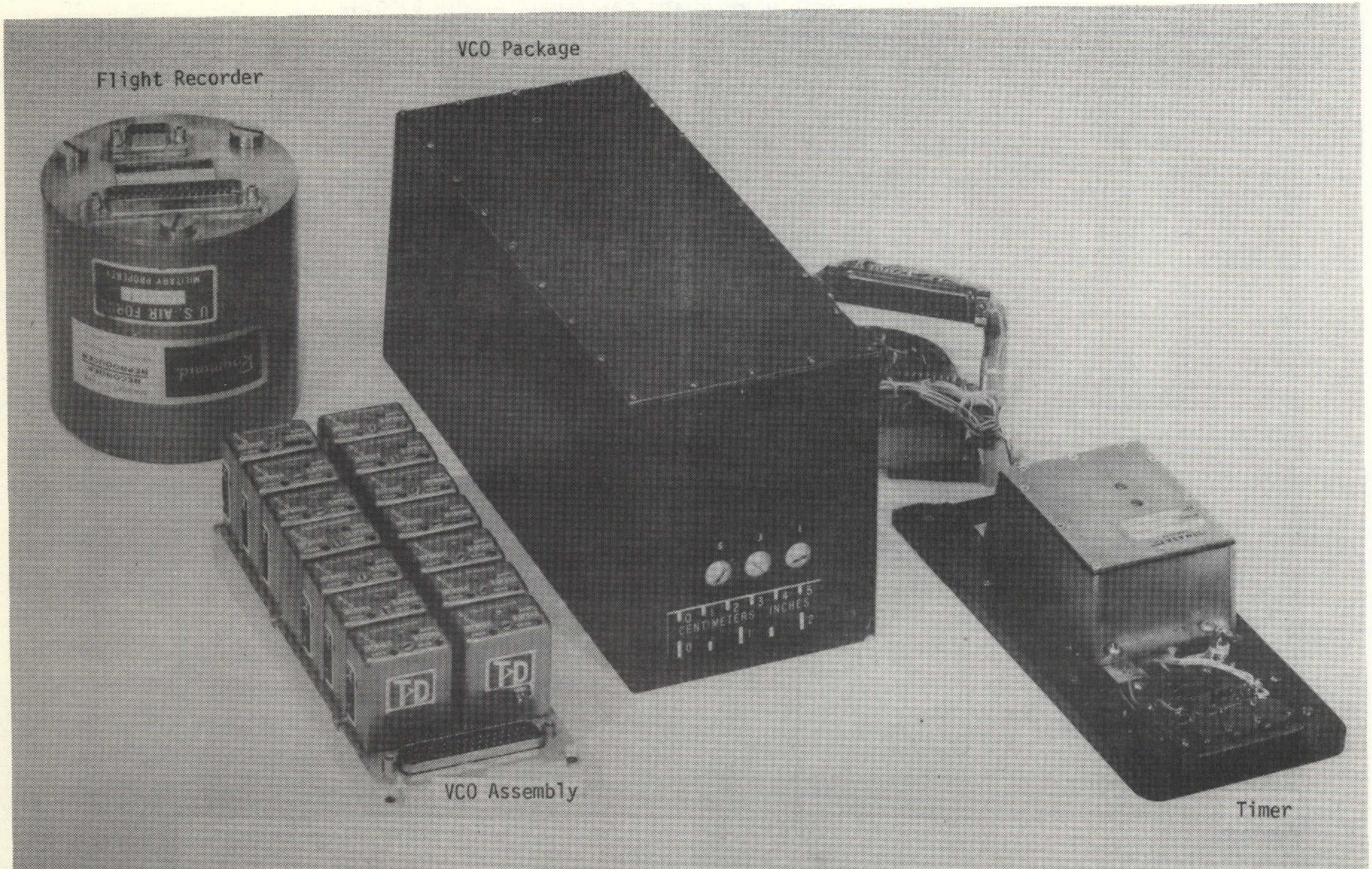


Figure A9. - Tape recorder, VCO assembly, and time-code generator.

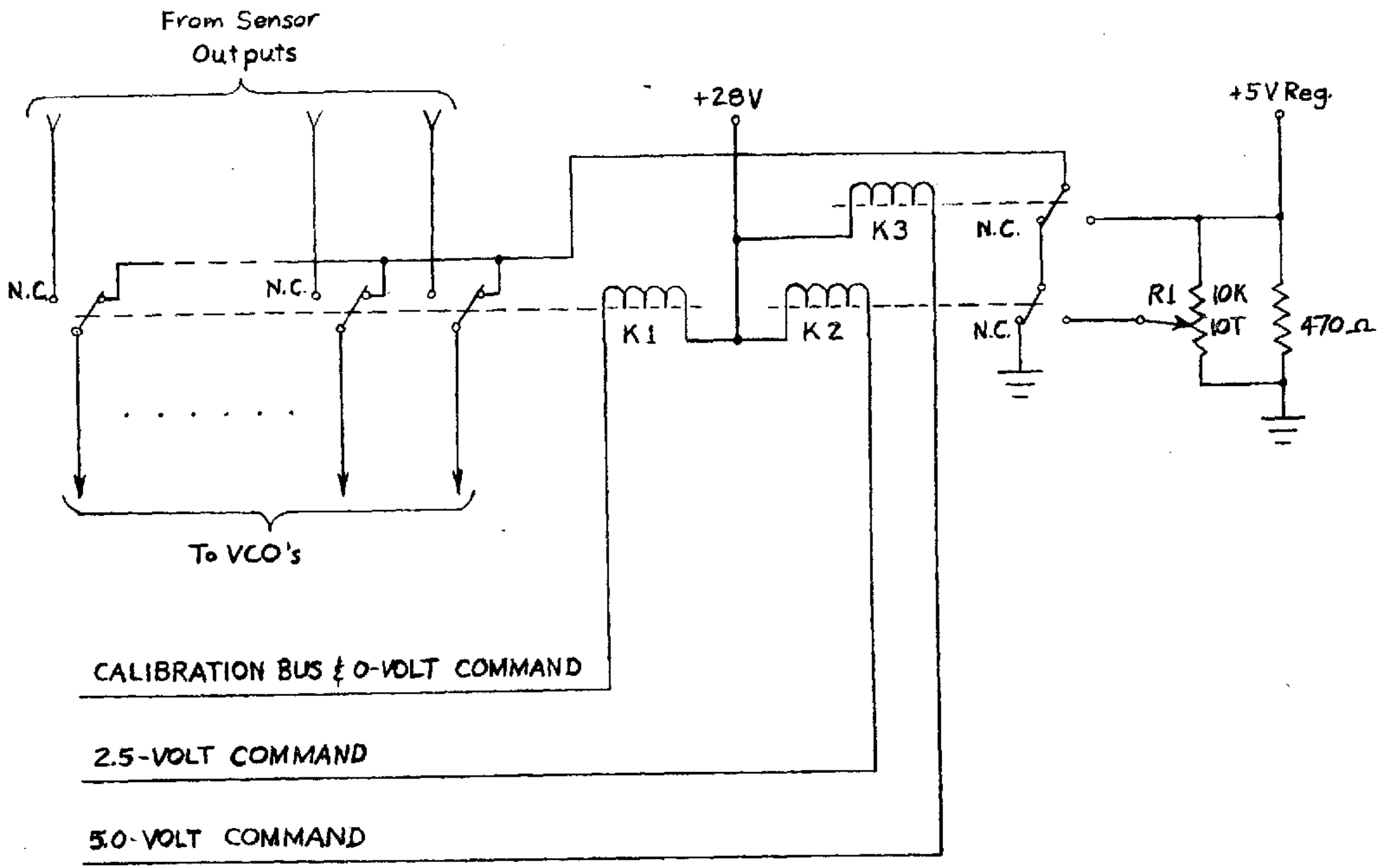


Figure A10. - Simplified calibration system diagram.

