NASA Technical Paper 1146

A Rotor-Mounted Digital Instrumentation System for Helicopter Blade Flight Research Measurements

Vernie H. Knight, Jr., William S. Haywood, Jr.,
and Milton L. Williams

APRIL 1978

NASA

NASA Technical Paper 1146

A Rotor-Mounted Digital Instrumentation System for Helicopter Blade Flight Research Measurements

Vernie H. Knight, Jr., William S. Haywood, Jr., and Milton L. Williams
Langley Research Center
Hampton, Virginia

NASA
National Aeronautics and Space Administration

Scientific and Technical Information Office

1978

SUMMARY

A rotor-mounted flight instrumentation system developed by the NASA Langley Research Center for helicopter rotor blade research is described. The system utilizes high-speed digital techniques to acquire research data from miniature pressure transducers on advanced rotor airfoils which are flight tested on an AH-1G helicopter. The system employs microelectronic pulse code modulation (PCM) multiplexer-digitizer stations located remotely on the blade and in a hub-mounted metal canister. As many as 25 sensors can be remotely digitized by a 2.5-mm-thick electronics package mounted on the blade near the tip to reduce blade wiring. The electronics contained in the canister digitizes up to 16 sensors, formats these data with serial PCM data from the remote stations, and transmits the data from the canister which is above the plane of the rotor. Data are transmitted over an rf link to the ground for real-time monitoring and to the helicopter fuselage for tape recording. The complete system is powered by batteries located in the canister and requires no slip rings on the rotor shaft.

The instrumentation described provides flight measurements of blade parameters such as pressures, bending moments, temperatures, rotor angles, and rotor control forces. These experimental measurements are of value to an improved understanding of rotor performance and for advancement of helicopter blade design techniques.

INTRODUCTION

Research investigations of helicopter aerodynamics and dynamics in pursuit of advanced V/STOL technology require measurement of numerous parameters in the rotor blade system such as pressures, structural loads, and angular positions. These experimental measurements are of great value to an improved understanding of rotor performance and for advancement of helicopter blade design techniques. They also provide the flight data necessary for correlation with wind-tunnel data and theory. Furthermore, rotor blade research imposes very stringent and challenging requirements on flight instrumentation. This is due not only to the rugged environment found on the rotor blades but also to the extreme importance of minimizing any blade structural modifications or reduction in blade aerodynamic performance caused by instrumentation.

A significant development in rotor blade instrumentation has been made which provides a versatile flight data collection capability for application to helicopter research programs. The development activity centered about a new data system approach which satisfies rotor blade research measurement requirements. The system utilizes digital techniques and is characterized by the following major features:

(1) A capability to transmit data from the rotor without using an expensive slip-ring installation

(2) Development of a thin microelectronic package for digital conversion of data at a site near the sensors on helicopter blades

(3) Application of miniature, low-profile, solid-state pressure transducers for making local pressure measurements on the blade surface

(4) Development of attachment techniques for installing instrumentation on helicopter blades

This paper describes the instrumentation design concepts, the system qualification, the flight research application of the instrumentation for advanced airfoil research, and the system performance.

SYMBOLS

D	PCM digital output value (range 0 to 255 counts)
F_{db}	drag-brace force, N
F_{pl}	pitch-link force, N
g	acceleration due to gravity, 9.8 m/sec^2
M_b	blade beamwise bending moment, N-m
M_c	blade chordwise bending moment, N-m
M_t	blade torsional moment, N-m
m_a	slope of reference line between end points of PCM temperature calibration at 22° C, mV/digital increment
m_p	slope of best straight-line response of pressure sensor, mV/Pa
p	pressure, Pa
p_{ls}	lower-surface blade pressure, Pa
p_{us}	upper-surface blade pressure, Pa
Q	mast torque, N-m
T_b	blade temperature, $^\circ$C
T_{ce}	canister electronics temperature, $^\circ$C
T_{re}	remote electronics temperature, $^\circ$C
V_a	voltage value corresponding to particular PCM digital output value, mV

$V_{a,o}$ voltage value at PCM zero output and 22° C, mV

V_p sensor output voltage corresponding to particular pressure, mV

$V_{p,o}$ voltage value at zero pressure, mV

V_T voltage input value obtained from PCM temperature calibration corresponding to particular digital output value, mV

β teeter angle, deg

$\theta_{3/4}$ blade pitch angle at 3/4 of radius, deg

ψ rotor azimuth angle, deg

Subscripts:

max maximum

min minimum

Abbreviations:

A-to-D analog-to-digital

Biϕ-L biphase level

dc direct current

FS full scale

GSE ground support equipment

NRZ-L nonreturn to zero level

PCM pulse code modulation

PROM programmable read only memory

rf radio frequency

SAR successive approximation register

SYSTEM DESIGN CONCEPTS

A self-contained digital instrumentation system incorporating modern materials and technologies has been implemented for rotor blade measurements. The new system which overcomes many limitations of conventional rotor instrumentation is conceptually depicted in figure 1. All measurements are telemetered from a metal canister located on the top of the rotor hub after they have been digitally processed by microelectronic encoding stations located near groups of sensors in the rotating system. Typically, pulse code modulation (PCM) multiplexer-digitizer stations are located on the blades and in the hub-mounted canister. As many as 25 sensors can be remotely digitized on the blade. The canister digitizes up to 16 sensors, formats these measurements with serial PCM from the remote electronics, and transmits the data from the rotor. The measurements are telemetered from the rotor hub over an rf link directly to the ground where they are displayed for real-time monitoring and to the body of the helicopter where they are recorded on magnetic tape. The instrumentation system is programmable and features extensive application of microelectronics and integrated circuitry.

A digest of the data acquisition capabilities of the system is

(1) Thirty programmable measurement channels plus two frame synchronization words

(2) Frequency response up to 400 Hz per channel based on 5 samples per cycle

(3) Eight-bit analog-to-digital conversion

(4) Gain-adjustable sensor amplifiers

(5) Bit rates up to 512 kilobits/sec

(6) PCM L-band telemetry with range up to 24 km

Inclusion of rechargeable batteries and a centrifugally actuated power switch in the canister in combination with the telemetry capability provides autonomy from other systems onboard the helicopter. The completely self-contained and independent telemetry system is easily attached to the rotor; therefore an expensive and time-consuming slip-ring installation on the helicopter rotor to acquire rotor blade measurements is unnecessary. The telemetry canister is attached to the rotor hub by simple replacement of the standard rotor mast nut with a canister attachment nut.

A thin electronic blade package has been developed for direct application to helicopter blades. A package which is only 2.5 mm thick contains microelectronic amplifiers, commutators, and analog-to-digital converters. Blade wiring is significantly reduced through remote on-blade multiplexing and digital encoding. With the electronic blade package, only 8 wires are required for up to 25 miniature pressure sensors located near the blade tip, whereas conventional techniques require a minimum of 52 wires. Analog-to-digital conversion near the sensors virtually eliminates noise pickup and cross talk produced by long sensor leads. Other types of rotor blade sensors, such as strain gages to measure structural loads, can also be processed by the blade electronics or by similar multiplexer-digitizer electronics located in the hub-mounted canister.

Advanced sensor technology is employed in the new system to provide a versatile measurement capability. The system uses commercially available solid-state pressure sensors small enough to make local on-blade measurements, yet rugged enough to withstand the extremely high centrifugal acceleration levels found near the blade tip. The solid-state sensors, which are only 1.9 mm thick, use a semiconductor strain-gage bridge (see refs. 1 and 2) as the sensing element. The miniature sensors completely eliminate any requirement for pressure tubing inside the blade connecting orifices on the blade surface to larger pressure sensors mounted inside the blades and thus significantly reduce instrumentation weight and blade structural modification.

To enhance the applicability of the data system to a wide range of helicopters, a choice of two methods is provided for attaching the thin blade electronics and pressure sensors on rotor blades. The preferred method of attachment involves installing the instrumentation within the nominal airfoil coordinates. The electronics and sensors are mounted in shallow preformed cavities below the blade surface; ample structure remains to carry the flight loads. Smooth aerodynamic covers fit over the cavities and screws secure the instrumentation and covers to the blades. This method is used when no variation in nominal airfoil shape can be tolerated and typically requires special blade construction to provide the instrumentation cavities. An alternate method of installation has been developed for applications which can allow small variations in nominal airfoil shape. The electronics and sensors are attached to the airfoil surface so that no structural alteration is required, structural integrity is preserved, and the aerodynamic properties of the airfoil remain essentially unchanged. The instrumentation is bonded to the airfoil surface in a small localized area with plastic foam, epoxy fillers, and glass cloth to provide a smooth aerodynamic fairing only 2.8 mm thick. This alternate method is advantageous when pressure measurements are needed on production rotor blades in that no special blade fabrication is required. A detailed description of the technique of attaching sensors and the microelectronics to existing helicopter blades in a thin aerodynamic fairing is presented in appendix A.

SYSTEM QUALIFICATION

Extensive qualification of the instrumentation to withstand the rugged rotor environment has been accomplished in special ground and flight tests. The data system was qualified by temperature, vibration, shock, and spin tests. Since the helicopter is a piloted aircraft, the rotor blades also had to be man-rated. A set of production rotor blades were instrumented with pressure sensors and electronics. The instrumented blades were installed on the Langley helicopter rotor test facility, run up to operating speed, and thrust was applied. The instrumentation was also qualified on an OH-4A helicopter. Several qualification flights were made including straight, level, and high-speed runs and maneuvers consisting of turns, high rates of descent, and high-g pull-ups. The rotor blade instrumentation and rf transmission were verified, and the externally applied blade instrumentation was visually inspected after each test phase.

RESEARCH APPLICATION

The data system has been applied to the AH-1G helicopter, shown in figure 2, for gathering research data and for real-time monitoring on three different sets of research blades. One blade of each set was constructed with cavities and fitted with an identical set of electronics and sensors. Each blade set has a unique airfoil shape and is flight tested separately. The flight performance of the telemetry system has been excellent on 30 test flights. A general description of the AH-1G instrumentation system and the system performance follows.

The rotor flight research conducted on new blade airfoil shapes on the AH-1G helicopter requires the following measurements:

(1) Chordwise pressure distribution at one spanwise location near the blade tip to evaluate the three-dimensional unsteady flow field of the rotor blades and permit comparison with wind-tunnel data and theory

(2) Strain loads for real-time flight monitoring and correlation with theory

(3) Angular positions for data analysis

(4) Temperature measurement for data correction

Figure 3 is a block diagram of the airborne instrumentation. The AH-1G instrumentation system is programmed to provide a total of 30 measurement channels: 15 sensors are digitized on one blade and 15 additional sensors are processed in the canister. The second blade of the AH-1G helicopter is not instrumented.

The microelectronic multiplexer-digitizer station, shown in figure 4, is mounted on the bottom of the blade near the tip and provides excitation, signal conditioning, and analog-to-digital conversion for 15 sensors. Figure 5 is a photograph of the bottom of the AH-1G blade showing the location of the remote electronics and sensors. The measurements shown in figure 3 consist of 13 pressures and 1 temperature at one spanwise location, in addition to 1 temperature measurement on the remote electronics. The thin sensors and microelectronics are installed in individual blade cavities as depicted in the cross-sectional drawing of figure 6. Holes are provided in the sensor cover for sensing pressure. The excitation and signal leads of the sensors are connected to the electronics by short wires installed below the blade surface. Typically, number 25 American Wire Gage (AWG) wire is used on the blade. The millivolt-level analog signals are routed to individual amplifiers and are then sequentially sampled and converted to eight-bit binary-coded PCM words which are serially transmitted down the blade over a pair of wires to the canister mounted over the hub. Only six additional leads are required; they provide power, timing, and synchronization for the blade station.

The hub-mounted canister and instrumentation are shown in figure 7. The canister contains electronics functionally similar to the remote blade station for encoding 14 analog measurements from sensors near the hub. Also, digital timing and control electronics, batteries, transmitter, and antenna are contained in the canister. The canister multiplexer-digitizer station accepts the near-hub sensor measurements shown in figure 3 which consist of eight blade bending moments, pitch-link and drag-brace forces, mast torque, blade pitch and teeter angles, and canister electronics temperature. The rotor azimuth angle measurement is derived from a digital shaft encoder whose output is digitally processed in the canister. The canister timing and control electronics provides the clock and synchronization signals for controlling the data sampling sequence of each multiplexer-digitizer station. It also combines the two serial PCM signals representing digitally encoded eight-bit data samples from separate groups of sensors at the blade tip and near the hub with the data from the digital shaft encoder. The resulting serial PCM representing all the rotor measurements operates at a bit rate of 256 kilobits/sec.

The PCM data are transmitted by a 1-W L-band frequency-modulated transmitter and associated antenna. Reliable air-to-ground communication is obtained over a range of up to 24 km by the generation of a reasonably omnidirectional antenna pattern from the helicopter rotor and by use of a multimode diversity ground receiving system. The data are also received onboard the helicopter fuselage and are direct recorded on one track of a wide-band flight magnetic tape recorder. Figure 8 is a photograph of the fuselage instrumentation. The onboard recorder is typically operated only during flight research maneuvers to conserve tape. The speed is 76.2 cm/sec which allows up to 30 minutes of recording. For operating ranges greater than 24 km, the rf data can be retransmitted from the fuselage to the ground station by a 10-W transmitter operated from main aircraft power.

The system batteries provide capacity for 1 hour of flight. Power is turned on by the centrifugal switch when the rotor speed exceeds 114 rpm. Regulation and dc-to-dc voltage conversion of the main battery outputs are performed in the canister.

In addition to the capability to program the number of data channels at each digitizing station, the system also provides a flexibility to adjust sampling rate and individual amplifier gain. For the AH-1G helicopter, the system is configured for a sampling rate of 1000 samples per second to provide a frequency response capability up to 200 Hz per channel for each of the 30 programmed data channels. Each PCM data channel also contains a single-pole resistance-capacitance (RC) filter. The nominal 3-decibel filter frequencies are 90 Hz for the force and moment channels and 200 Hz for the pressure channels.

Table I presents a list of the rotor parameters measured and the maximum error over the flight environment. Appendix B gives a detailed description of the sensors and instrumentation subassemblies. Additional measurements to determine aerodynamic and inertial flight states are made on the helicopter fuselage by a separate instrumentation system. This additional information, along with time of day, is also recorded on the onboard tape recorder and is necessary to evaluate the data from rotor blade measurements.

INSTRUMENTATION SYSTEM PERFORMANCE

The overall accuracy of the instrumentation system over the flight environmental conditions is on the order of 1.5 percent of full scale after correction for temperature-induced errors in the pressure sensors.

Figure 9 shows the performance of a typical PCM measurement channel, exclusive of the sensor, at -1° C, 22° C, and 55° C referenced to the straight line between the end points of the 22° C data. This figure indicates the difference between the PCM system output at -1° C, 22° C, and 55° C and a straight line between the end points of the 22° C data when a reference set of voltages are input at each temperature. The maximum error including nonlinearity and zero drift does not exceed 0.5 percent of full scale over the 56° C temperature range. The full-scale range of the PCM system is 0 to 255. The data points in figure 9 were obtained from the following equations:

$$V_a = m_a D + V_{a,o} \tag{1}$$

$$\text{Error in \% FS} = \left(\frac{V_a - V_T}{255 m_a}\right) 100 \tag{2}$$

Equation (1) is the slope-intercept form of the reference line, and equation (2) gives the percent error.

Table II shows the sensor input to system output performance of a typical data channel on the AH-1G helicopter at ambient temperature. The table is for the blade pitch angle sensor and shows data which were processed from angular input at the sensor to output from the computerized data reduction. The maximum error does not exceed 0.18° out of a total range of 52°.

