EQUIPMENT DESIGN FOR A TANDEM PROPELLER SUBMARINE FREE-RUNNING MODEL

Prepared For:
OFFICE OF NAVAL RESEARCH
MATHEMATICAL SCIENCE DIVISION
DEPARTMENT OF THE NAVY
WASHINGTON, D.C.

APPENDIX TO THE PHASE III FINAL REPORT ON THE HYDRODYNAMICS AND STABILITY AND CONTROL OF A TANDEM PROPELLER SUBMARINE

BY: Roy S. Rice and William G. Wilson

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INTRODUCTION

This appendix contains information on the design, installation, and interconnections of equipment used in the free-running model test program. Emphasis is placed on describing those portions of the system designed and assembled by CAL for these specific tests and for which information is not elsewhere available. Where possible, reference will be made to prior publications for descriptions of equipment which was supplied with the model (e. g., the propeller and blade actuator servomechanisms) or which was used in unmodified form for remote control demonstrations (e. g., the Conalog). Certain changes in the supplied equipment, as used in earlier captive tests of the model, were made for compatibility with units introduced into the system for free-running tests and these changes will be noted where applicable.

Figure 6. 1-1 in the main body of this report shows a functional block diagram of the system. In Figure A-1, a diagram showing the individual equipment units and their interconnections is given. Each of the elements, including cabling, are described in the following paragraphs and detailed schematic drawings are provided. A photograph showing several units of the control system is presented as Figure A-2.