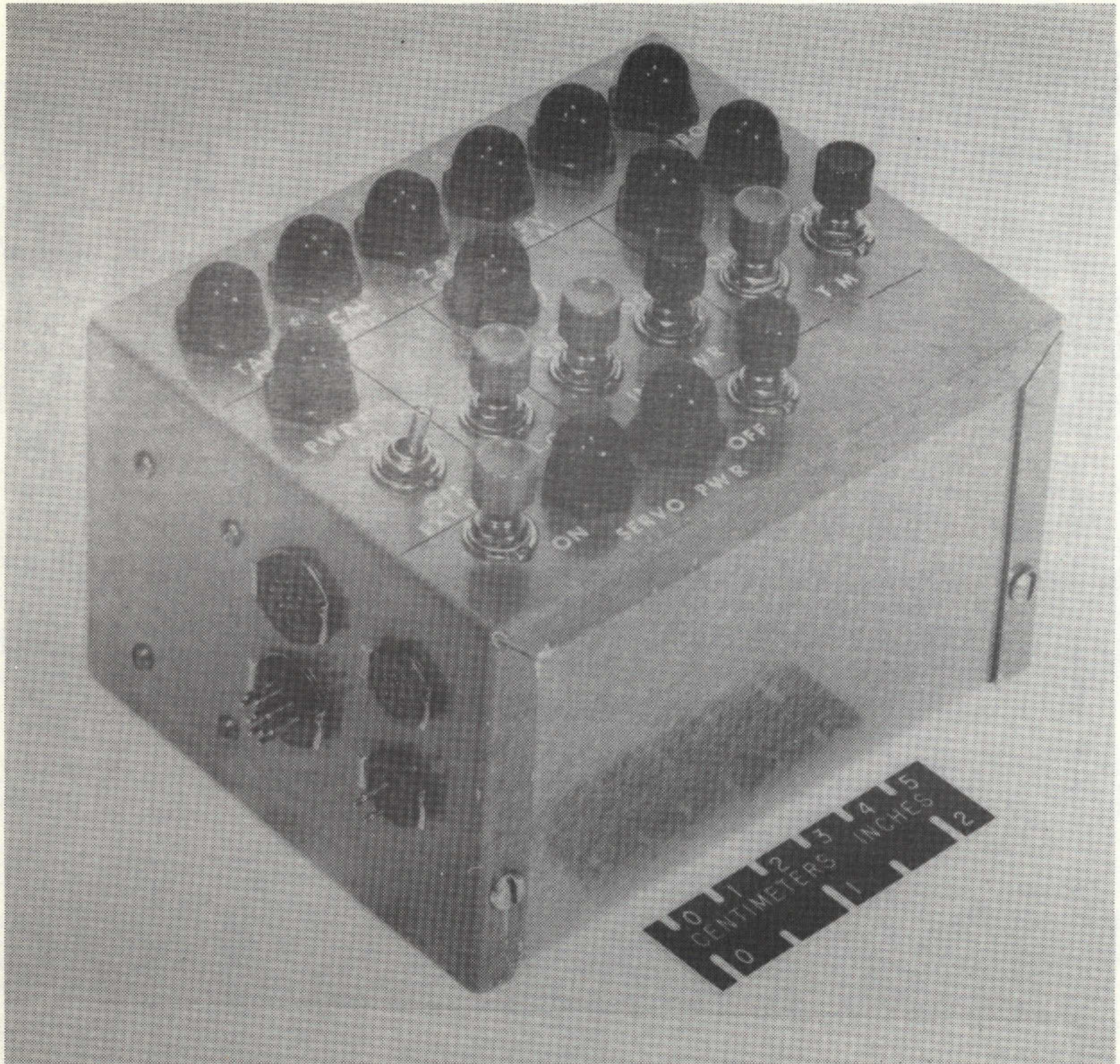


Figure A11. - Automatic calibration and launch sequencer.

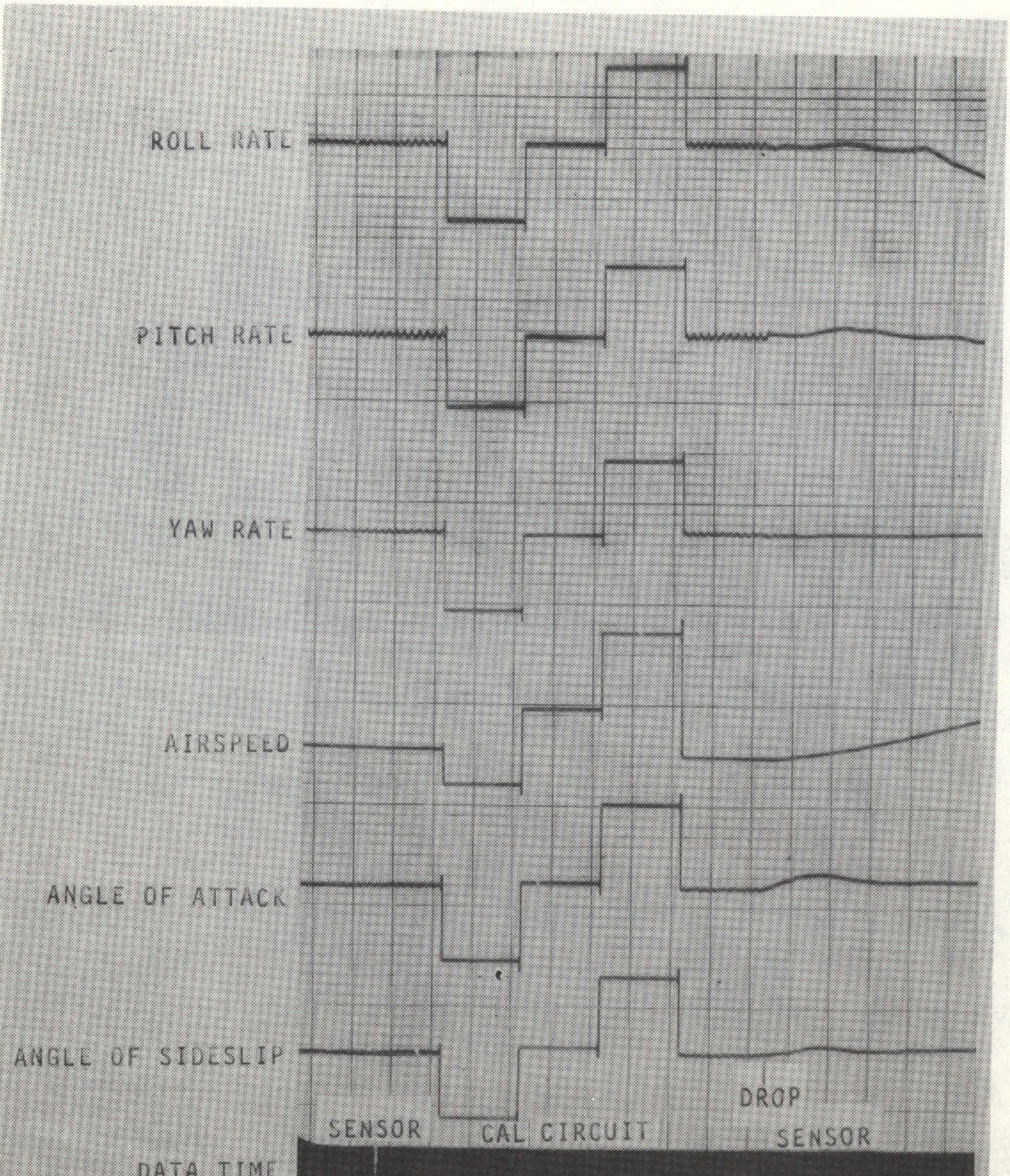


Figure A12. - In-flight calibration data.