Figure 10 shows the performance of a typical AH-1G pressure sensor over a full-scale range of 124.1 kPa (13.78 kPa to 137.88 kPa). Figure 10(a) shows the performance of the pressure sensor during laboratory calibration at -1° C, 24° C, and 49° C referenced to the best straight line at 24° C. The data for figure 10(a) were obtained as follows. First, equations for the best straight lines were computed for each set of calibration data points at each temperature using the least-squares method. The general equation is

$$V_p = m_p p + V_{p,o} \tag{3}$$

Next, values of V_p are obtained at -1° C, 24° C, and 49° C for identical values of p. The percent error is obtained from the following equations:

$$\text{Error in \% FS at 49° C} = \left\{\frac{V_{p(49°C)} - V_{p(24°C)}}{m_{p(24°C)}\left[p_{max(24°C)} - p_{min(24°C)}\right]}\right\} 100 \tag{4}$$

$$\text{Error in \% FS at } -1^\circ \text{ C} = \left\{ \frac{V_{p(-1^\circ C)} - V_{p(24^\circ C)}}{m_{p(24^\circ C)}\left[P_{max(24^\circ C)} - P_{min(24^\circ C)}\right]} \right\} 100 \qquad (5)$$

The hysteresis at each temperature is also shown. The maximum error is approximately 5 percent of full scale due primarily to sensor zero and sensitivity shift with temperature and is representative of the state-of-the-art in semiconductor gages small enough for helicopter blade application. The combined nonlinearity and hysteresis error is less than 0.5 percent of full scale. Figure 10(b) shows the uncorrected performance of the same pressure sensor during a special thermal test and the performance after correcting the data for temperature error. The pressure sensor and a temperature sensor were placed in a temperature chamber while connected to the data recording system. Two identical levels of static pressure were applied at each temperature, and the system output was recorded for the pressure and temperature sensors. The test sequence duplicated the system preflight calibration for the pressure and temperature sensor at ambient temperature and exposed the sensors to a range of temperatures expected in flight. The temperature measurement is required for the determination of the pressure measurement. The recorded test data were computer processed to obtain the corrected data. The error after correction did not exceed 0.6 percent of full scale. The equations and procedure used to obtain the sensor data shown in figure 10(b) are presented in appendix C.

CONCLUDING REMARKS

A rotor blade telemetry instrumentation system has been developed and successfully utilized for airfoil research in a flight test program using an AH-1G helicopter. The developed telemetry system obtained satisfactory oscillating pressure and loads research measurements on helicopter rotor blades. The overall accuracy of the instrumentation system is on the order of 1.5 percent of full scale over the flight environment after correction for temperature-induced errors in the pressure sensors. The flight performance of the telemetry system has been excellent on 30 test flights.

Blade wiring has been significantly reduced through application of remote on-blade multiplexing and digital encoding, and the use of slip rings for acquiring rotor data has been eliminated.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
February 23, 1978

APPENDIX A

METHOD OF APPLYING A THIN AERODYNAMIC INSTRUMENTATION FAIRING ON HELICOPTER BLADES

A flight-qualified and flight-tested method of attaching instrumentation to the external surface of a rotor blade has been developed. This method is advantageous when measurements are needed on existing helicopter blades. The method permits attachment of the instrumentation to an airfoil surface so that no structural alteration is required, structural integrity is preserved, and aerodynamic properties of the airfoil remain essentially unaltered. Figure 11 is a photograph of a typical instrument installation on an airfoil section. Figure 12 is a cross-sectional drawing of the externally applied instrumentation on a rotorcraft airfoil.

The instrumentation is installed as follows. First, the airfoil paint is removed from the areas where the instrumentation is to be attached. The areas are cleaned, and glass fiber cloth is bonded to the airfoil by means of a fuel-resistant adhesive. The adhesive resists degradation by petroleum fuels yet provides a strippable base to facilitate ultimate removal with a solvent without damaging the helicopter blades or instrumentation. Next, cellulose acetate foam filler material is bonded by epoxy to the airfoil and trimmed to form a taper towards the edges. Areas are cut out of the foam to allow for the instrumentation. The instrumentation consists of a microelectronic printed circuit board, sensors, and interconnecting wiring. The foam is faired to the contours of the airfoil and thinned to the thickness of the instrumentation. The printed circuit board is attached with epoxy along its edges. It is held in place during curing by a nonadhering layer of scrim cloth and a vacuum bag. The bag is placed and evacuated so that a force is maintained between the surface of the blade and the bag.

The sensors are placed in their recesses in the foam and secured by self-vulcanizing silicone rubber. In the case of pressure sensors, the sensing diaphragms are installed level and flush with the foam profile. The instrumentation wiring is connected in recessed wireways and held in place with epoxy. After the wiring and instrumentation checkout is completed, the remaining voids are filled with an epoxy silica filler and worked to a smooth surface.

Finally, three layers of epoxy-resin-saturated glass fiber cloth, 25.4 μm thick, are applied, with cutouts for the instrumentation. A fourth layer is applied which covers the printed circuit board but not the sensors. Each layer is cut to overlap the preceding layer to provide a smooth transition of laminate. The entire assembly is sanded with fine abrasives to provide a smooth aerodynamic surface. An epoxy paint is applied over the glass fiber for weather protection.

The instrumentation can be removed from the blade by stripping the glass fiber cloth after softening the epoxy bond with a solvent. After the instrumentation is removed, the circuit board, sensors, and helicopter blades are reusable.

APPENDIX B

SENSORS AND INSTRUMENTATION SUBASSEMBLIES

Sensors

An example of each type of AH-1G rotor sensor is shown in figure 13. Blade pitch and teeter angles are measured with control position transducers (CPT) which are mechanically coupled to the helicopter blade. The CPT sensing element is a precision rotary potentiometer that provides approximately 360° of electrical rotation. The potentiometers are excited by a ±6 V dc regulator and have a combined hysteresis and nonlinearity of 0.2 percent of the full-scale range of the potentiometer resistance.

Rotor azimuth angle is measured by a digital shaft encoder which is mounted inside the canister assembly. The encoder is an electromechanical device that converts the shaft angle using contact closures. The contact closures are provided by brushes which ride on multiple tracks of a coded drum. Each track operates as a more familiar generator commutator with conducting and nonconducting segments arranged in a Gray code digital format. The encoder generates an eight-bit digital word by providing contact closures which sink current from +5-V logic detector circuits located in the canister. The encoder has a full-scale range of 360°. The eight-bit code divides the 360° range into 256 segments which provide rotor location in 1.4° increments. The measurement accuracy of the shaft encoder commutator is 0.3°. The encoder operates in-flight at 5.4 rps and is sampled approximately 185 times per 360° revolution. The encoder is approximately 2.5 cm in diameter and 3 cm high. A description of the mechanical installation of the shaft encoder is covered in the section "Canister Mechanical Design Features" in this appendix.

Absolute pressure measurements are made with semiconductor strain gages as the sensing elements which are connected in a four-active-arm Wheatstone bridge configuration, having approximately a 500-Ω bridge resistance. Each bridge is compensated to minimize thermal zero shift and sensitivity errors. The semiconductor gages measure strain in a beryllium-copper diaphragm which is 6.3 mm in diameter and 0.76 mm thick. The pressure sensor is bonded to a stainless steel mounting pallet 1.9 cm in diameter. The total thickness of a sensor and pallet is about 1.9 mm. The pressure sensors are excited by +4 V dc and have the following characteristics: sensitivity of 1.0 mV/kPa, temperature effect on zero of 0.06 percent full scale per °C, temperature effect on sensitivity of 0.06 percent full scale per °C, combined hysteresis and linearity error of 0.3 percent full scale, and a natural frequency of 30 kHz. The volume of the pressure sensor installation cavities is very small and has negligible effect on the desired dynamic response. The typical frequency response of the sensor is flat within 0.6 percent of the applied pressure level from dc to 200 Hz, and the natural frequency of the combined sensor and installation cavity is about 800 Hz. The filter characteristics of the cavity combined with the resistance-capacitance (RC) filter characteristic of each measurement channel provide ample attenuation of unwanted acoustical noise pressure. The sensors are held inside the rotor blade cavities by dowel pins and rubber inserts to provide negligible sensor output due to strain produced by the rotor blade bending. The sensors are also unaffected by the operational acceleration levels near the blade tip. Excitation and signal wires for the pressure sensors interface directly with the remote microelectronic blade station.

Moment and force measurements are made with approximately 0.08-mm-thick metal-foil strain gages (see ref. 2) connected in a four-active-arm Wheatstone bridge arrangement. Strain gages are installed on the helicopter blade at various locations to measure bending moments. Three additional structural members are instrumented with strain gages. The first is the rotor mast for measuring mast torque, the second is the rotor blade pitch link for measuring applied force, and the third is the rotor drag brace for measuring applied force. The individual strain gages within each four-active-arm bridge are matched for equal resistance to provide negligible thermal zero shift and sensitivity shift. The gages are excited by a ±6 V dc regulator and have the following characteristics: bridge resistance of 350 Ω ± 1 percent, gage factor of 2.0, ±0.1-percent nonlinearity, and ±0.15-percent hysteresis. Leads from the moment gages are run down the top of the blade to a connector located on the blade close to the hub. Power and signal leads for the moment and force sensors interface with the canister electronics. Offset resistors are added to each Wheatstone bridge measuring circuit as required to obtain the desired quiescent signal operating point.

Temperatures are measured with a single active temperature-sensitive element and three fixed resistors mounted together to form a Wheatstone bridge sensor. Two of the sensors measure temperature near the blade tip and use a nickel resistive sensing element. The first, which measures blade temperature near the pressure transducers, is mounted on a metal pallet 1.9 cm in diameter. The total thickness of sensor and pallet is 1.9 mm. The second sensor is bonded to the remote multiplexer-digitizer printed circuit board and measures electronics temperature. Both sensors interface with the remote electronic station and operate from +4 V dc. A third sensor which uses a silicon thermistor active element is mounted on a canister printed circuit board and measures canister internal temperature. It interfaces with the canister electronics and is excited by ±6 V dc. The sensitivity of the sensors is set at approximately 0.8 mV/°C, and there is no discernible hysteresis. The sensors are capable of measuring temperature at their mounting location within ±1.0° C.

Remote Multiplexer-Digitizer Station

Under control of the hub-mounted canister, the remote blade-mounted electronics shown in figure 4 provides excitation, amplification, sampling, and analog-to-digital (A-to-D) conversion of 15 AH-1G sensors. The data are returned to the canister as a serial nonreturn to zero level (NRZ-L) PCM train and become channels 1 to 15 of the master PCM frame. Figure 14 is a block diagram of the remote multiplexer-digitizer.

Capability is provided to accommodate millivolt-level signals from up to 25 sensors. Each channel has its own signal conditioning amplifier which contains a single-pole RC filter. Gain, offset, and frequency response of each channel are individually adjusted to maintain the analog signal within the desired operating range. Each amplifier output is applied to a separate voltage level comparator with sampling accomplished by digital multiplexers which sequentially select the appropriate comparator. An eight-bit A-to-D conversion is made with a successive approximation register (SAR). The SAR controls a resistive ladder network whose output is buffered and applied as a reference for all the individual channel comparators. The conversion is implemented by successively comparing the reference feedback voltage with the amplified sensor voltage one bit at a time beginning with the most significant bit. The output of the A-to-D converter is a serial NRZ-L PCM train of eight-bit binary-coded data words representing the analog data sampled by the blade station electronics.

The remote station accepts regulated ±15 V dc and unregulated +5 V dc from the canister for the analog and digital circuitry and generates regulated +4 V dc for sensor excitation and reference voltage for the A-to-D converter. It also accepts clock and synchronization signals from the canister and generates timing and control signals for channel sampling and A-to-D conversion. The remote station is 17.8 cm by 25.4 cm. It is 2.5 mm thick and weighs 0.156 kg.

Canister Multiplexer-Digitizer Station

The canister-mounted multiplexer-digitizer station provides amplification, sampling, and analog-to-digital conversion of 14 AH-1G transducers connected directly to the canister. The data are converted to a serial NRZ-L PCM train and become channels 16 to 29 of the master PCM frame. Figure 15 is a block diagram of the canister multiplexer-digitizer; the electronics is contained on two printed circuit boards shown in figure 7.

The canister station can accept millivolt-level signals from a maximum of 16 sensors. Each signal is amplified by a gain-adjustable instrumentation amplifier and applied to the input of a 16-channel analog multiplexer. Each amplifier channel also contains an adjustable single-pole RC filter. A-to-D conversion is accomplished on each of the signals by first buffering the multiplexer output and then applying the multiplexed signals to an A-to-D converter. The A-to-D converter contains an internal voltage comparator and ladder network and operates on the successive approximation principle. The output of the A-to-D converter is a serial NRZ-L PCM train of eight-bit binary-coded data words representing the analog data sampled by the canister electronics. The analog multiplexer sampling sequence and the A-to-D conversion are under control of the canister master timing and control electronics.

The canister multiplexer-digitizer station requires regulated ±15 V dc for the analog circuitry, regulated ±6 V dc for sensor excitation and reference voltage for the canister A-to-D converter, and unregulated +5 V dc for the digital circuitry.

APPENDIX B

Master Timing and Control

The system master timing and control electronics is contained on one of the canister printed circuit boards shown in figure 7. Figure 16 is a master timing and control diagram. A crystal-controlled oscillator generates a 1024-kHz clock signal which is divided by 4 to produce a 256-kHz bit rate clock. The bit rate clock is further divided to produce word rate, frame rate, bit count, and word address. For the AH-1G system, there are 32 words per frame and 1000 frames per second. An optional bit rate of 512 kHz can be selected in the countdown timing generator. Lower bit rates can also be obtained by utilization of a lower master clock frequency.

A programmable read only memory (PROM) is used to program the combination of data channels and control the system timing. The PROM is sequenced by the word addresses from the clock countdown timing generator. The PROM also controls the generation of two frame synchronization words. The system provides a multiplexer-digitizer capability for 30 channels - any combination of up to 25 remote channels and up to 16 canister channels. The AH-1G system is programmed for a combination of 15 remote channels, 15 canister channels, and 2 frame synchronization words.

Output control signals are sent to both the canister and the remote multiplexer-digitizer stations. The canister station receives bit and word rate clocks for controlling the A-to-D converter and four discrete binary bits for cycling the analog multiplexer switch. The remote station receives a bit rate clock and a master frame rate reset pulse to control the remote channel sampling and A-to-D conversions.

Serial NRZ-L digital data from both the canister and the remote multiplexer-digitizer stations and parallel data from the azimuth angle shaft encoder are accepted by the master timing and control electronics to form a master serial PCM frame. Under PROM control, a complete 32-word frame is generated as follows:

(1) Fifteen remote station analog channels are synchronized, sampled, and converted to serial digital words during time slots 1 to 15 of the main frame.

(2) Fourteen canister station analog channels are synchronized, sampled, and converted to serial digital words during time slots 16 to 29.

(3) The azimuth angle digital sensor is converted from parallel Gray code to offset binary and is output serially during time slot 30.

(4) Data combiner gates select, at the proper time, serial words 16 to 29 from the canister A-to-D converter, word 30 from the digital shaft encoder, and words 31 and 32 from the PCM frame synchronization generator.

(5) The resulting words 16 to 32 are merged by the master data combiner gates with words 1 to 15 from the remote blade station to form the complete

PCM main frame. The combined 256-kilobit NRZ-L data are converted to biphase level (Biϕ-L) code and sent to the transmitter located in the canister.

The master timing and control logic circuits require unregulated +5 V dc in addition to regulated -9 V dc for the PROM.