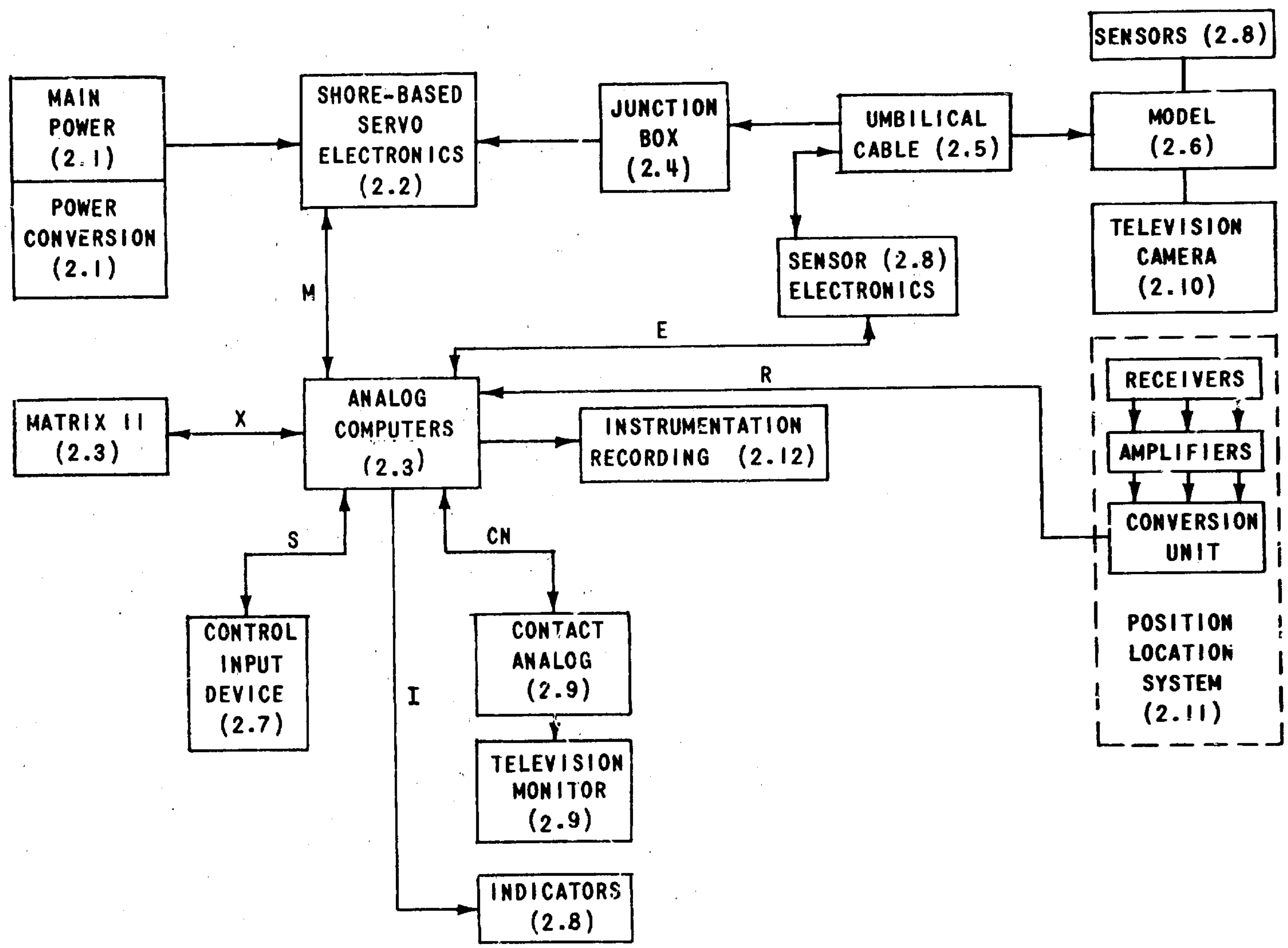

Figure A-1 MAJOR EQUIPMENT AND INTERCONNECTIONS FOR FREE-RUNNING MODEL

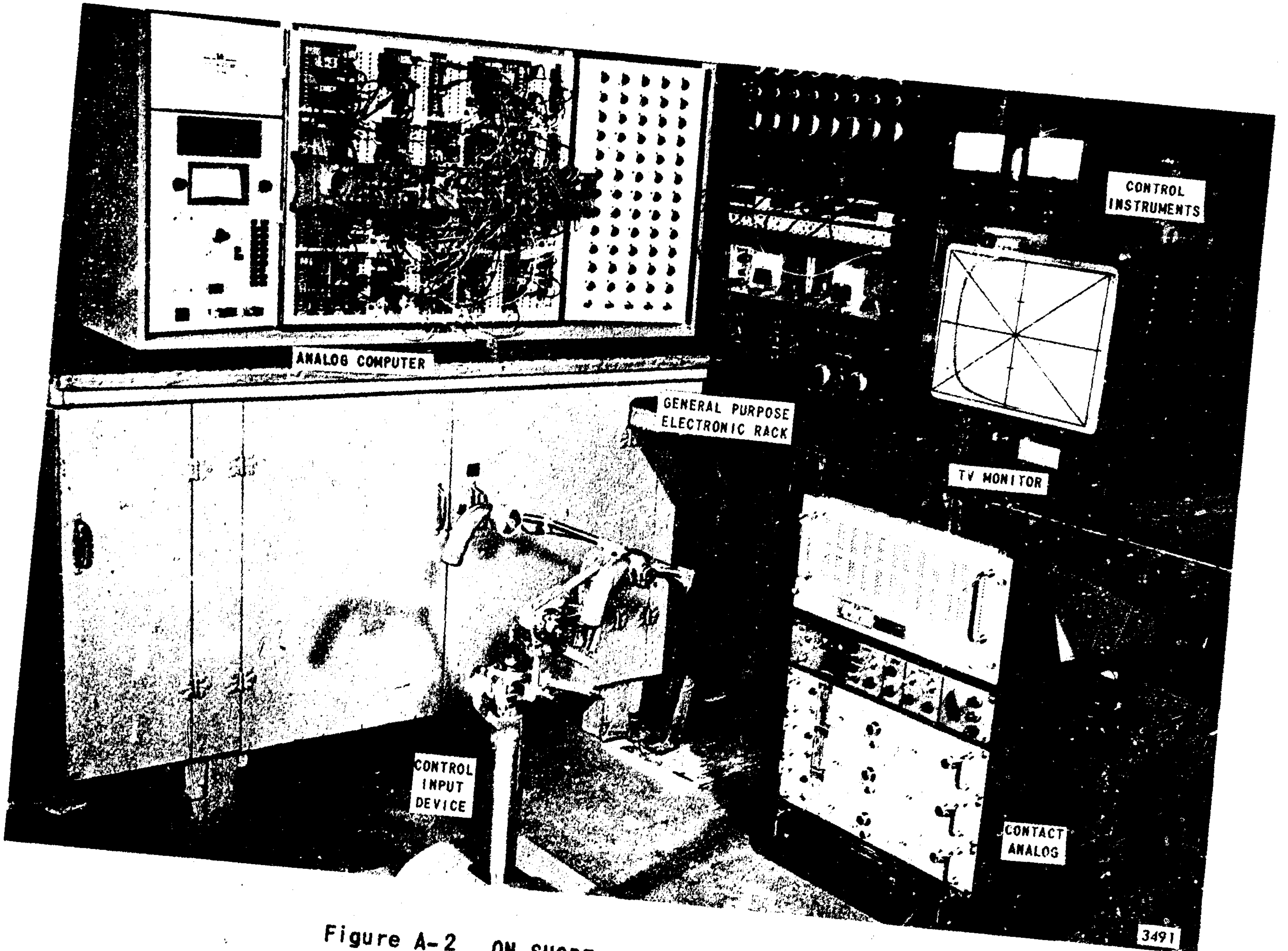

Figure A-2 ON SHORE CONTROL EQUIPMENT

2

DISCUSSION

2.1 Main Power Supply

The primary electrical power system for operation of the propeller drive motors and blade actuation servo systems designed by the Netherlands Ship Model Basin (NSMB) is predicated on use of the standard European three-phase power source of 380/220 volts at 50 cycles per second. Utilization of this equipment with normal U.S.A. electrical power sources necessitated the incorporation of a transformation system in the supply. This was accomplished, as diagrammed in Figure A-3. Three General Radio Variac autotransformers were connected in wye to accept four-wire, three-phase 208/125 volt, 60 cycle power. The three transformers were adjusted to provide 220 volt line-to-neutral power with the attendant 380 volt line-to-line power. Operation of the 50 cycle machines at 60 cycles produced no problems.

In addition to this three-phase power, several thousand watts of 125 volt, 60 cycle, single-phase power were used directly for operation of associated shore-based equipment and to supply the drive motor of a motor-generator set from which the 400 cps power for the model-borne sensing equipment was developed.