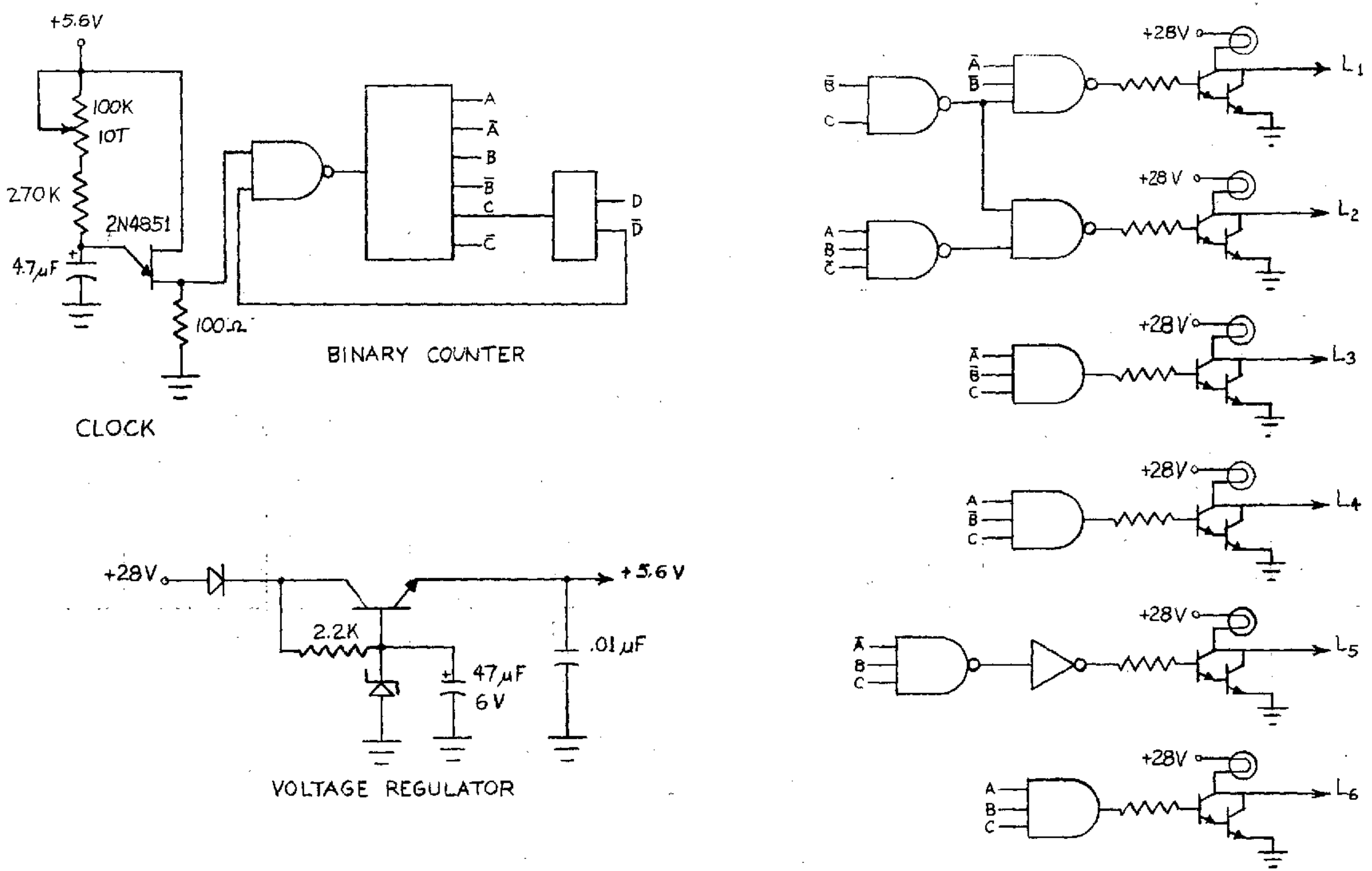
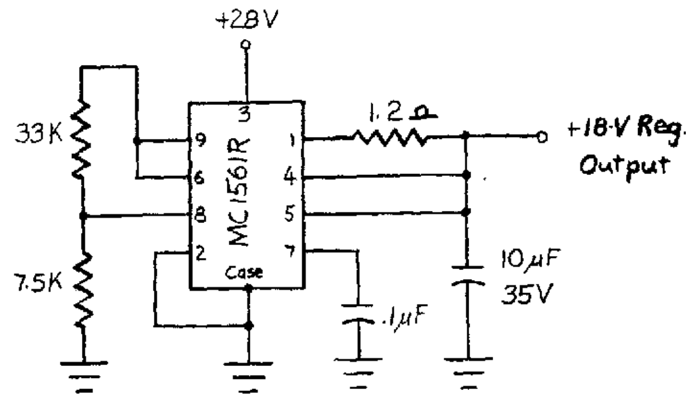
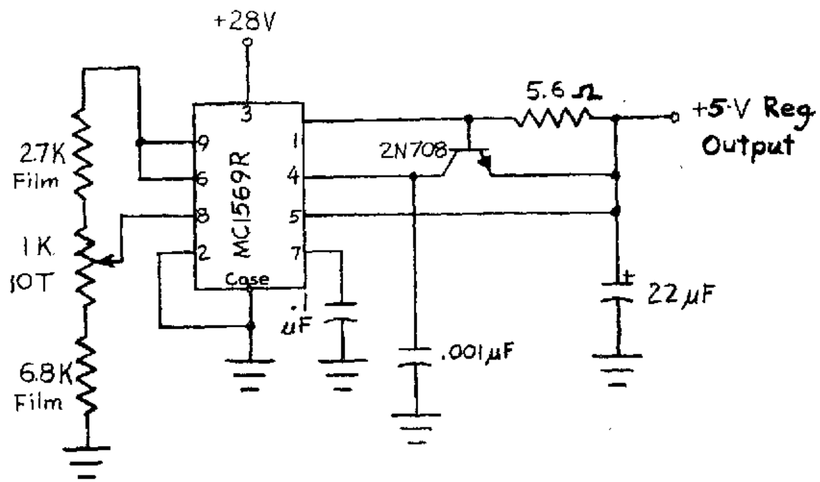


Figure A13. - Automatic calibration sequencer schematic diagram.



(a). 18-VOLT REGULATOR



(b). 5-VOLT REGULATOR

Figure A14. - Voltage regulator schematic diagrams.

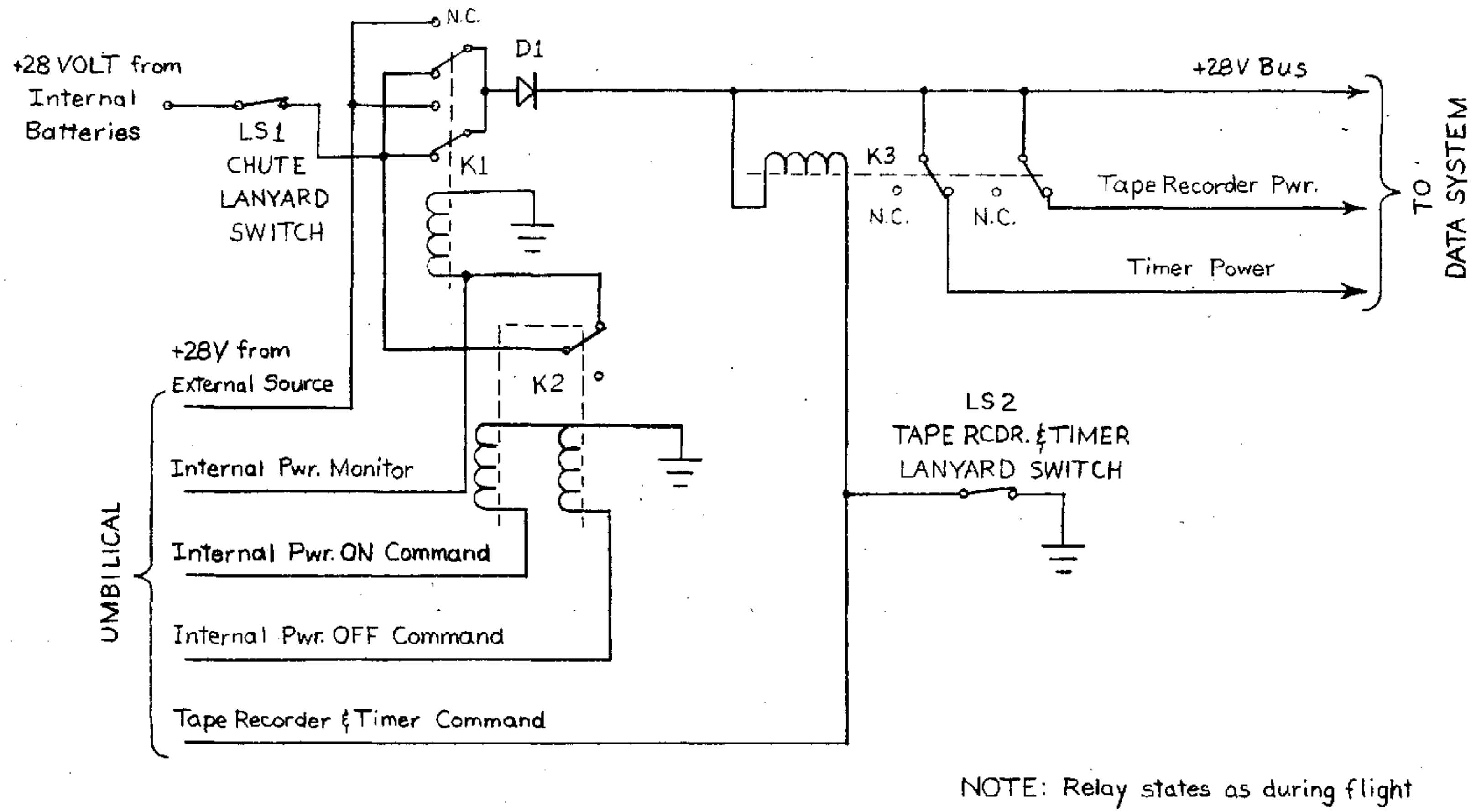


Figure A15. - Power distribution system schematic diagram.