Airborne Telemetry and Data Recording

PCM data are telemetered from the rotor to the ground and to the helicopter fuselage where they are received and recorded on the magnetic tape recorder. Figure 7 shows the transmitter and its associated antenna. Figure 8 is a photograph of the receiver and tape recorder. Figure 17 is a photograph of the fuselage-mounted receiving antenna.

The transmitter is 8.3 cm by 3.4 cm by 5.7 cm and has an output power of 1 W. It operates directly from the 28-V battery and requires 16 W. The transmitter is an L-band frequency-modulation type with the following characteristics: rf power output of 1 W, carrier deviation of ±600 kHz, frequency response from 10 Hz to 1 MHz, and deviation sensitivity of ±200 kHz/V peak to peak. The transmitting antenna, mounted on the top of the canister, is a quarter-wave monopole spike which provides an omnidirectional radiation pattern in the azimuthal plane. The antenna is approximately 1.3 cm in diameter and 5.1 cm high.

The fuselage-mounted L-band receiver has an input sensitivity of -85 decibels below a 1-mV level and an output sensitivity of 0.01-V peak per kHz deviation. The unit is 4.4 cm by 17.8 cm by 8.3 cm. The receiver operates from 28 V dc and requires 3.5 W. The receiving antenna is a low-profile type which is mounted on the top of the cockpit canopy and conforms to the exterior surface. The antenna consists of a microstrip disk which is constructed on a 0.16-cm-thick laminate material. The rf characteristics of the antenna are equivalent to a quarter-wave monopole spike which provides an omnidirectional receiving pattern in the azimuthal plane.

The fuselage-mounted magnetic tape recorder is a 14-channel analog unit which meets the Inter-Range Instrumentation Group (IRIG) Telemetry Standards (ref. 3) for Wideband II direct recording. The recorder is operated at 76.2 cm/sec for a maximum of 30 minutes and provides a bandwidth from 400 Hz to 500 kHz. The recorder can operate at six speeds between 4.76 cm/sec and 152.4 cm/sec. The recorder is approximately 40.6 cm by 30.5 cm by 12.7 cm. In order to avoid errors caused by bit jitter due to variations in tape speed during recording and playback, the Biϕ-L code was selected for the PCM output data. The Biϕ-L code has a transition density of at least one transition per bit time which enables the data processing station to lock on the reproduced PCM data during playback of the flight tape and maintain frame synchronization in the presence of bit jitter caused by variations up to 3 percent. The power spectral density of the Biϕ-L code has no dc frequency component; thus, the need for a tape recorder having dc frequency response is eliminated. The bandwidth normally allocated for Biϕ-L data is twice the PCM bit rate. Thus, a tape recorder covering the bandwidth of 400 Hz to 500 kHz was compatible with the bit rate of 256 kilobits/sec.

APPENDIX B

Power Distribution

Flight power for the instrumentation is provided by a nickel-cadmium battery power supply located in the bottom of the canister. The battery contains 18 cells rated at 1.5-A-hr capacity and 11 cells rated at 3.5-A-hr capacity. The batteries are connected in series to produce +5 V, +12 V, +28 V, and -6 V. The batteries are packaged in a balsa wood container which is shown in figure 7. Figure 18 is a simplified diagram of the power distribution system. During ground checkout operations, power can be supplied to the electronics from either the internal batteries or through an umbilical cable from external power supplied under control of the ground support equipment (GSE). The system is turned on by a centrifugal switch mounted in the canister when the rotor speed exceeds 114 rpm. System voltage regulation and dc-to-dc conversion are performed in the canister with the exception of +4 V dc which is regulated in the remote electronics for the blade station sensors and A-to-D converter reference. The regulated voltages generated in the canister are ±6 V dc for canister sensor excitation and A-to-D converter reference, ±15 V dc for all system analog circuitry, and -9 V dc required by the PROM. The system logic circuits and the transmitter are powered by unregulated battery voltage of +5 V and +28 V, respectively. The battery outputs are protected from overload by fuses.

Canister Mechanical Design Features

The canister and its instrumentation are shown in figure 7. The canister contains three printed circuit boards, the battery power supply, the transmitter, and the antenna. The batteries are packaged in the bottom of the canister to provide a low center of gravity. The printed circuit boards and transmitter are assembled on a metal baseplate and mounted over the top of the battery. The canister design permits easy installation and removal of electronics and batteries through the top cover for setup, maintenance, and battery charging. Electrical connectors provide quick connection or separation of the canister electrical-mechanical interface. The canister also contains the umbilical interface connector for external power operation and internal/external control.

A simplified drawing of the canister mechanical assembly excluding the electronics and batteries is shown in figure 19. Figure 20 is a photograph of the canister mounted on the AH-1G rotor. The canister, approximately 26.7 cm in diameter and 18.4 cm high, is attached to a support assembly which is approximately 7.6 cm in diameter and 14.8 cm high. The canister and support assembly are attached to the rotor by a special nut which replaces the standard AH-1G rotor mast nut and is screwed onto the rotor mast. The base of the attachment nut is approximately 10.4 cm in diameter and 5.7 cm high. The complete canister assembly including electronics and batteries weighs 13.4 kg.

The digital shaft encoder housing is mounted inside the canister support assembly. The canister, support assembly, and encoder housing turn with the rotor. The shaft of the encoder is held stationary by a spacer shaft which is connected to a nonrotating standpipe. The standpipe is a hollow tube attached to the bottom of the helicopter transmission and extends through the hollow rotor mast. The standpipe has a vertical slot which couples with a shear pin in the spacer.

Preflight Calibration

An abbreviated calibration procedure is performed on the instrumentation prior to each flight. The procedure consists of recording on the aircraft tape recorder the system digital values corresponding to (1) an "ambient" reading of all sensor channels, (2) two levels of applied pressure for each pressure sensor, and (3) a shunt resistor calibration of the moment and force sensors. The preflight calibrations are used during data reduction to correct the sensors for any long-term drift and to correct the pressure sensors for any temperature errors which occur in flight.

APPENDIX C

DERIVATION OF EQUATIONS AND PROCEDURE FOR

PRESSURE SENSOR DATA REDUCTION

Symbols

The following list includes symbols which are used in this appendix. Some of them were defined in the main text and are redefined here for completeness.

D PCM digital output value (range 0 to 255 counts)

m_1 slope representing sensor response at preflight calibration temperature, Pa/mV

$m_1(T)$ slope representing sensor response at any temperature, Pa/mV

Δm_1 change in m_1 per change in temperature for pressure sensor

m_2 slope representing PCM electronic response, mV/digital increment

p pressure, Pa

p_i input pressure, Pa

p_o pressure which produces zero output from sensor at preflight calibration temperature, Pa

$p_o(T)$ pressure which produces zero output from sensor at any temperature, Pa

Δp_o change in p_o per change in temperature for pressure sensor, Pa

$p(T)$ corrected pressure at any temperature, Pa

p_u uncorrected pressure, Pa

T temperature of sensing element for which temperature coefficients are available, ^{o}C

ΔT difference in temperature between preflight calibration condition and actual temperature at time of measurement for sensor, ^{o}C

ΔT_r temperature differential between two data sets utilized to obtain a correction coefficient, ^{o}C

V input to PCM electronics required to produce particular output count, mV

V_o input to PCM electronics which produces zero digital output value, mV

APPENDIX C

Equations and Procedure

The general equation for the pressure sensor is

$$p = m_1 V + p_o \tag{C1}$$

where m_1 is the slope and p_o is the zero intercept as depicted in figure 21. The equation for the PCM electronics is

$$V = m_2 D + V_o \tag{C2}$$

The equation for the pressure sensor at any temperature is

$$p(T) = m_1(T)V + p_o(T) \tag{C3}$$

Assume a linear variation in slope and zero intercept with temperature. Let

$$m_1(T) = m_1 + \Delta m_1 \; \Delta T \tag{C4}$$

and let

$$p_o(T) = p_o + \Delta p_o \; \Delta T \tag{C5}$$

Obtain $p(T)$ by substituting equations (C2), (C4), and (C5) in equation (C3) and expanding:

$$\begin{aligned} p(T) &= (m_1 + \Delta m_1 \; \Delta T)(m_2 D + V_o) + p_o + \Delta p_o \; \Delta T \\ &= (m_1 + \Delta m_1 \; \Delta T) m_2 D + p_o + \Delta p_o \; \Delta T + (m_1 + \Delta m_1 \; \Delta T) V_o \\ &= (m_1 m_2 + m_2 \; \Delta m_1 \; \Delta T) D + (p_o + m_1 V_o) + \Delta p_o \; \Delta T + \Delta m_1 \; \Delta T \; V_o \end{aligned} \tag{C6}$$

The preflight calibration procedure for the pressure sensors resulted in the direct determination of the product $(m_1 m_2)$ and the sum $(p_o + m_1 V_o)$. The values of m_2 and V_o are determined from laboratory calibration of the PCM electronics. Two sets of values of Δm_1 and Δp_o were obtained from the best straight-line sensor calibrations. One set was computed for the temperature range from -1^o C to 24^o C as follows:

$$\Delta m_1 = \frac{m_1(24^o C) - m_1(-1^o C)}{\Delta T_r} \tag{C7}$$

$$\Delta p_o = \frac{p_o(24^\circ C) - p_o(-1^\circ C)}{\Delta T_r} \tag{C8}$$

A second set was obtained for the range from 24° C to 49° C. The uncorrected pressures are obtained by setting ΔT equal to zero in equation (C6). The correction procedure requires that ΔT be computed first and then substituted in equation (C6) with the appropriate Δm_1 and Δp_o to obtain the corrected pressures. The data shown in figure 10(b) were obtained from the following equations:

$$\text{Uncorrected error in \% FS} = \left(\frac{p_i - p_u}{\text{FS pressure}}\right)100 \tag{C9}$$

$$\text{Corrected error in \% FS} = \left(\frac{p_i - p(T)}{\text{FS pressure}}\right)100 \tag{C10}$$

REFERENCES

1. Dean, Mills, III; and Douglas, Richard D., eds.: Semiconductor and Conventional Strain Gages. Academic Press, Inc., 1962.

2. Kottkamp, E.; Wilhelm, H.; and Kohl, D.: Strain Gauge Measurements on Aircraft. Volume 7 of AGARD Flight Test Instrumentation Series, K. C. Sanderson and A. Pool, eds., AGARD-AG-160, Vol. 7, Apr. 1976.

3. Telemetry Working Group: Telemetry Standards - Revised January 1971. [IRIG] Doc. 106-71, Range Commanders Counc.

TABLE I.- AH-1G INSTRUMENTATION SYSTEM MEASUREMENTS

Channel number	Measurement	Range	Maximum error
1	p_{us}	8.7 to 144.8 kPa	2.04 kPa
2	p_{ls}	16.5 to 136.0 kPa	1.79 kPa
3	p_{us}	11.8 to 127.2 kPa	1.73 kPa
4	p_{ls}	26.1 to 132.2 kPa	1.59 kPa
5	p_{us}	23.0 to 118.5 kPa	1.43 kPa
6	p_{ls}	22.2 to 130.8 kPa	1.63 kPa
7	T_{re}	0° to 80° C	1° C
8	p_{us}	16.9 to 115.5 kPa	1.48 kPa
9	p_{ls}	38.1 to 116.4 kPa	1.17 kPa
10	T_b	0° to 80° C	1° C
11	p_{us}	33.8 to 114.0 kPa	1.2 kPa
12	p_{ls}	46.1 to 121.4 kPa	1.13 kPa
13	p_{us}	48.8 to 119.9 kPa	1.07 kPa
14	p_{ls}	44.7 to 118.6 kPa	1.11 kPa
15	p_{ls}	47.6 to 126.8 kPa	1.19 kPa

TABLE I.- Concluded

Channel number	Measurement	Range	Maximum error
16	$\theta_{3/4}$	40° to -12°	0.78°
17	β	12° to -12°	0.3°
18	F_{db}	16.9 to -12.5 kN	0.44 kN
19	Q	30.5 to -9.3 kN-m	0.60 kN-m
20	F_{pl}	14.2 to -16.9 kN	0.47 kN
21	M_c	27.1 to -9.9 kN-m	0.55 kN-m
22	M_c	45.2 to -26.0 kN-m	1.07 kN-m
23	M_b	9.0 to -9.9 kN-m	0.28 kN-m
24	M_b	3.6 to -2.8 kN-m	0.10 kN-m
25	M_b	3.2 to -3.4 kN-m	0.10 kN-m
26	M_b	0.4 to -4.5 kN-m	0.07 kN-m
27	M_b	3.2 to -1.4 kN-m	0.07 kN-m
28	M_t	2.8 to -1.0 kN-m	0.06 kN-m
29	T_{ce}	0° to 80° C	1° C
30	ψ	0° to 360°	0.3°

TABLE II.- AH-1G DATA SYSTEM STATIC PERFORMANCE FOR BLADE PITCH ANGLE CHANNEL

Input, deg	Output, deg	Error	
		Absolute, deg	Percent of full scale
39.22	39.40	0.18	0.35
33.19	33.25	.06	.12
28.40	28.47	.07	.13
24.55	24.48	-.07	.13
20.35	20.50	.15	.29
16.82	16.93	.11	.21
13.45	13.31	-.14	.27
9.57	9.68	.11	.21
6.15	6.23	.08	.15
2.75	2.78	.03	.06
-.63	-.67	-.04	.08
-4.05	-4.12	-.07	.13
-7.48	-7.57	-.09	.17
-11.86	-11.94	-.08	.15

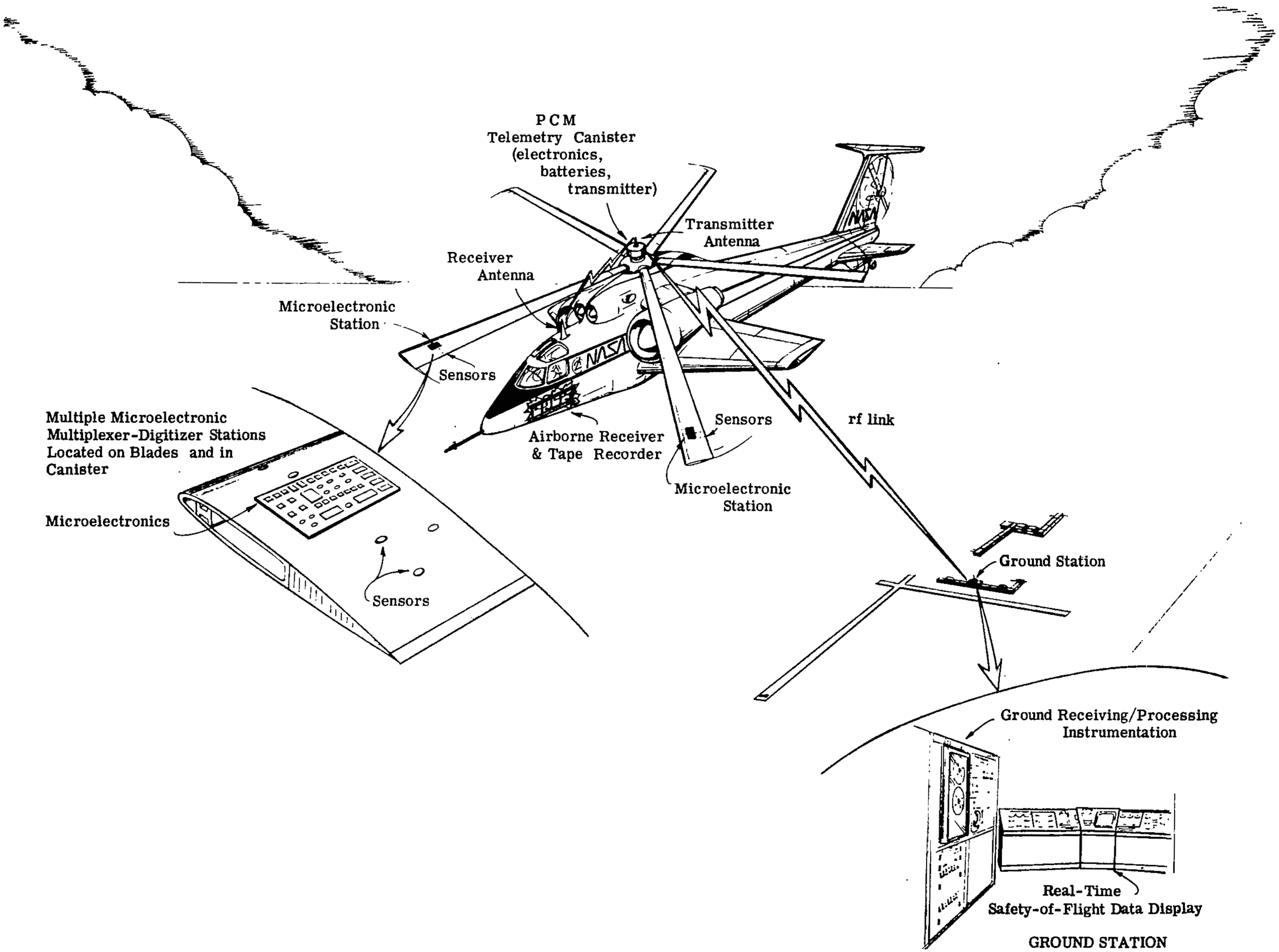


Figure 1.- Helicopter rotor-mounted instrumentation system concept.