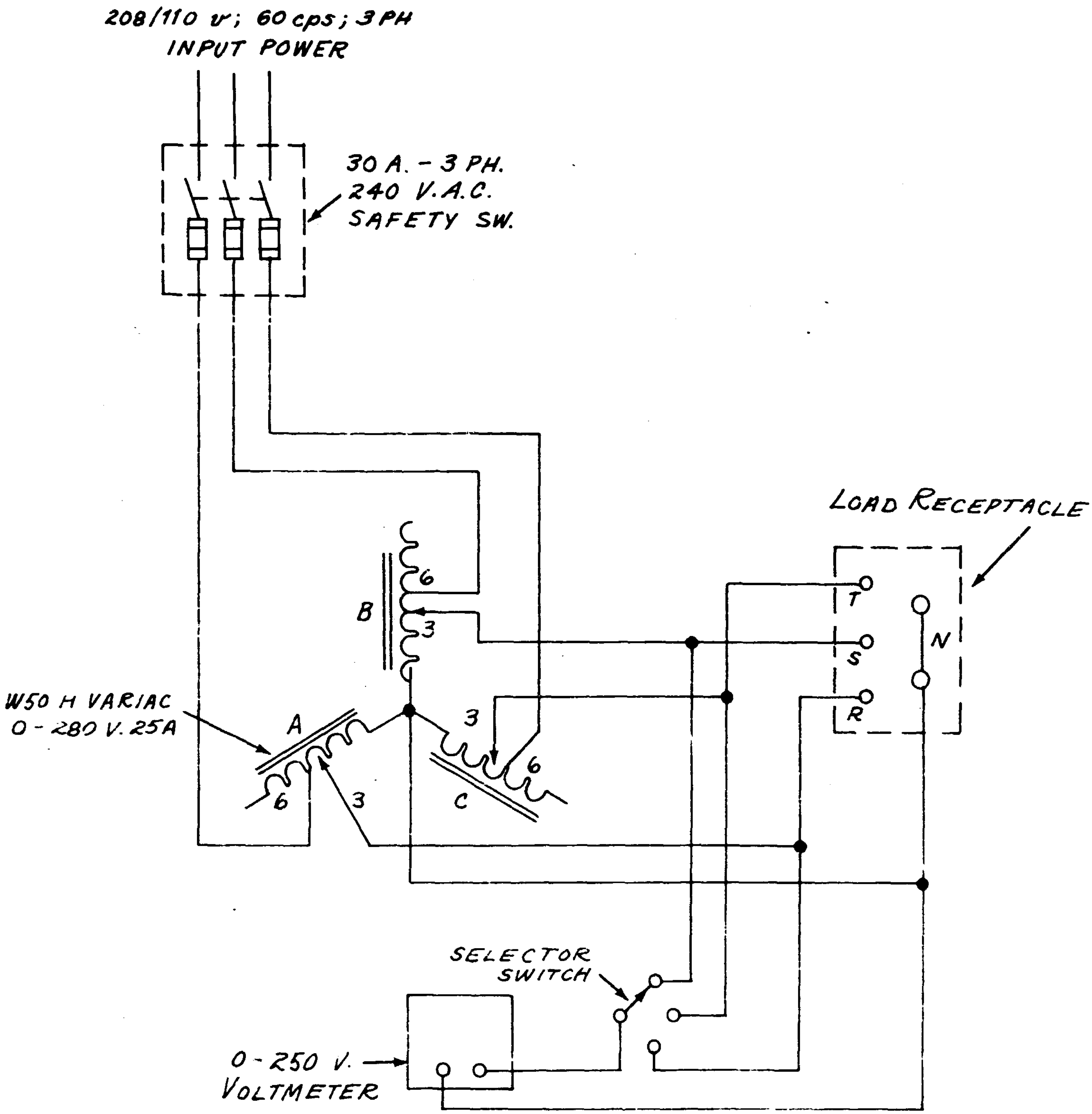

Figure A-3: MAIN POWER SUPPLY

2.2 Shore-Based Servo Electronics

The electrical and electronic equipment associated with the propeller and blade-angle drive control systems were designed and assembled by the Netherlands Ship Model Basin. Schematic diagrams, including details of components and interconnecting cables, are given in Reference A1. In general, these units were used without modification in the free-running test program although certain minor variations, primarily in voltage sources, were made in order to minimize the number of wires in the umbilical cable.

Figure A-4 shows a generalized block diagram of the electrical and electronic equipment as used in the free-running tests. It may be compared with the figure on Page 2 of Reference A1 or NSMB Drawing S3481-66 to identify the major changes in the system (i. e., removal of the control panel, strain gage balance system, and potentiometer supplies). Specific changes include:

1. Replacement of the external input resistors on the propeller motor control amplifiers to increase the range of allowable motor speed variation.

2. Addition of four input resistors on each of the servo control amplifiers to accept external inputs from the model control system. (Only one of these on each amplifier was finally used because summing of the command and motion feedback signals was accomplished in the central analog computer.)

3. Replacement of the sources for both reference voltage and armature supply voltages (rectifier packs on each servo amplifier chassis) with a single source of power (a Lambda Corporation Model LA-20-05B power supply).