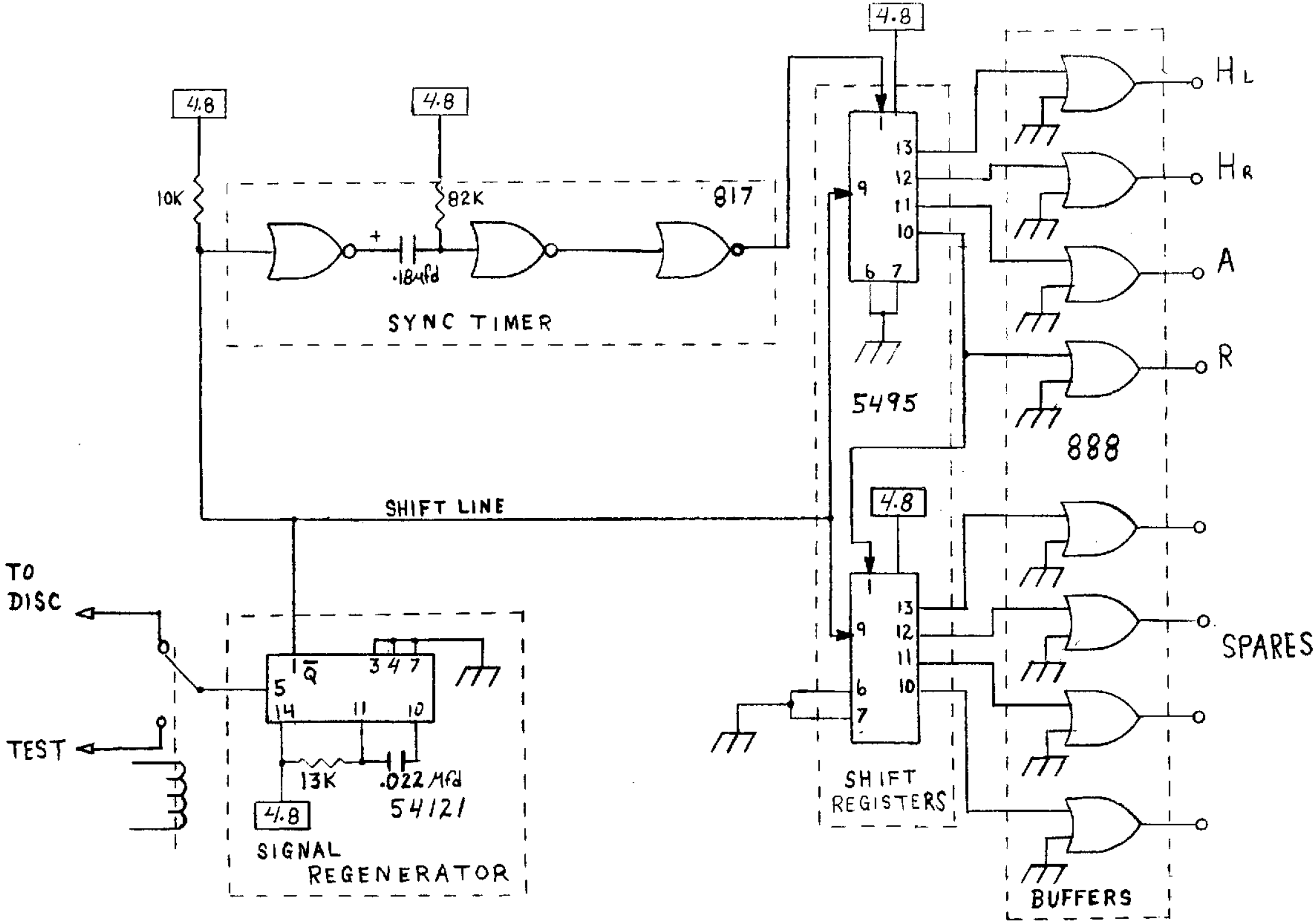


Figure B1. - Control signal decoder schematic diagram.

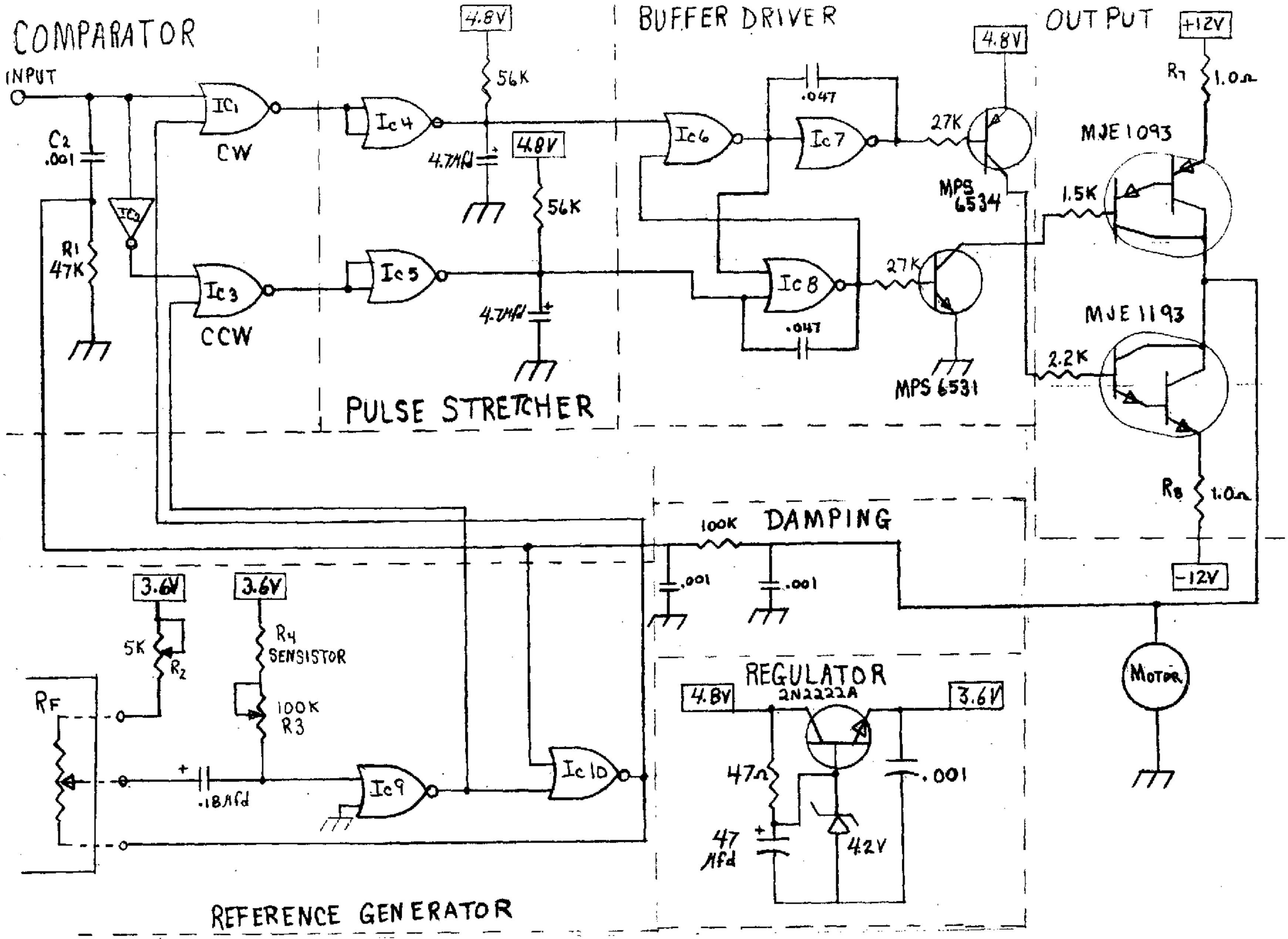
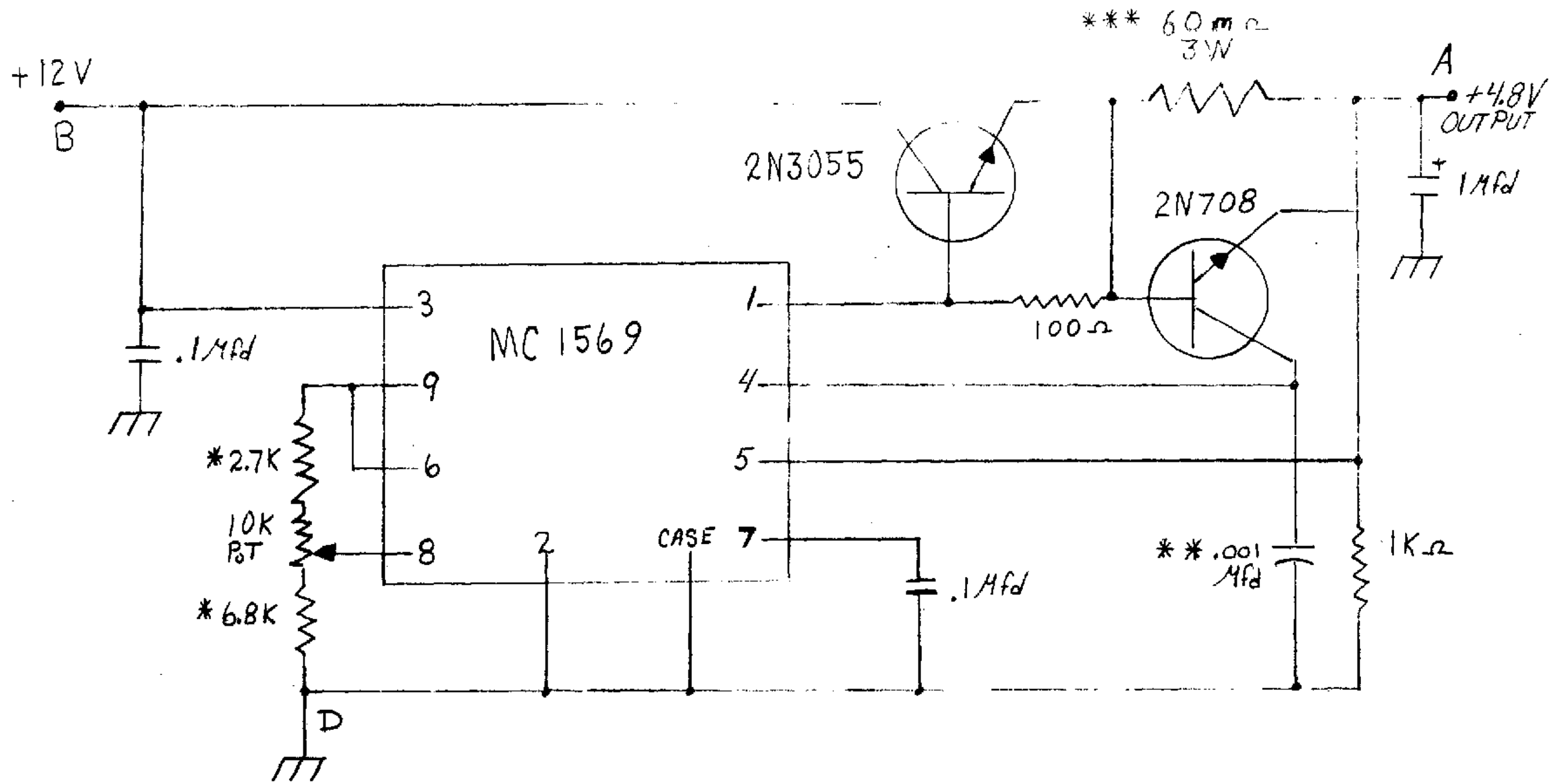