L-76-5213.1

Figure 2.- AH-1G research helicopter.

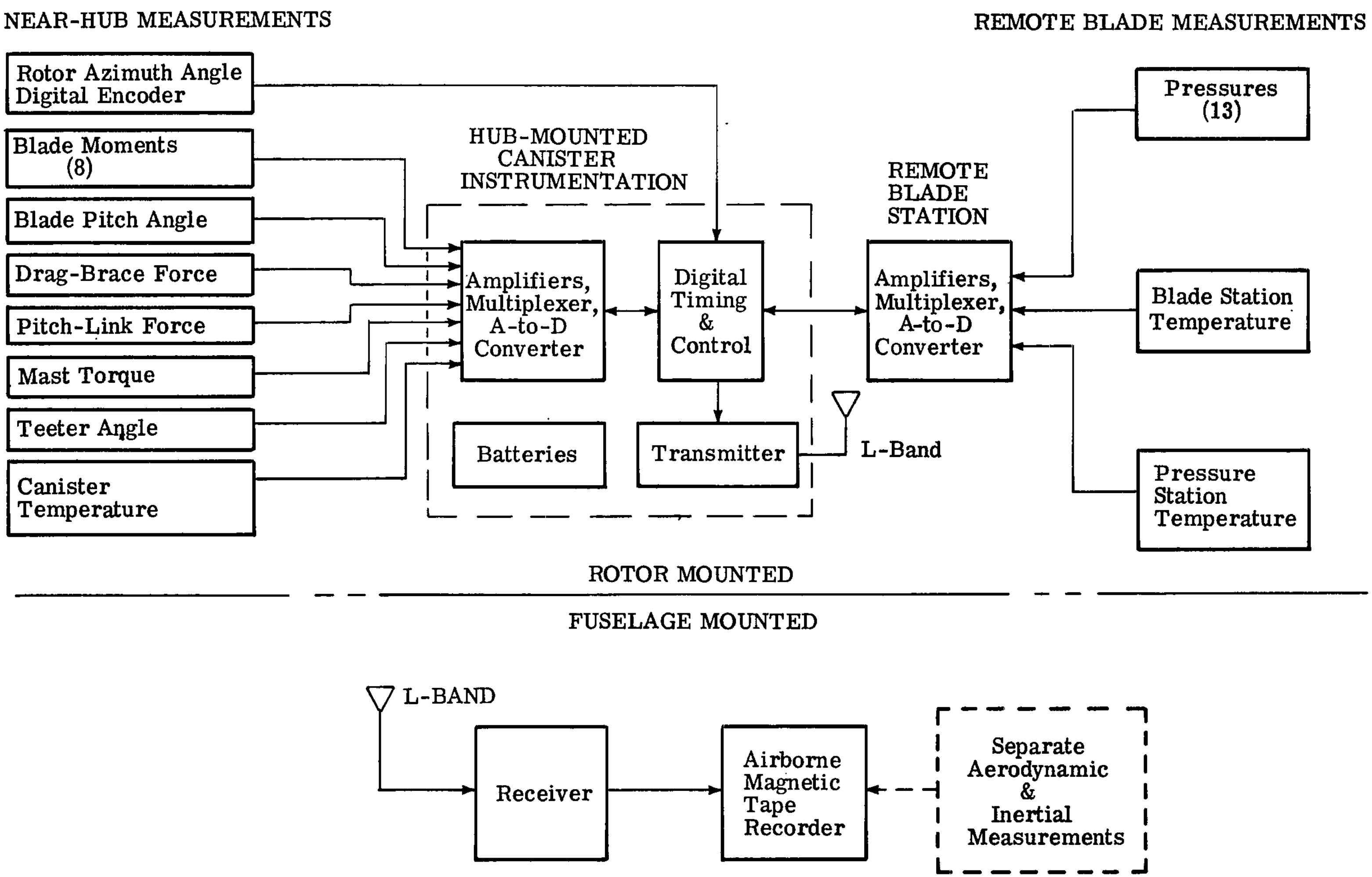
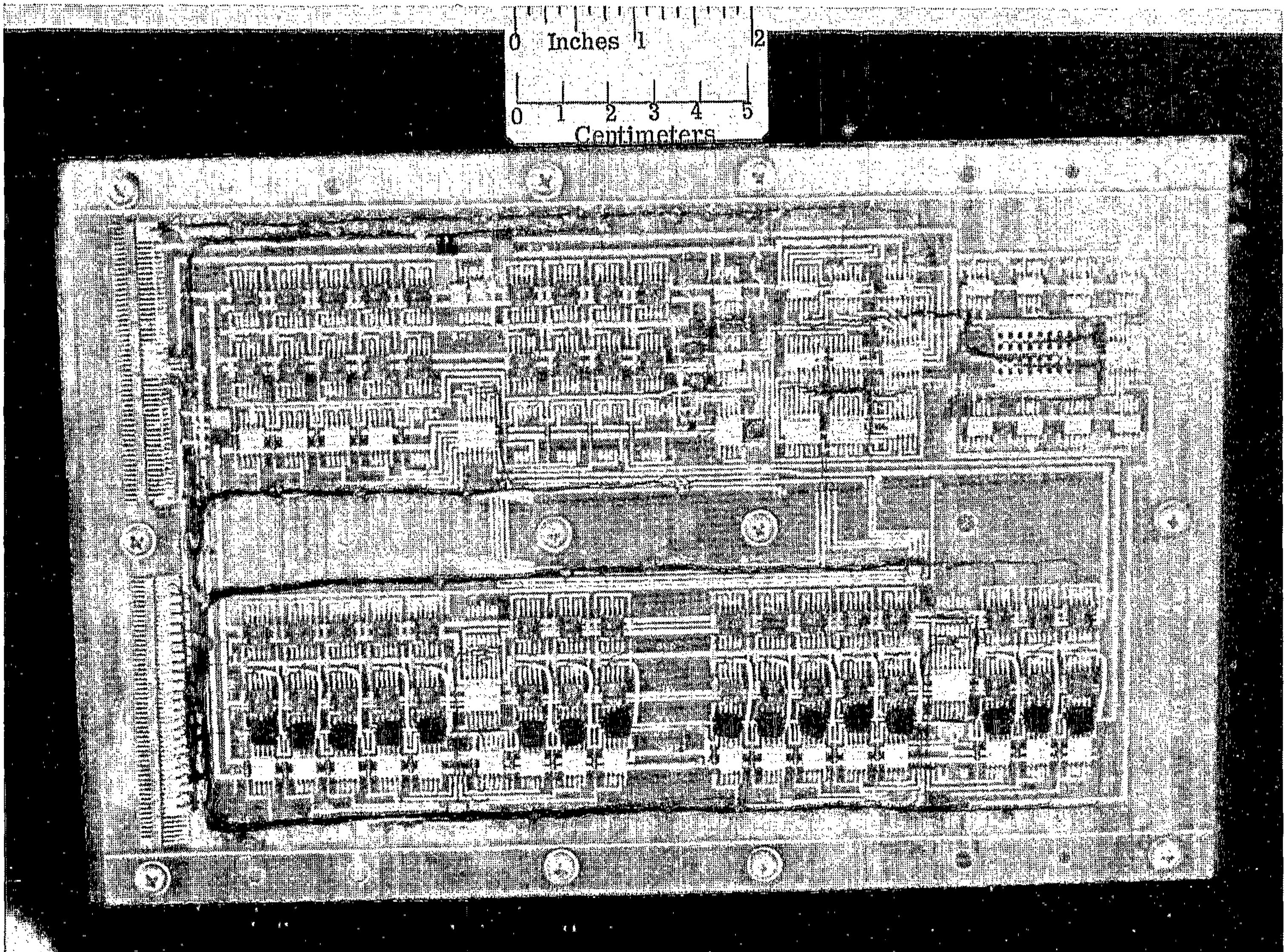
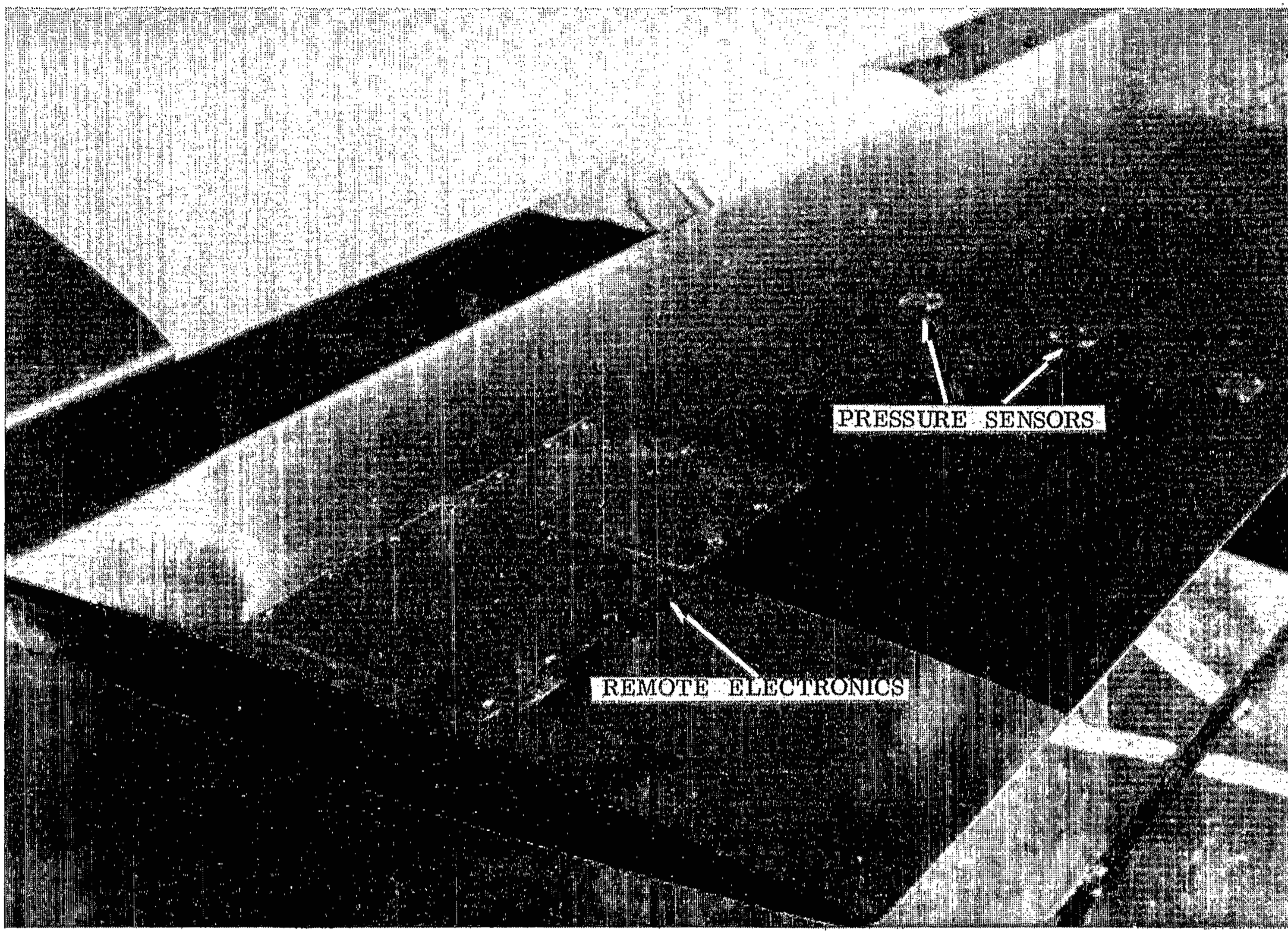


Figure 3.- Block diagram of AH-1G airborne instrumentation system.



L-75-5397.1

Figure 4.- Microelectronic multiplexer-digitizer blade station.



L-75-7755.1

Figure 5.- Location of remote electronics and pressure sensors on AH-1G blade.