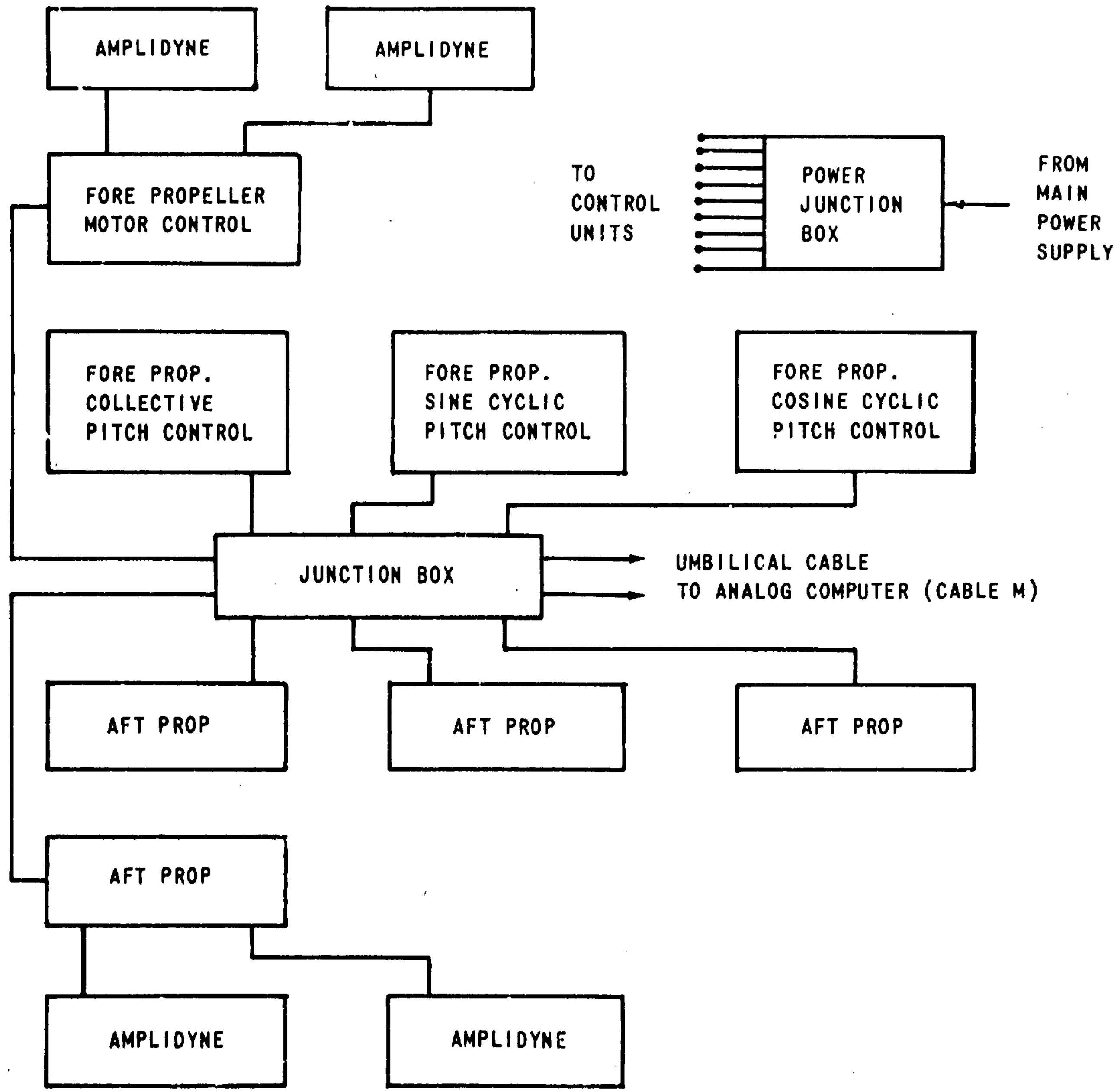

Figure A-4: SHORE BASED SERVO ELECTRONICS

2.3 Analog Computers

Two TR-48 Electronics Associated, Inc., 10 volt transistorized analog computers with associated solid state complements were rented to perform the real time computations required for the TPS free-running model tests (see Figure A-2). These particular units were chosen primarily because of their small size and easy maintenance. Each computer complement included the following items:

1 Digital Voltmeter
48 Amplifiers
60 Potentiometers
16 Integrator Networks
5 Multipliers
4 Variable Diode Function Generators
4 Comparators
40 Trunks
5 Function Switches

The computations required of these two computers can be divided into three essentially separate parts: (1) implementation of control system logic, (2) position location system computations, and (3) Conalog input conditioning. Since parts (1) and (2) were, for the most part, programmed on one computer and (3) on the other, it was anticipated that tests without the Conalog display could be performed should either of the two computers become unavailable because of maintenance requirements. The computers were programmed so that the patch boards were readily interchangeable.