Figure B2. - Servo mechanism electronics schematic diagram.



* USE TEMP STABLE RESISTORS

** MOUNT AS CLOSE TO MC1569 PIN 4 AS POSSIBLE

*** 1.5′ of #26 GAUGE WIRE WRAPPED AROUND ½ WATT RESISTOR

Figure B3. - Control system 4.8-volt regulator schematic diagram.

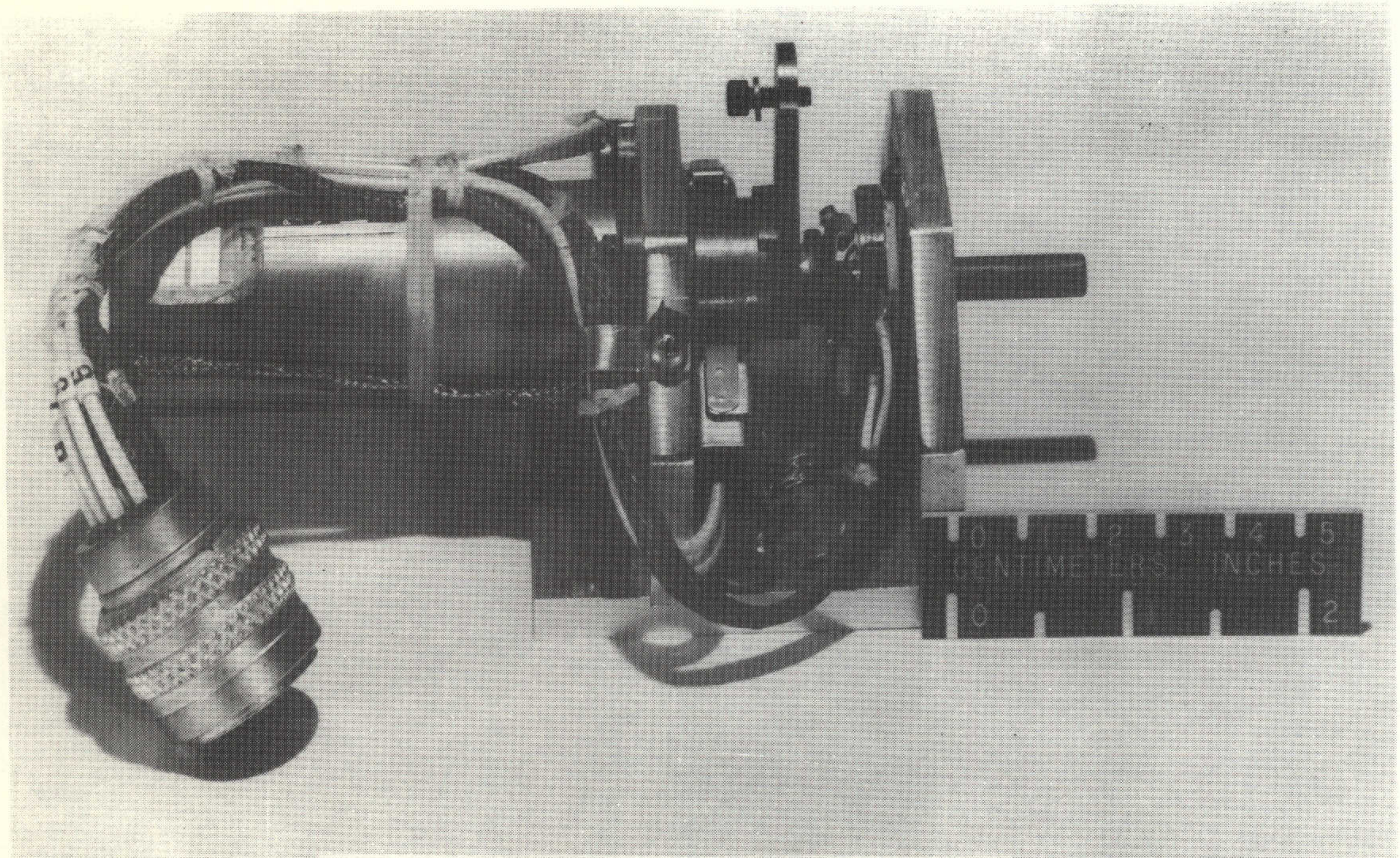


Figure B4. - Servo motor assembly.