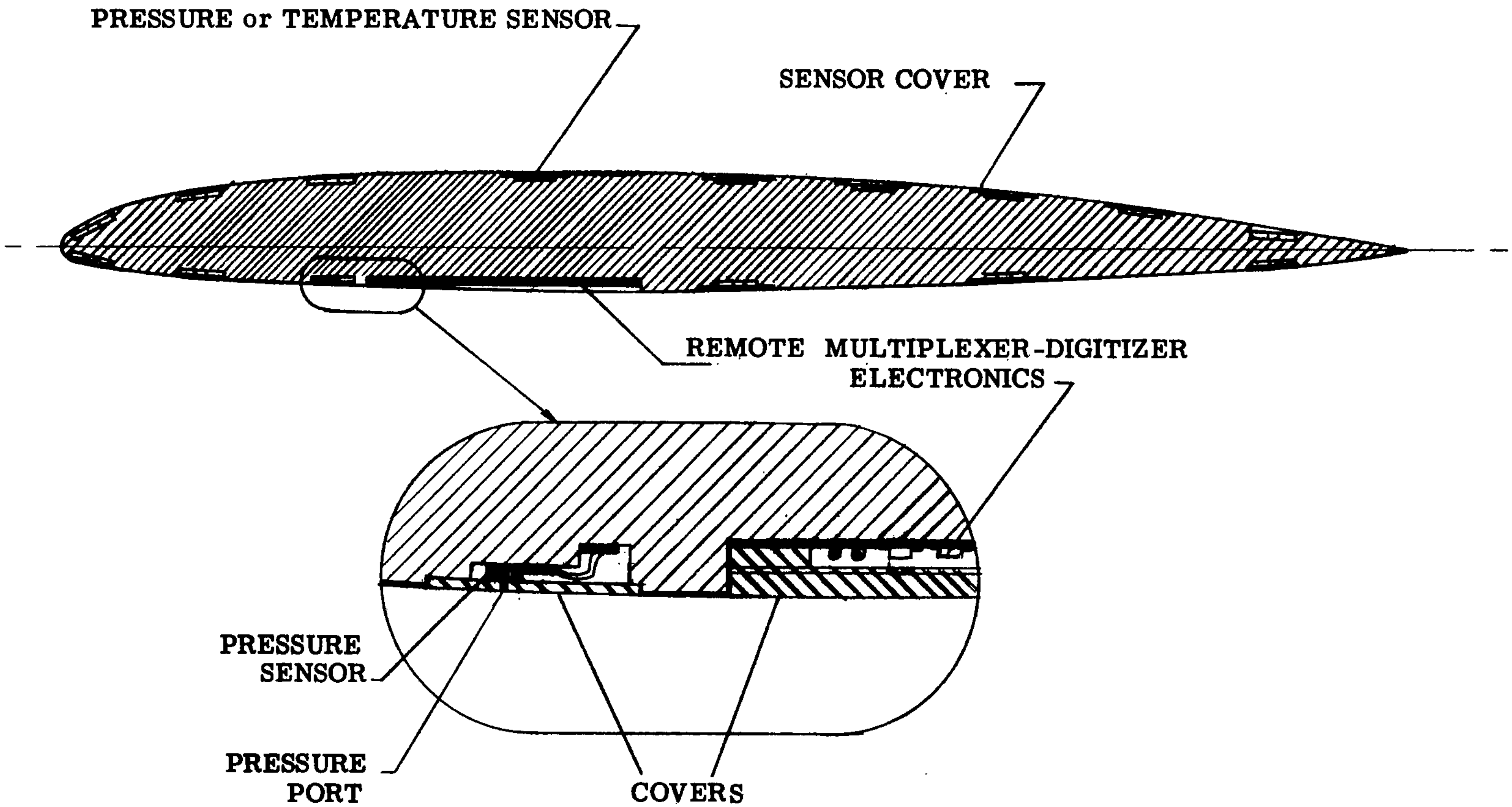
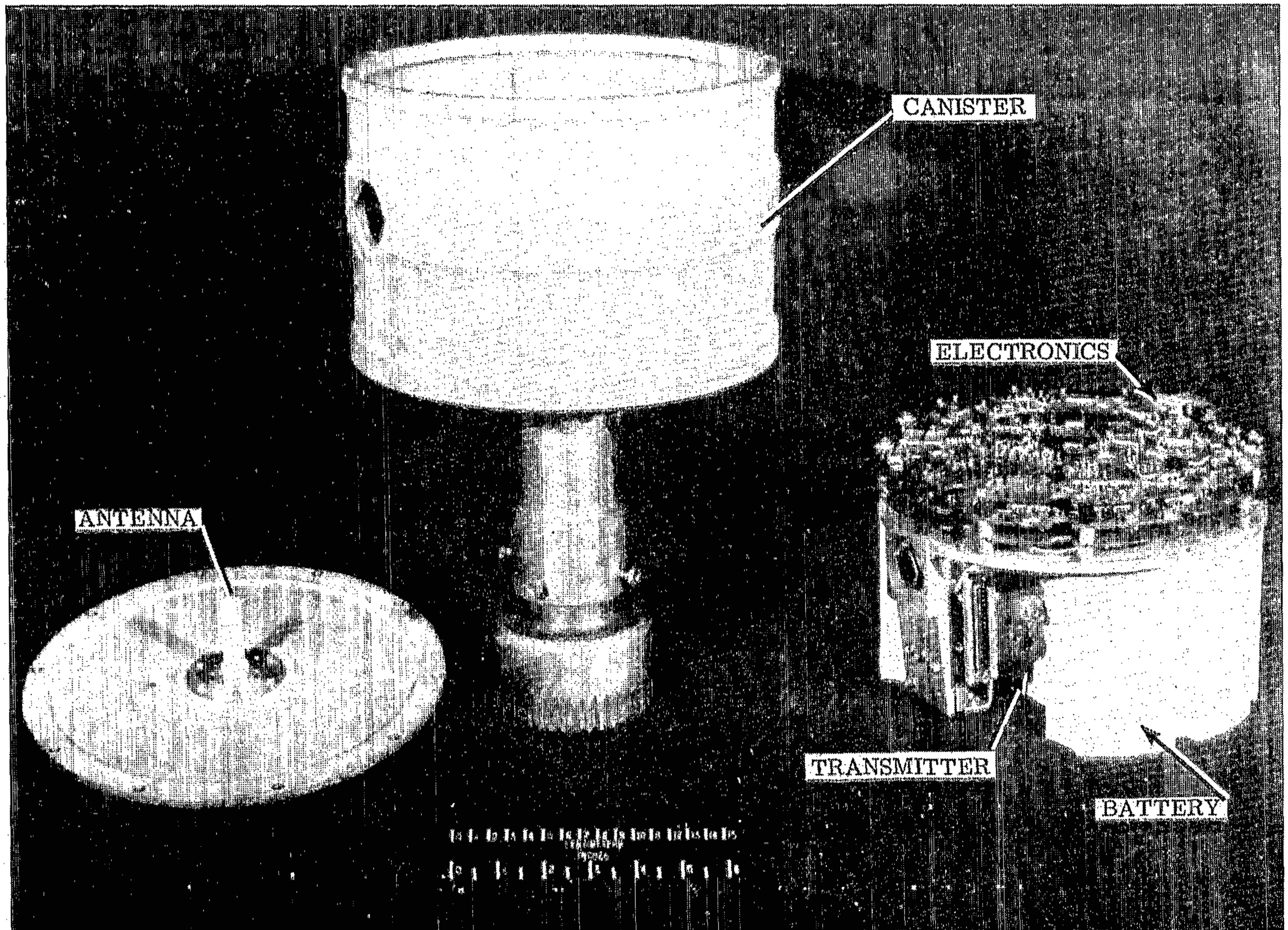
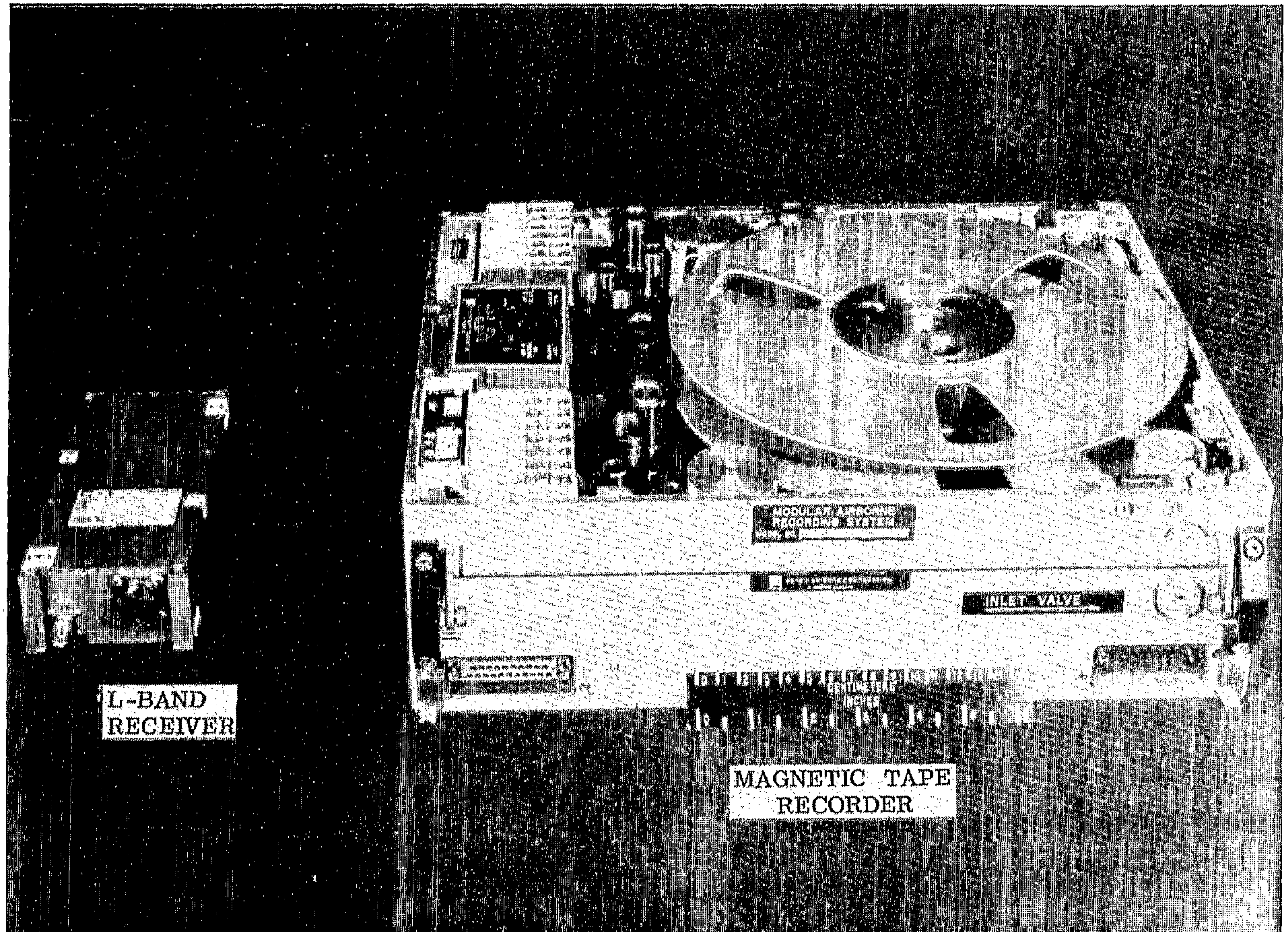


Figure 6.- Cross section of AH-1G helicopter blade with tip instrumentation in cavities.



L-77-2648.1

Figure 7.- Hub-mounted canister and instrumentation.



L-77-2645.1

Figure 8.- Fuselage-mounted instrumentation.

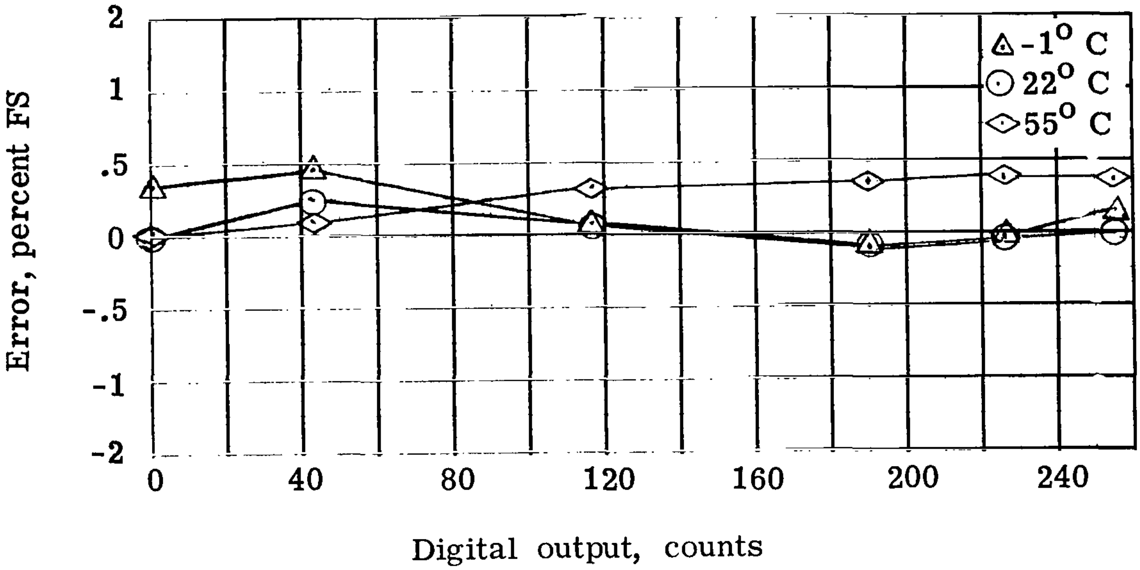
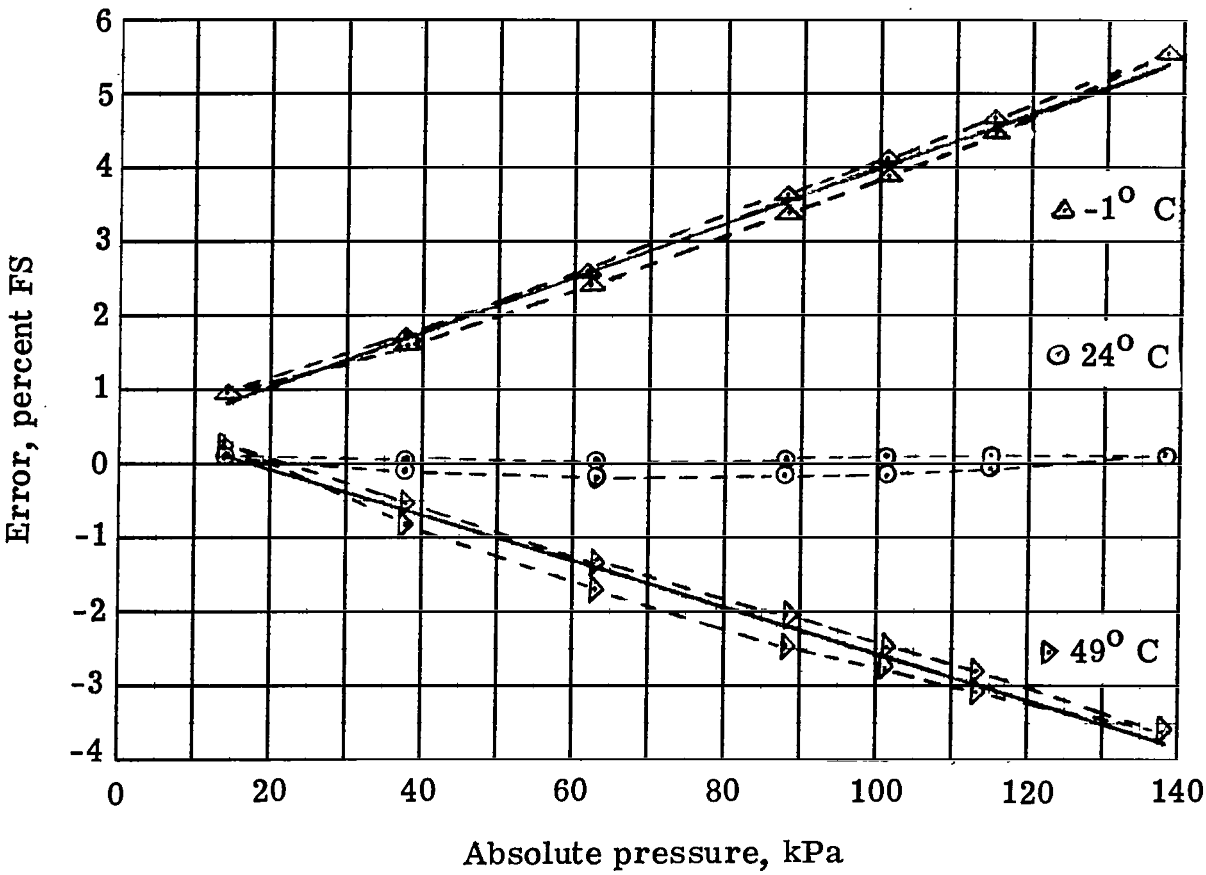
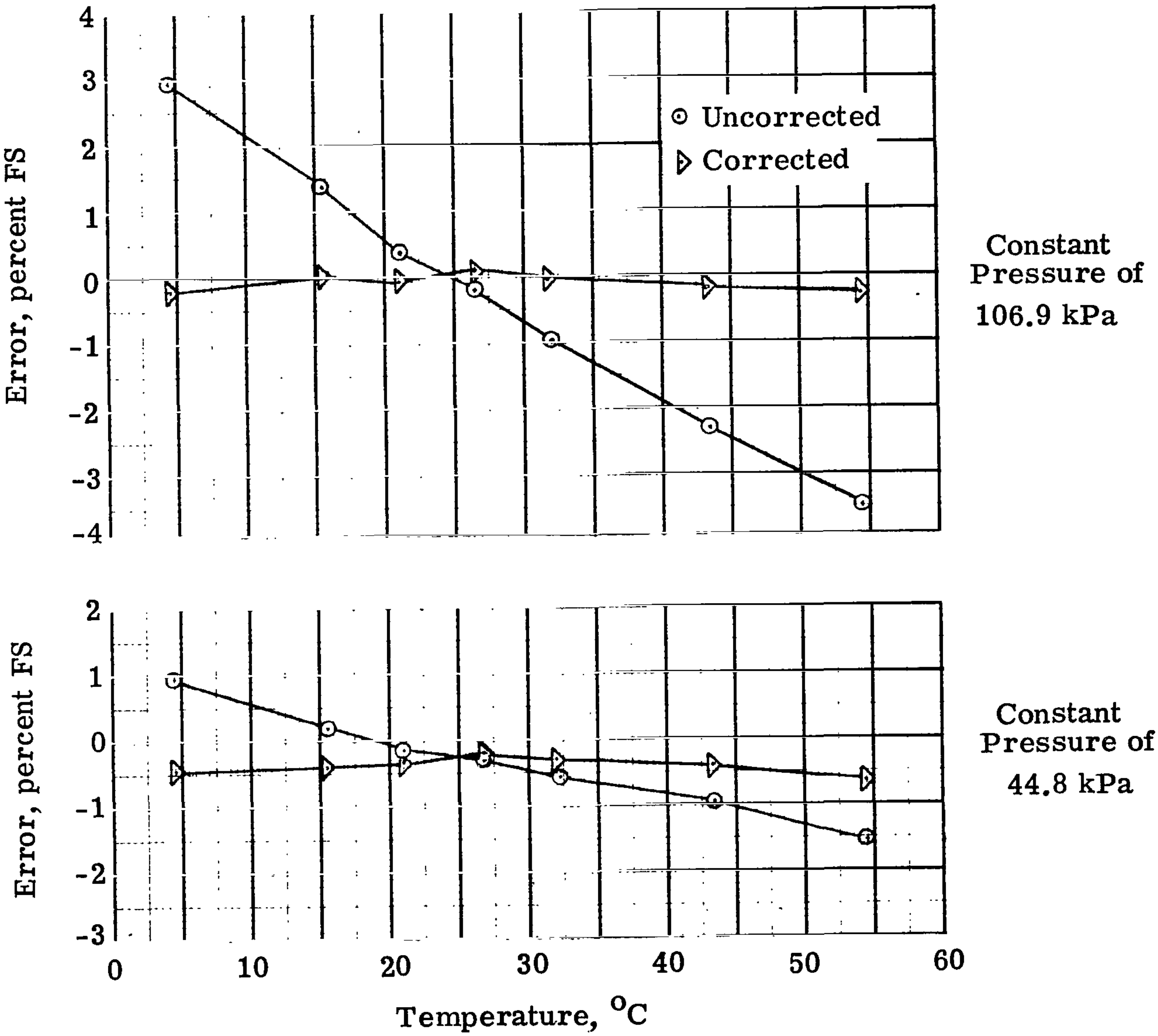