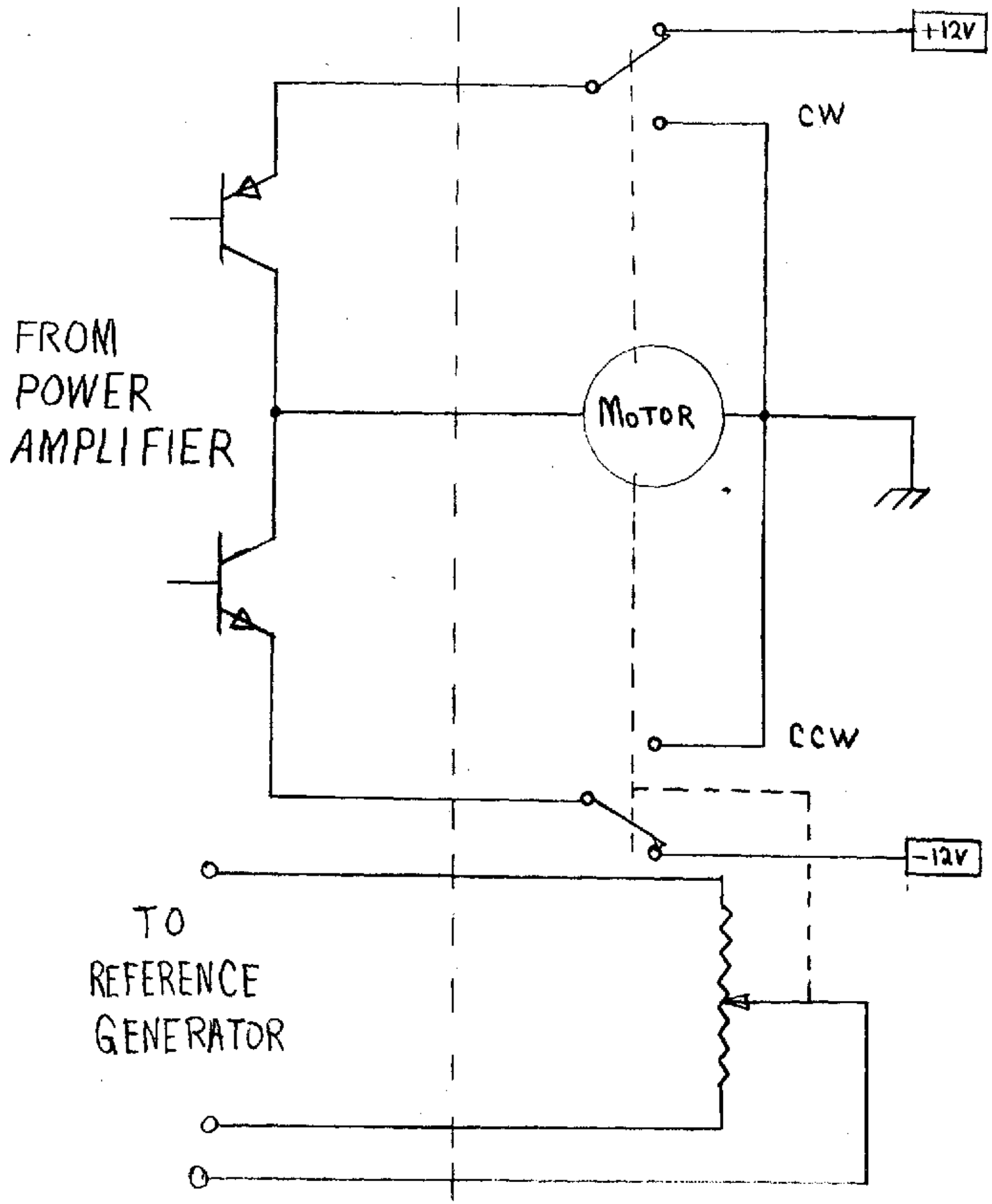


Figure B5. - Simplified servo motor schematic diagram.

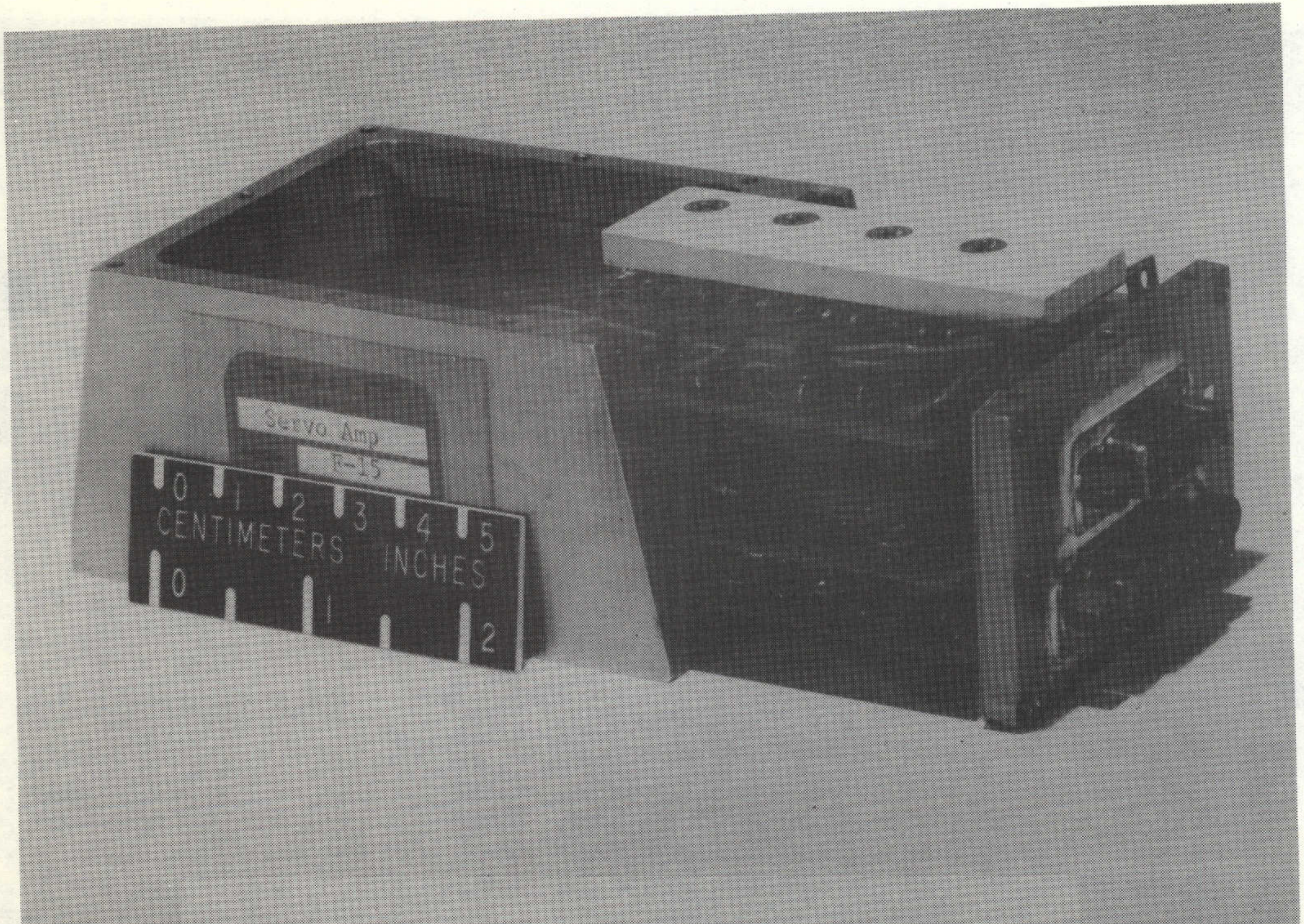


Figure B6. - Servo mechanism electronics package.

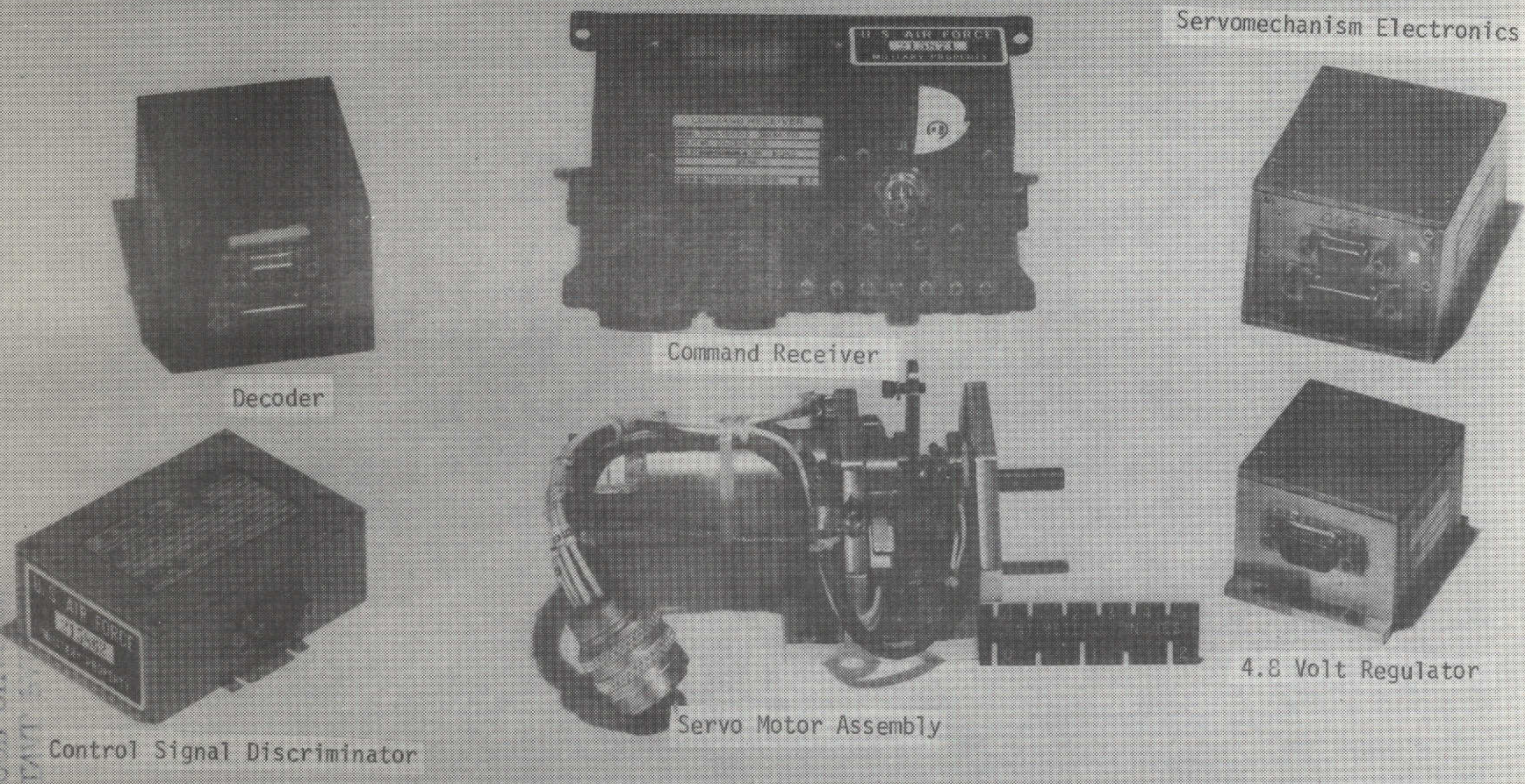


Figure B7. - Typical control system components.

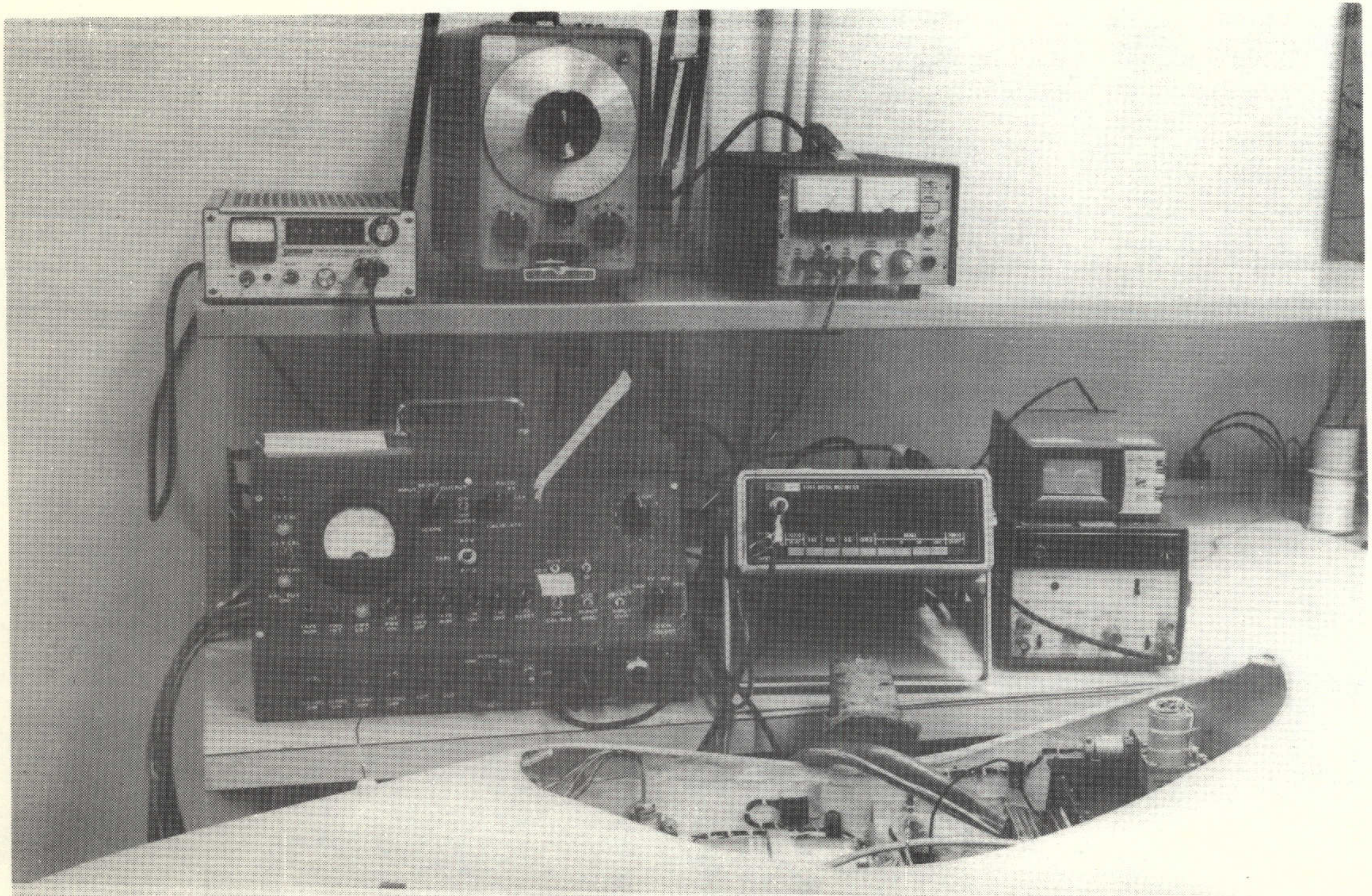


Figure C1. - Instrumentation and control system monitor and control unit.

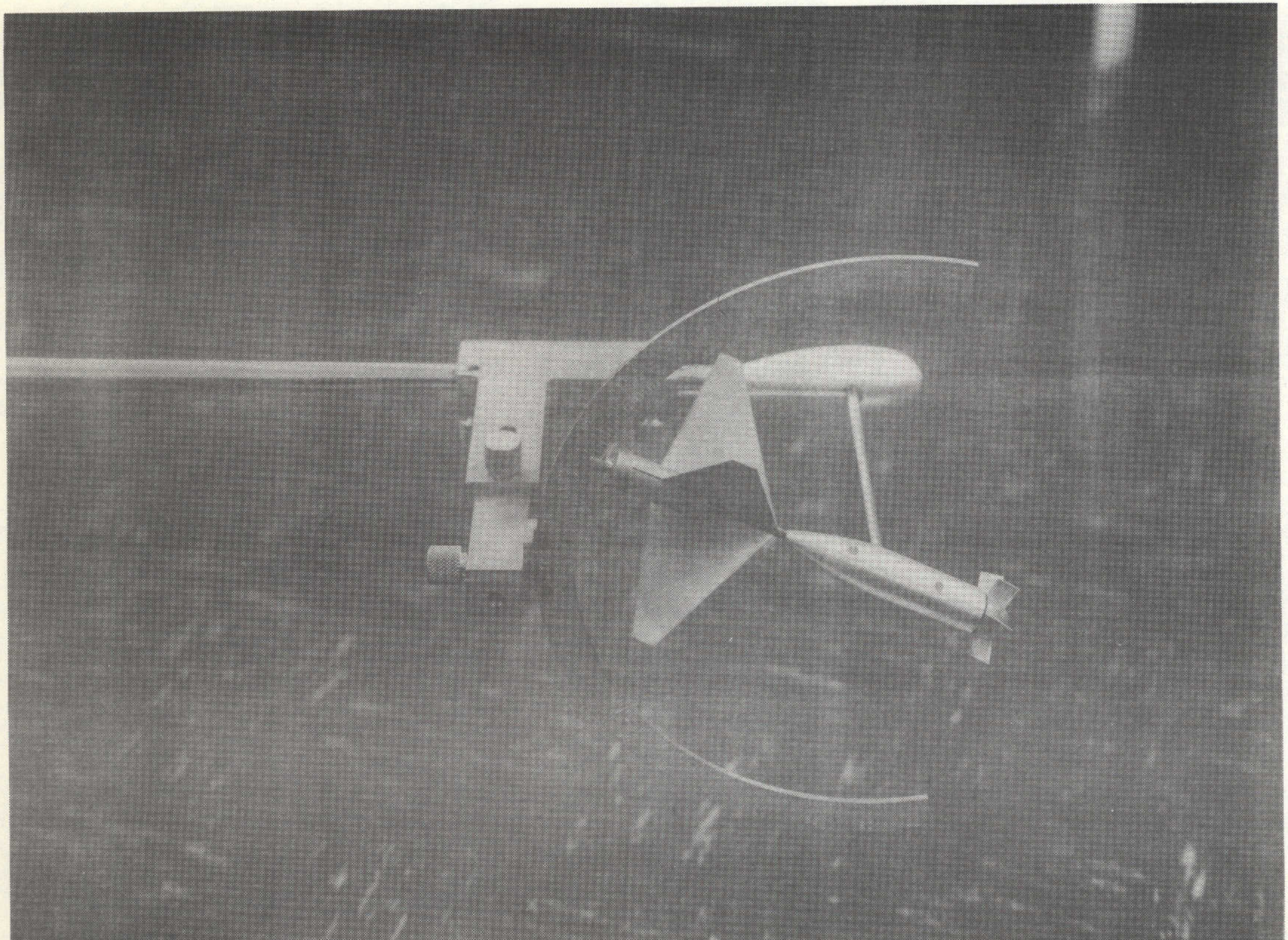


Figure C2(a). - Calibration fixture for angle-of-attack.