Figure 9.- Performance of a typical PCM measurement channel.



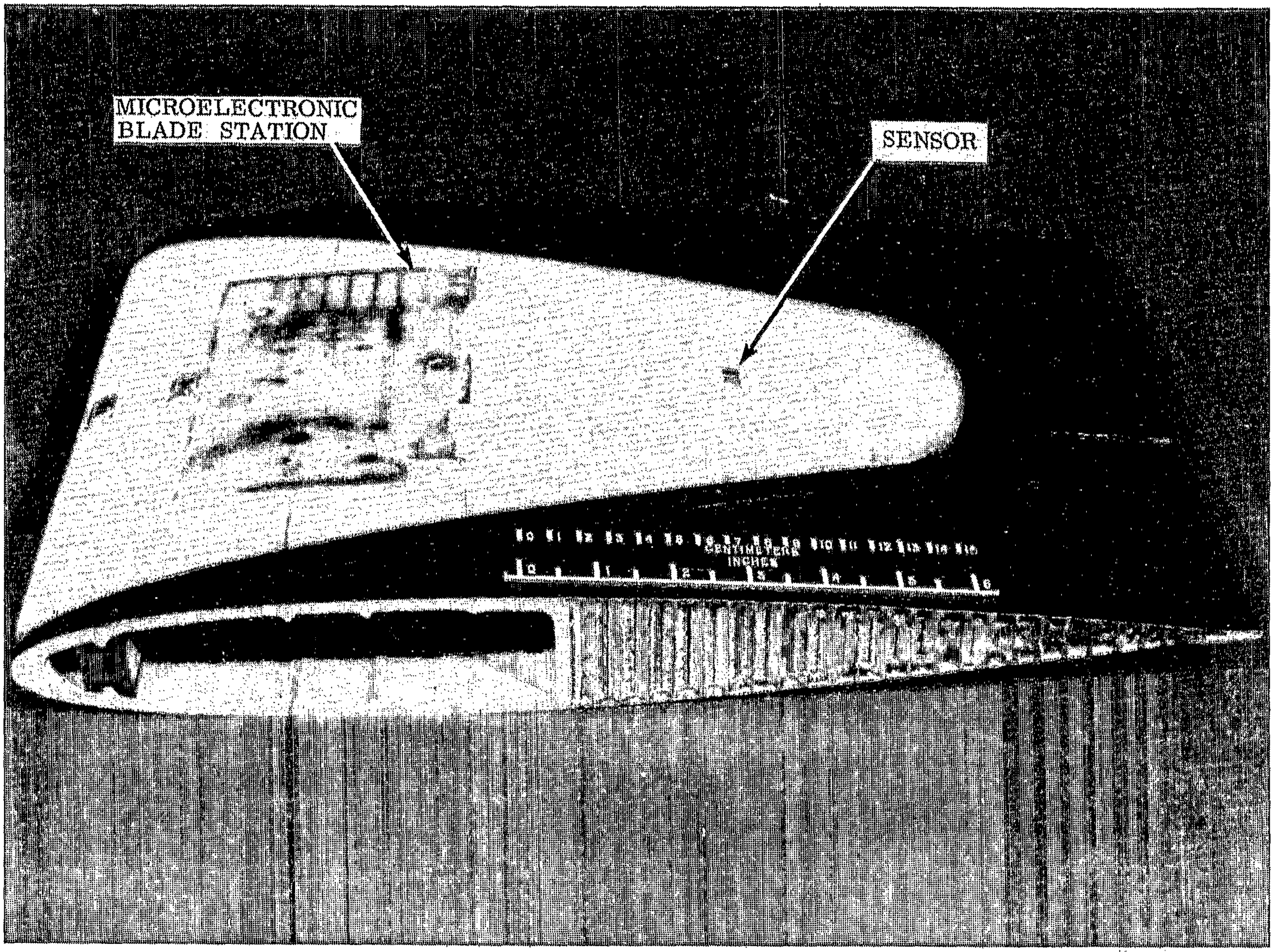
(a) During laboratory calibration.

Figure 10.- Performance of a typical pressure sensor with full-scale range of 124.1 kPa (13.78 to 137.88 kPa).



(b) Before and after correction for temperature error.

Figure 10.- Concluded.



L-77-2646.1

Figure 11.- Rotor blade section with instrument fairing attached.

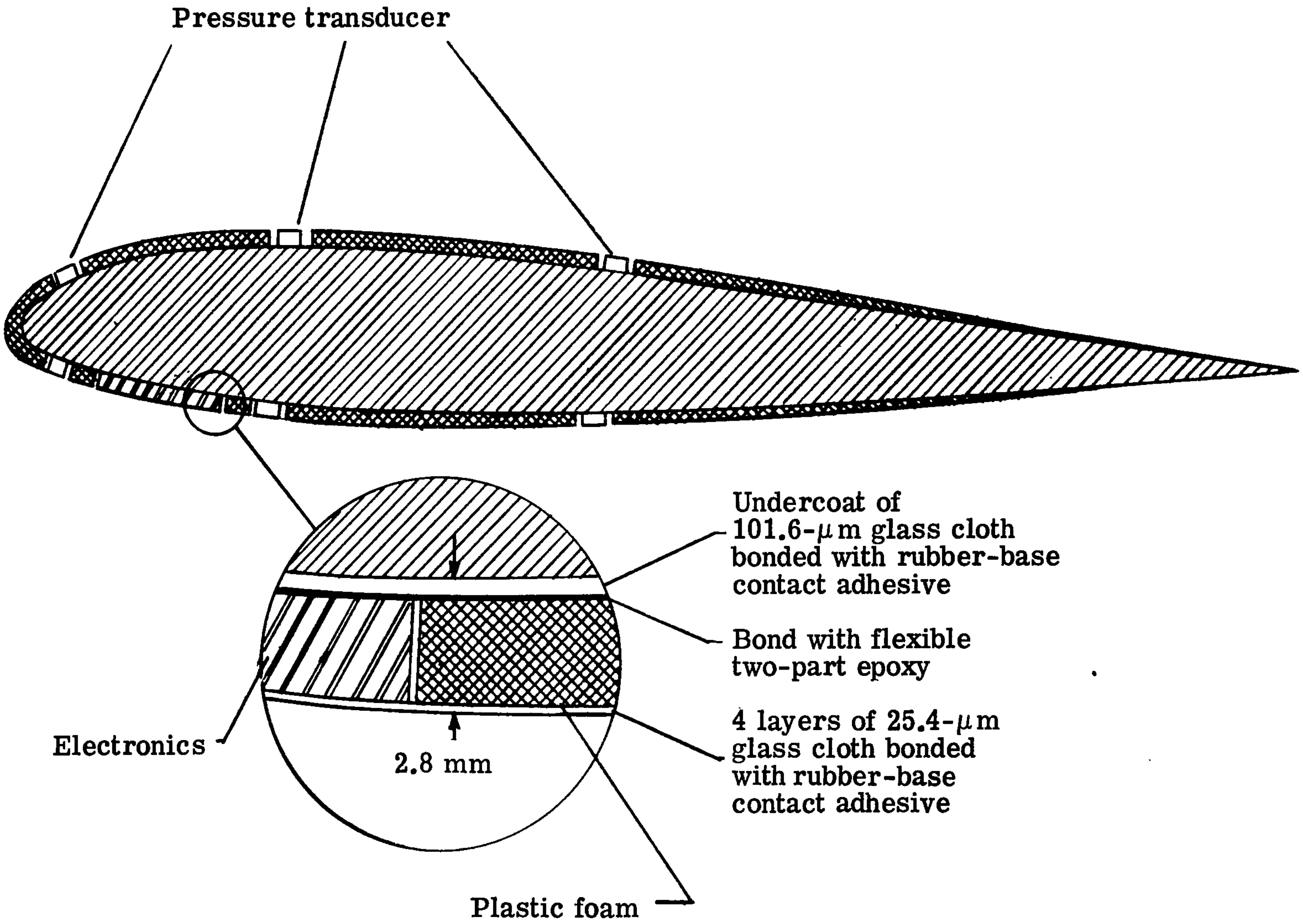
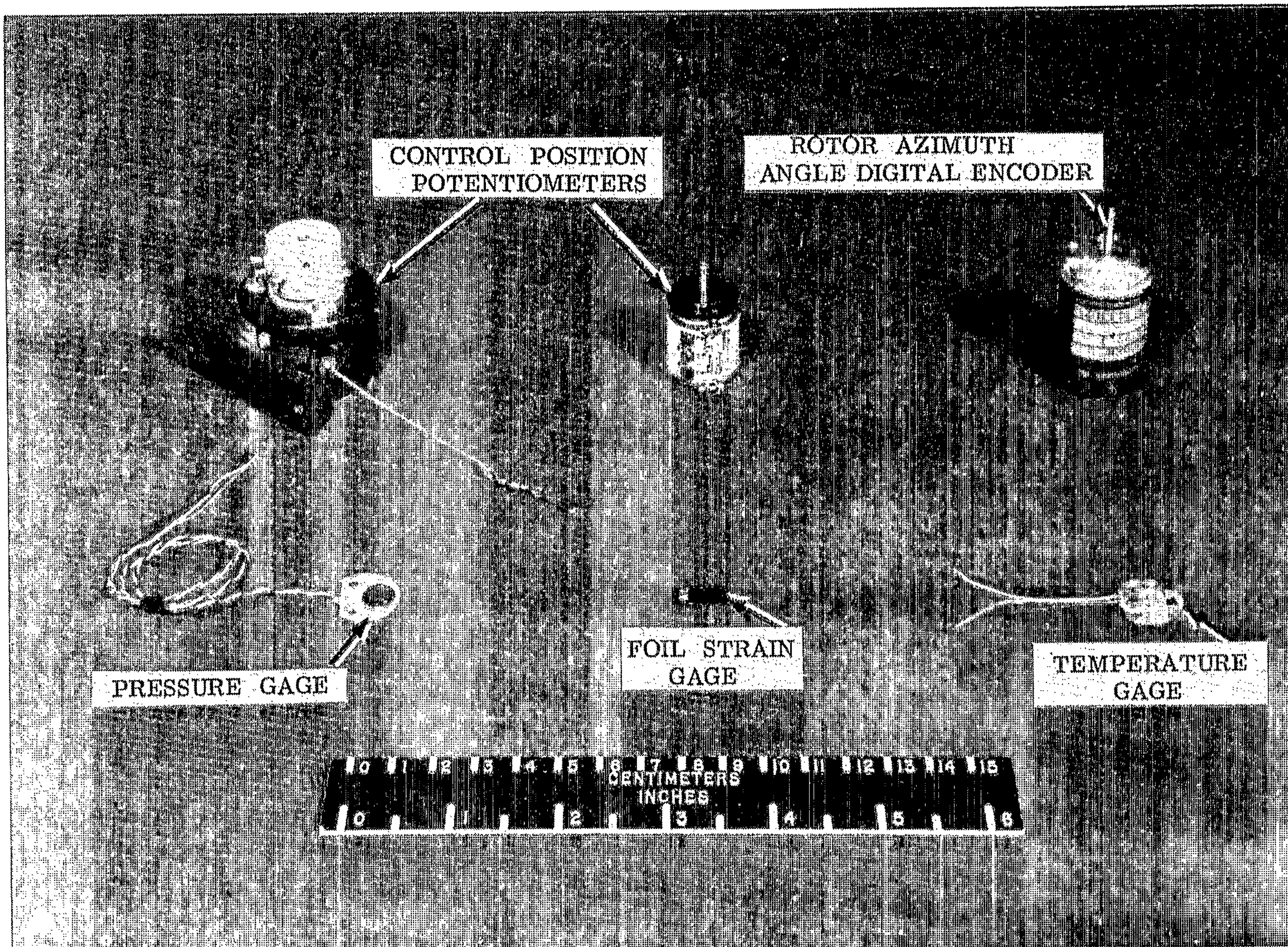


Figure 12.- Cross section of externally applied instrumentation on rotorcraft blade.



L-77-2644.1

Figure 13.- AH-1G rotor sensors.