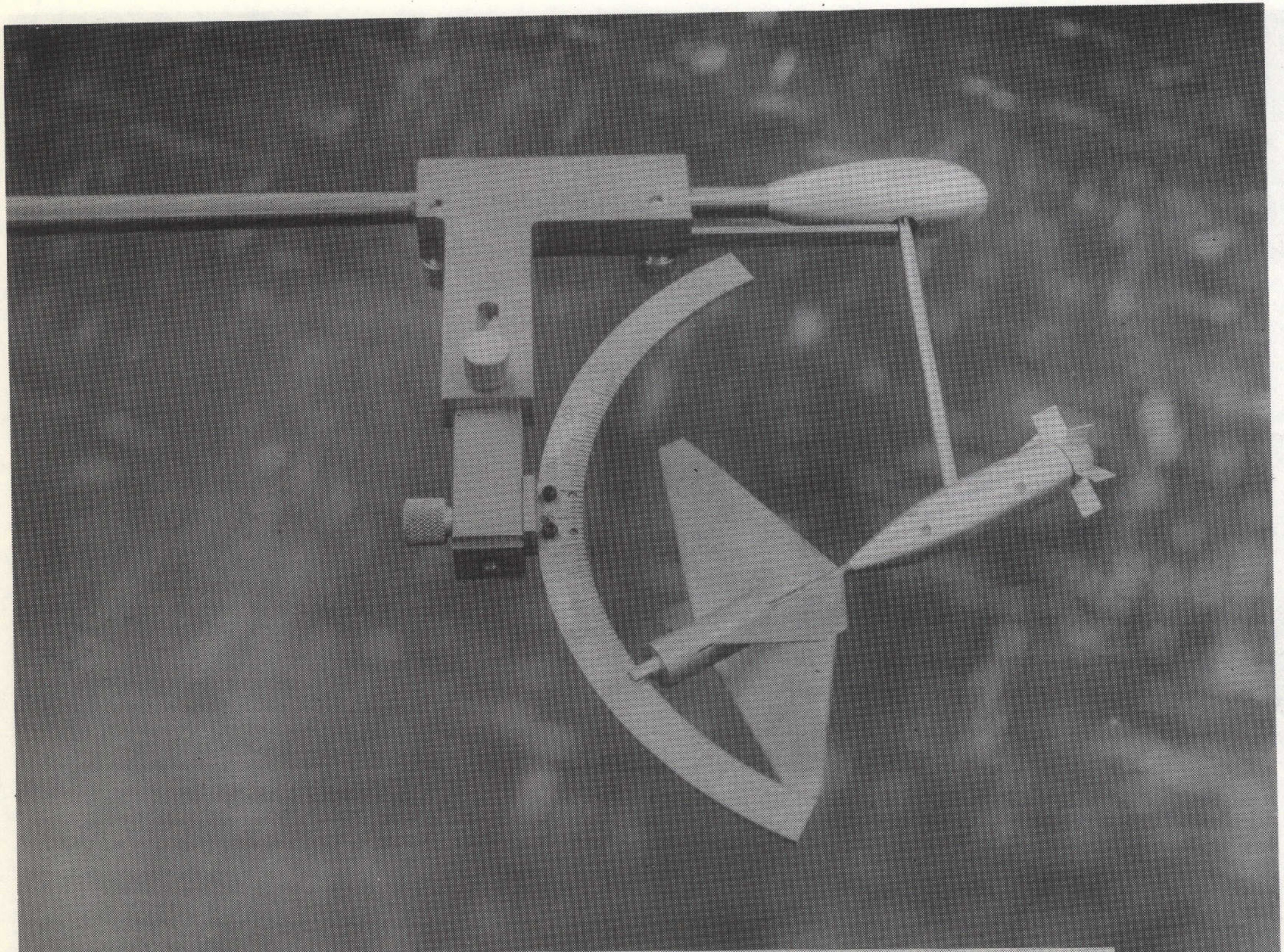


Figure C2(b). - Calibration fixture for angle-of-sideslip.

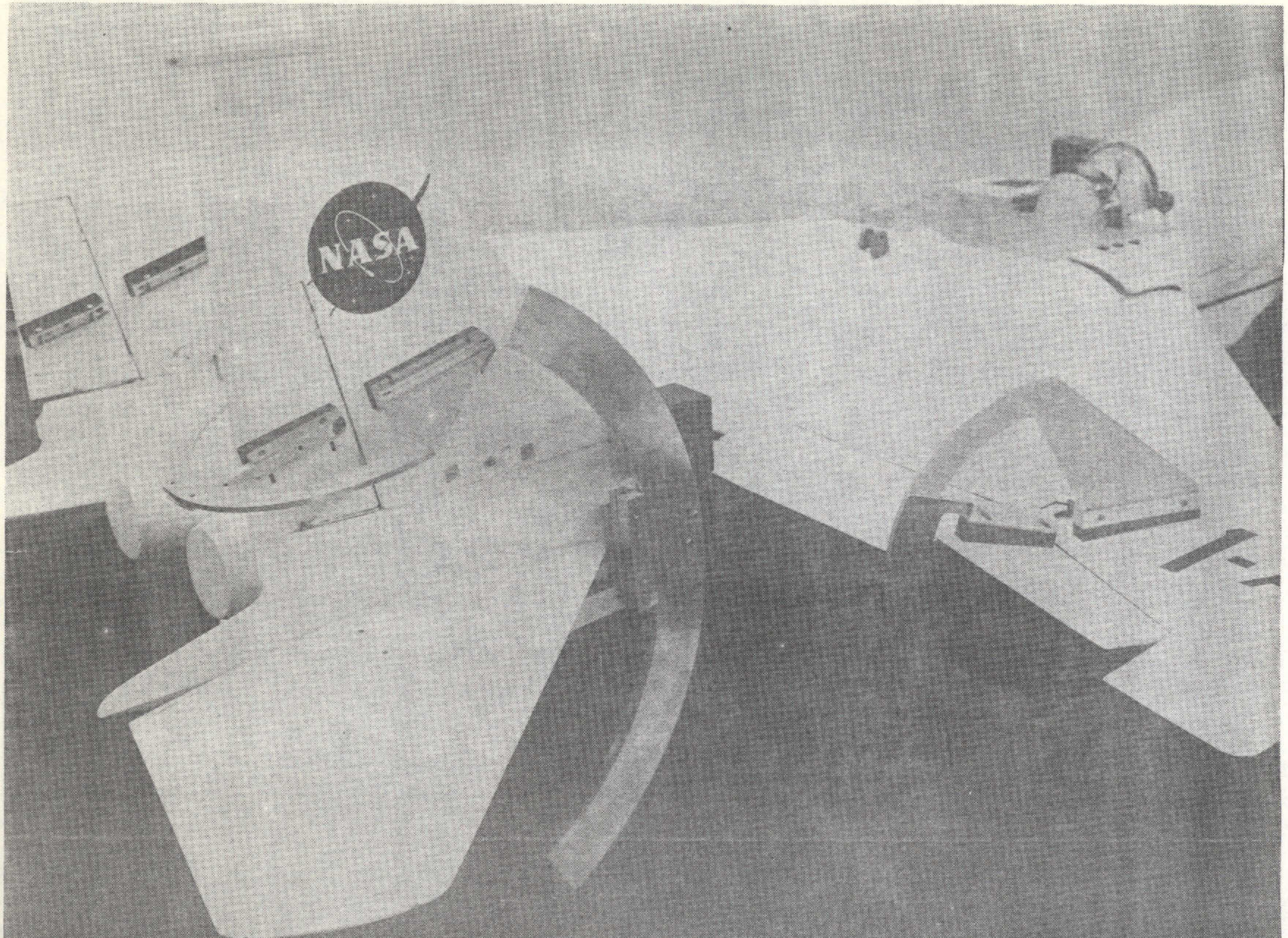


Figure C3. - Control surface protractors.