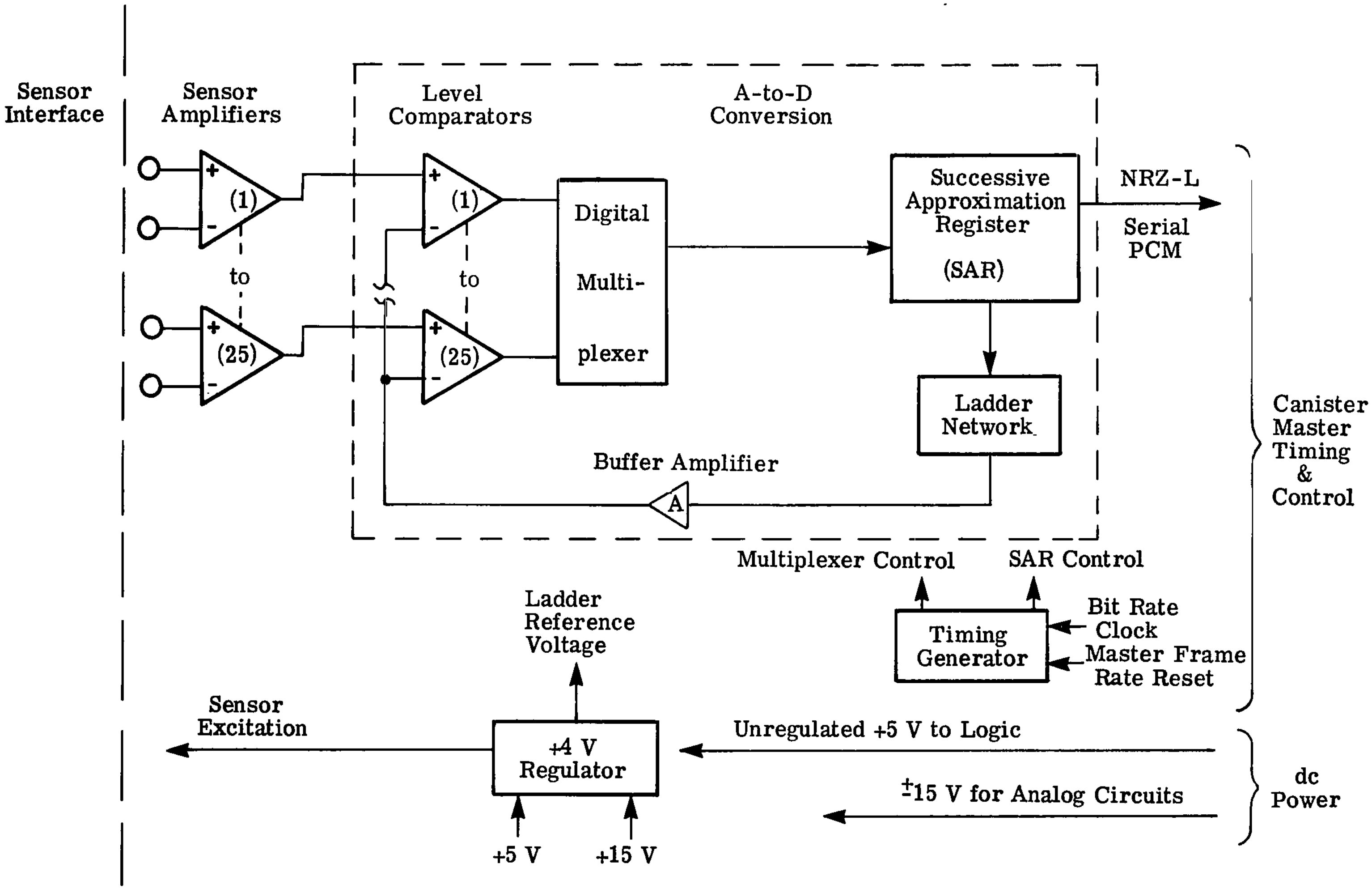


Figure 14.- Block diagram of blade station multiplexer-digitizer.

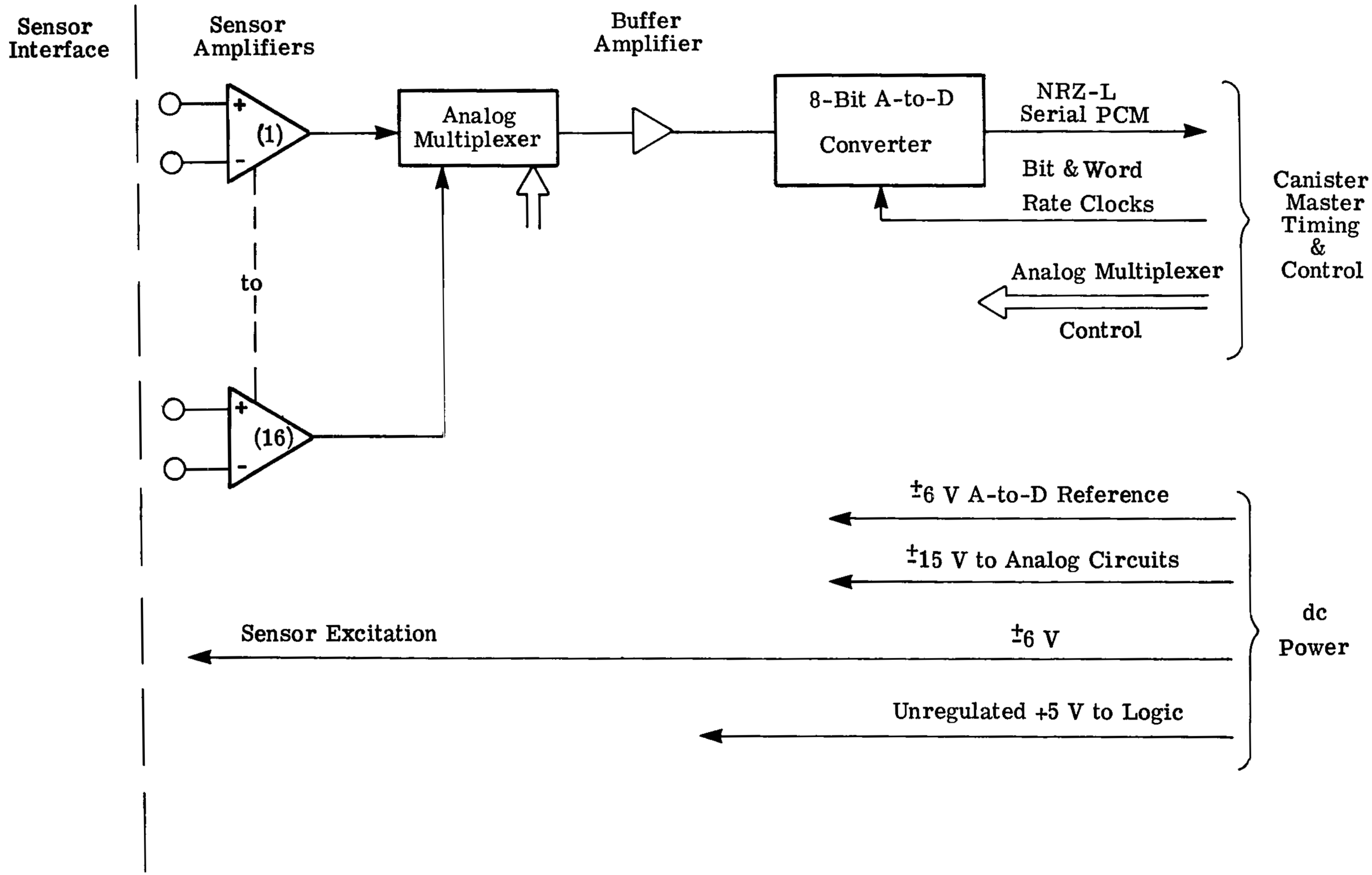


Figure 15.- Block diagram of canister multiplexer-digitizer.

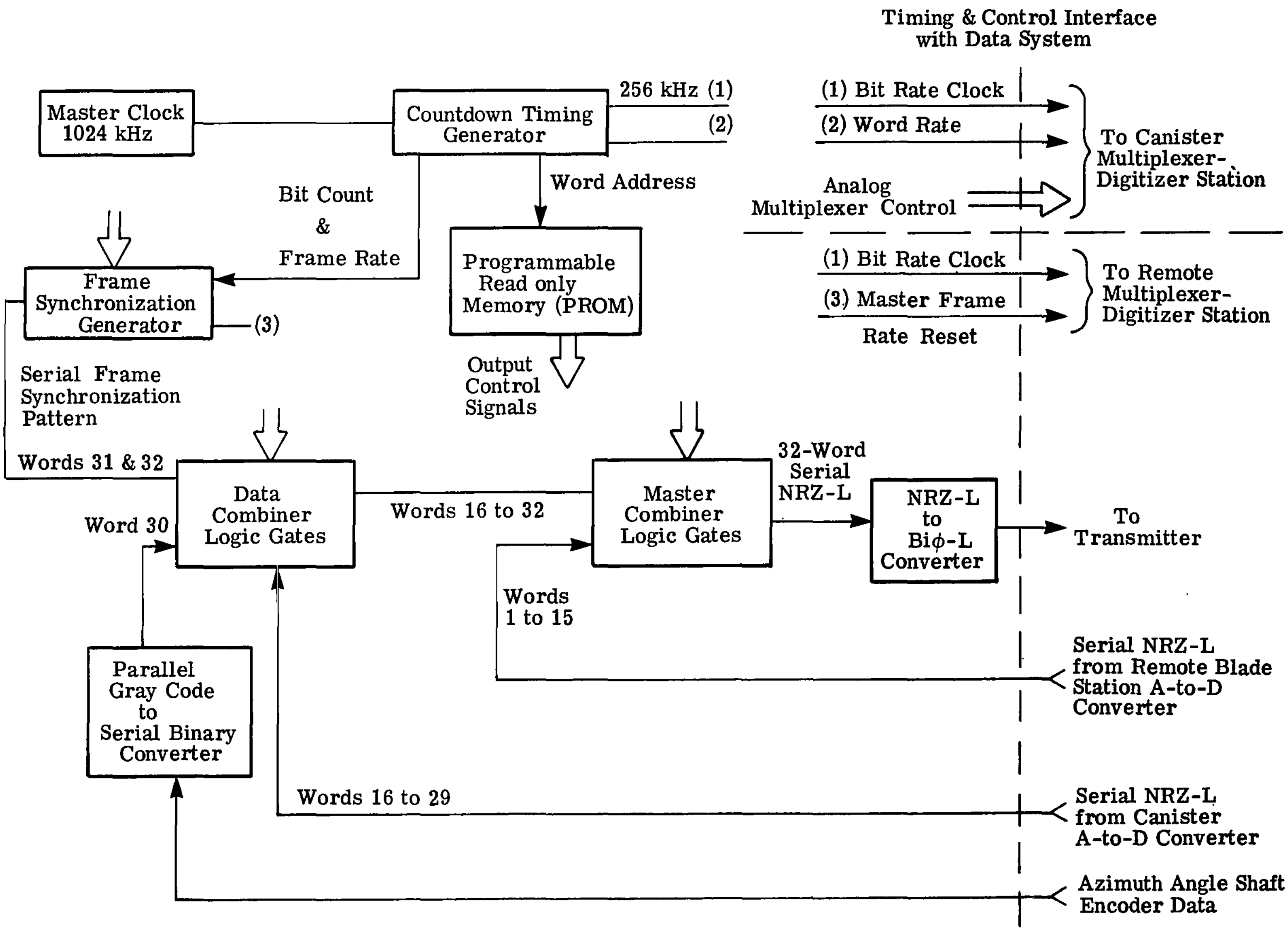
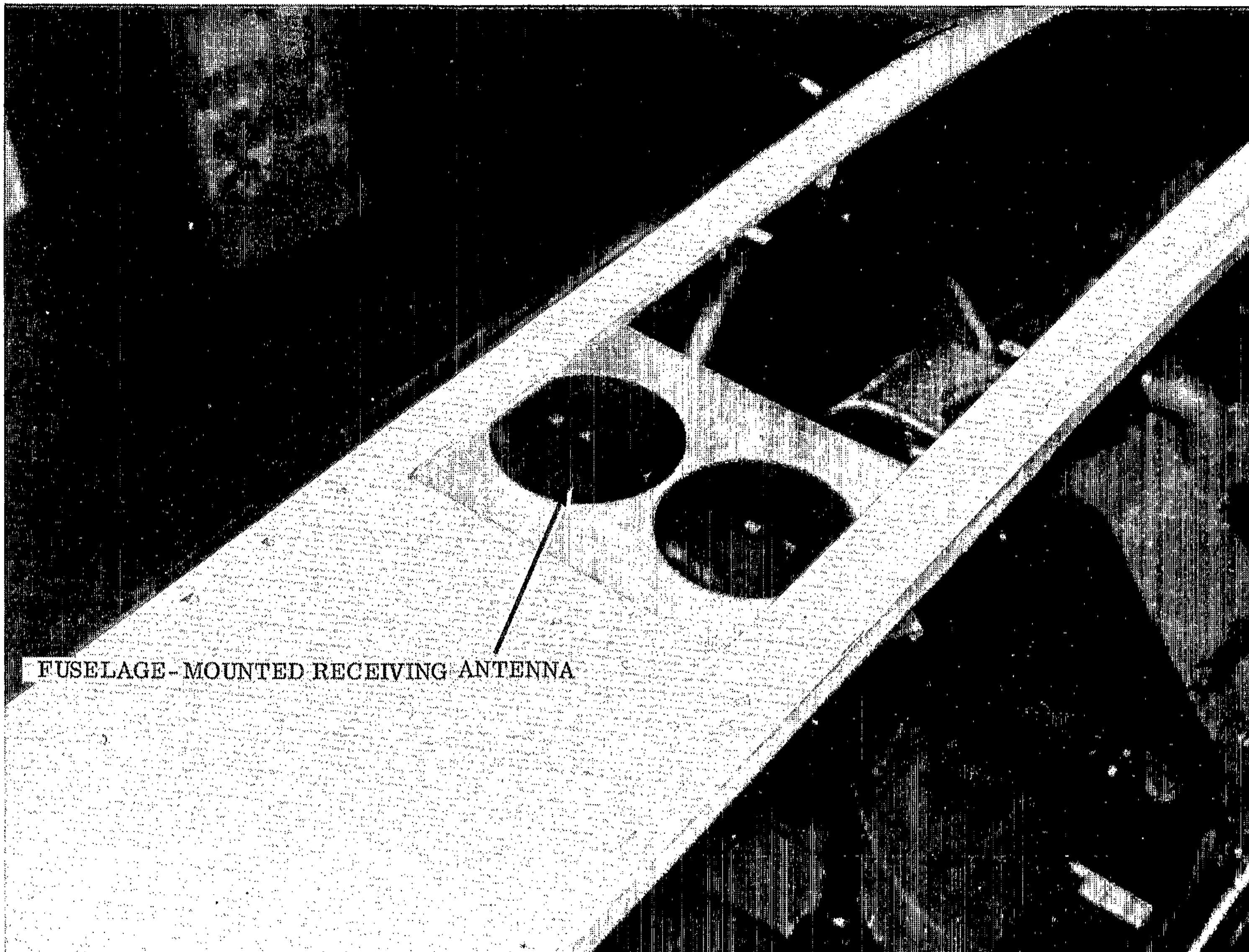


Figure 16.- Diagram of master timing and control.



L-76-602.1

Figure 17.- Fuselage-mounted receiving antenna.

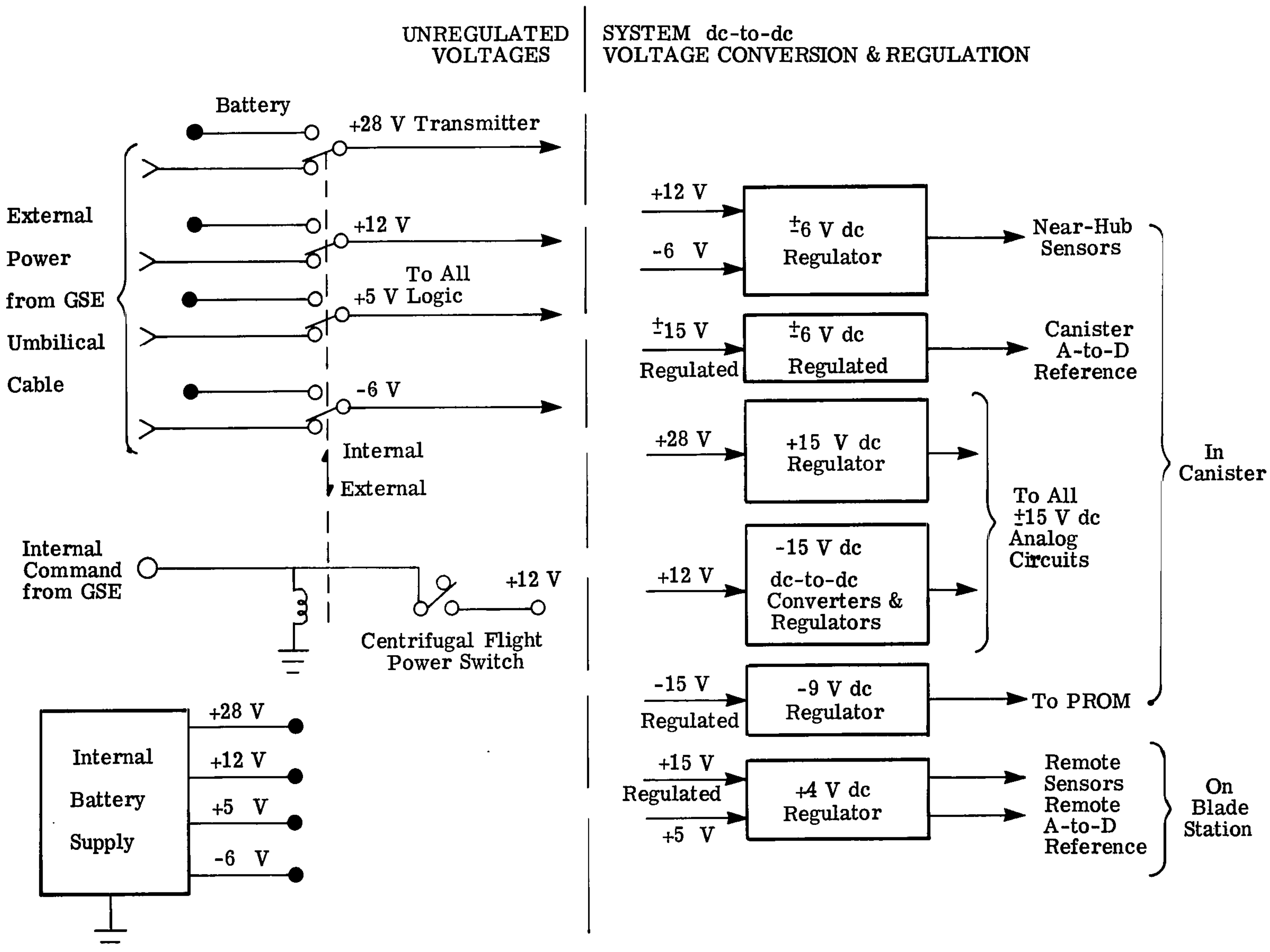


Figure 18.- Simplified block diagram of power distribution system.

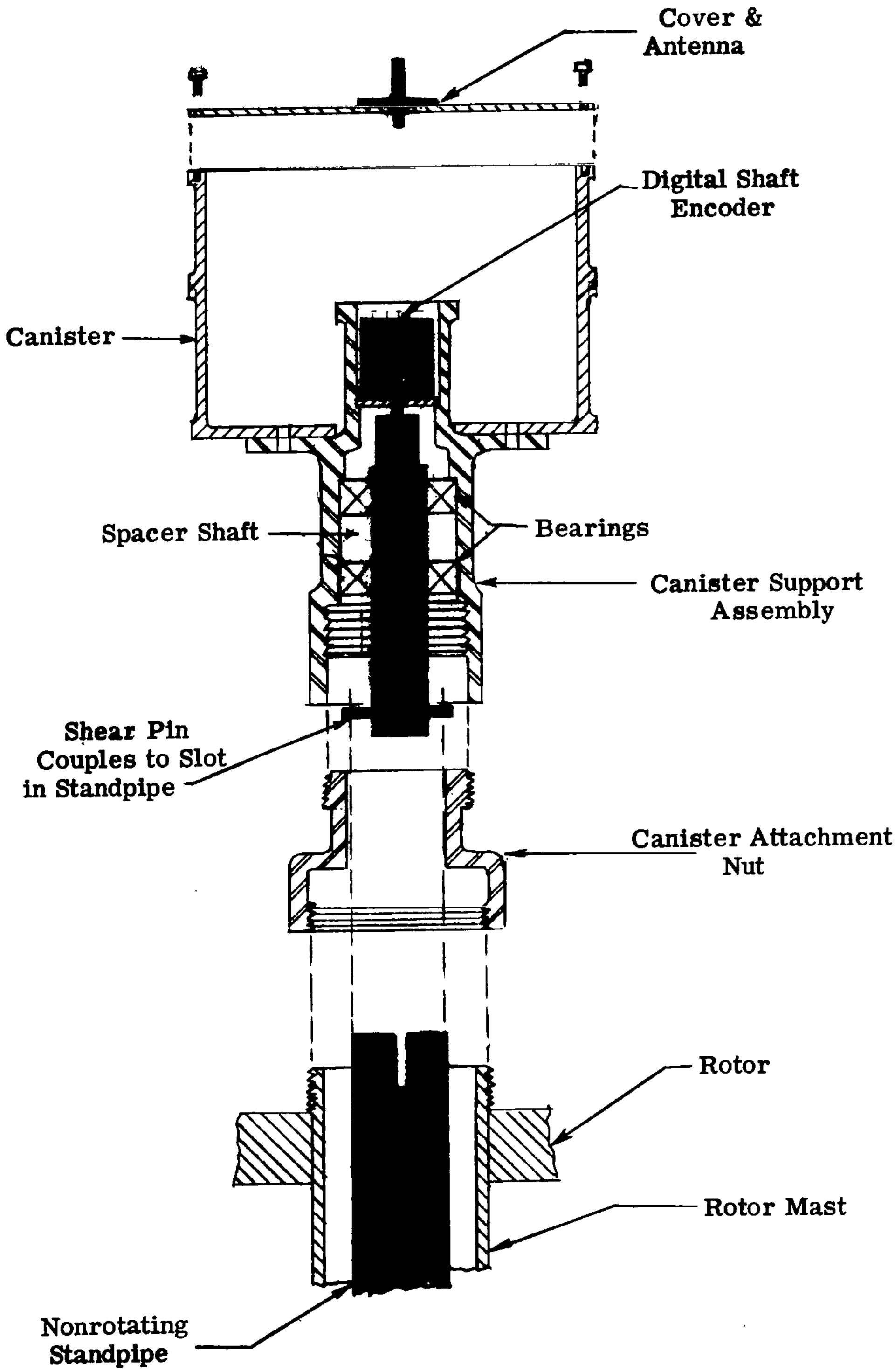
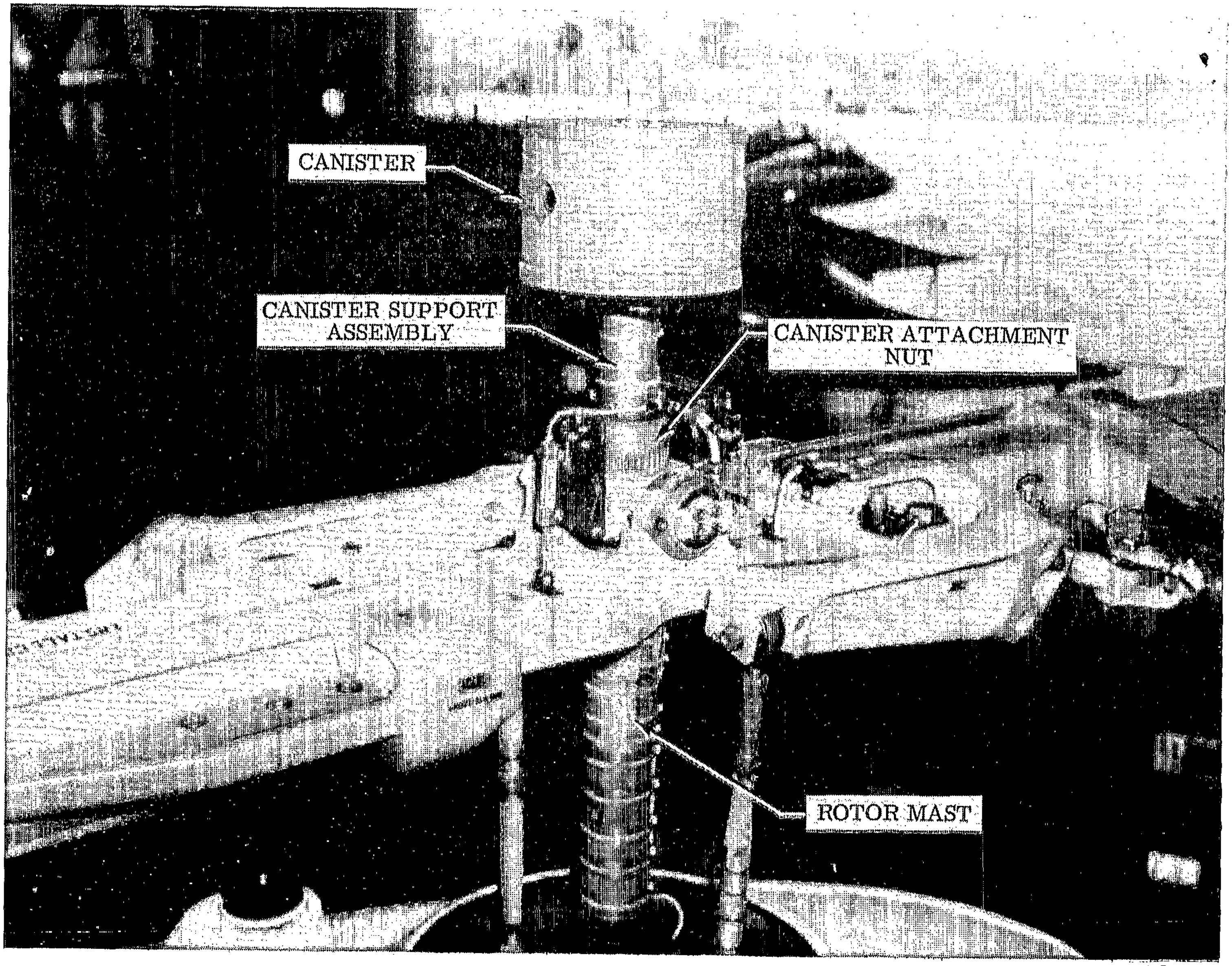


Figure 19.- Simplified drawing of canister mechanical assembly.



L-77-4833.1

Figure 20.- Canister, mounted on AG-1G rotor mast.

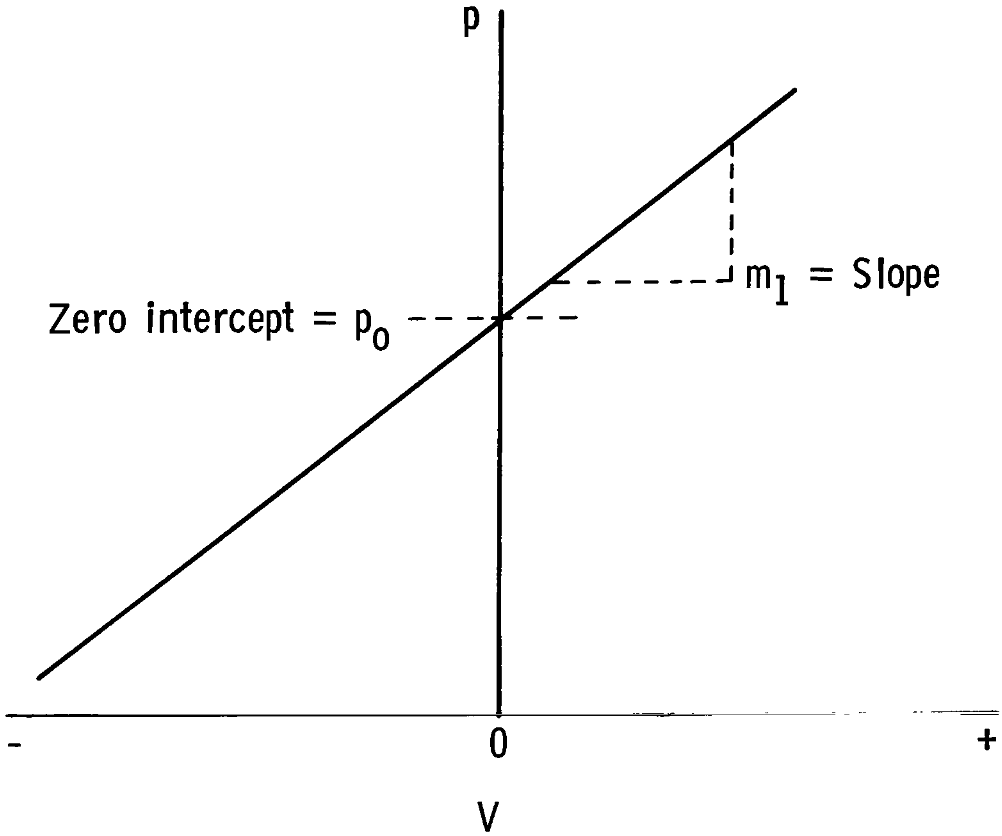


Figure 21.- Typical slope and intercept characteristics of a linear pressure sensor.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-1146		

4. Title and Subtitle	5. Report Date
A ROTOR-MOUNTED DIGITAL INSTRUMENTATION SYSTEM FOR HELICOPTER BLADE FLIGHT RESEARCH MEASUREMENTS	April 1978
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Vernie H. Knight, Jr., William S. Haywood, Jr., and Milton L. Williams	L-11956
	10. Work Unit No.
9. Performing Organization Name and Address	505-10-23-07
NASA Langley Research Center Hampton, VA 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Paper
National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A rotor-mounted flight instrumentation system developed by the NASA Langley Research Center for helicopter rotor blade research is described. The system utilizes high-speed digital techniques to acquire research data from miniature pressure transducers on advanced rotor airfoils which are flight tested on an AH-1G helicopter. The system employs microelectronic pulse code modulation (PCM) multiplexer-digitizer stations located remotely on the blade and in a hub-mounted metal canister. As many as 25 sensors can be remotely digitized by a 2.5-mm-thick electronics package mounted on the blade near the tip to reduce blade wiring. The electronics contained in the canister digitizes up to 16 sensors, formats these data with serial PCM data from the remote stations, and transmits the data from the canister which is above the plane of the rotor. Data are transmitted over an rf link to the ground for real-time monitoring and to the helicopter fuselage for tape recording. The complete system is powered by batteries located in the canister and requires no slip rings on the rotor shaft.

The instrumentation described provides flight measurements of blade parameters such as pressures, bending moments, temperatures, rotor angles, and rotor control forces. These experimental measurements are of value to an improved understanding of rotor performance and for advancement of helicopter blade design techniques.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Flight instrumentation of helicopter rotors Pulse code modulation rf telemetry Battery-powered rotating instrumentation On-blade remote electronics Miniature pressure transducers	Unclassified - Unlimited Subject Category 06

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	46	$4.50

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1978

National Aeronautics and Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

2 1 1U,A, 032178 S00903DS
DEPT OF THE AIR FORCE
AF WEAPONS LABORATORY
ATTN: TECHNICAL LIBRARY (SUL)
KIRTLAND AFB NM 87117

NASA

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return