2.3.1 Control Logic

The control logic is described, in general, in Section 5.3.5 of the main body of this report and in Section 4 of Reference A2. The initial and final control coefficients are given in Section 6.3 of the main body of this report. The control logic equations upon which the control mechanization was based are listed in Table A-1. The control mechanization diagram is shown in Figure A-5.

The left portion of this mechanization diagram shows isolation and summing of the control input device (stick) inputs, feedback signals from motion sensors, and input command biases. (The bias potentiometers were also used in place of the input device for precise control input commands during calibration and testing.) The center section of the diagram represents the two transverse control matrices. The upper right portion of the diagram shows the longitudinal control mechanization. Sensor isolation amplifiers for signals not used in the control system are included in the lower right portion of the diagram. This computer mechanization was modified slightly during the model testing phase for more efficient and easier use, but the initial mechanization shown worked satisfactorily.

Because of a shortage of potentiometers with the analog computer complement and a need for instantaneous multiple-pole switching, a special purpose unit, which contained the alternative control matrix described in Section 5.3.5 of the main body of this report, was designed and constructed by CAL. This special purpose unit, designated Matrix II, consisted of sixteen 10-turn helipots, four 6-pole relays, eight DPDT switches, and sixteen 100K precision resistors wired to a "patch board" so that each component could be used independently and program mechanizations could be readily changed. The internal wiring diagram for one of four identical modules of Matrix II is shown in Figure A-6. External wiring is shown on the control mechanization diagram, Figure A-5. Matrix II components are designated by an X preceding their code number. Photos showing front and back views of the 19-inch rack housing the Matrix II circuitry are included as Figures A-7 and A-8. The upper portion of the rack space is occupied by Matrix II. Also mounted on the rack are a pair of standard 5 volt reference supplies and a general purpose chassis assembled by CAL which contains a 28 volt D.C. supply, sensor demodulators, a switch for caging the directional gyro, and two potentiometers for setting the nominal propeller speeds.

TRANSVERSE

$$\delta_Y = k_y(\delta_{Y_c} + \delta_{Y_c}\ bias)|$$

$$\delta_Z = k_z(\delta_{Z_{CR}} + \delta_{Z_{CL}} + \delta_{Z_c}\ bias)|$$

$$\delta_M = k_M(\delta_{M_c} + \delta_{M_c}\ bias + k_\theta \sin\theta + k_q q)|$$

$$\delta_N = k_N(\delta_{N_c} + \delta_{N_c}\ bias + k_r r)|$$

$$\delta_{1f} = (\delta_{1f}\ bias + b_{11}\delta_Y + b_{12}\delta_Z + b_{13}\delta_M + b_{14}\delta_N)|$$

$$\delta_{2f} = (\delta_{2f}\ bias + b_{21}\delta_Y + b_{22}\delta_Z + b_{23}\delta_M + b_{24}\delta_N)|$$

$$\delta_{1a} = (\delta_{1a}\ bias + b_{31}\delta_Y + b_{32}\delta_Z + b_{33}\delta_M + b_{34}\delta_N)|$$

$$\delta_{2a} = (\delta_{2a}\ bias + b_{41}\delta_Y + b_{42}\delta_Z + b_{43}\delta_M + b_{44}\delta_N)|$$

LONGITUDINAL

$$\delta_\chi = k_\chi(\delta_{\chi_c} + \delta_{\chi_c}\ bias)|$$

$$\delta_k = k_k(\delta_{k_c} + \delta_{k_c}\ bias + k_\phi \sin\phi + k_p p)|$$

$$\delta_{0f} = \delta_{0f}\ bias - c_1\delta_\chi + c_2\delta_k$$

$$\delta_{0a} = \delta_{0a}\ bias - c_1\delta_\chi + c_2\delta_k$$

$$\Delta\Omega_f = -40\delta_\chi - 40\delta_k$$

$$\Delta\Omega_a = +40\delta_\chi + 40\delta_k$$

NOTE: VERTICAL LINES (|) INDICATE THAT THE VALUES ARE LIMITED.

Table A-I CONTROL EQUATIONS

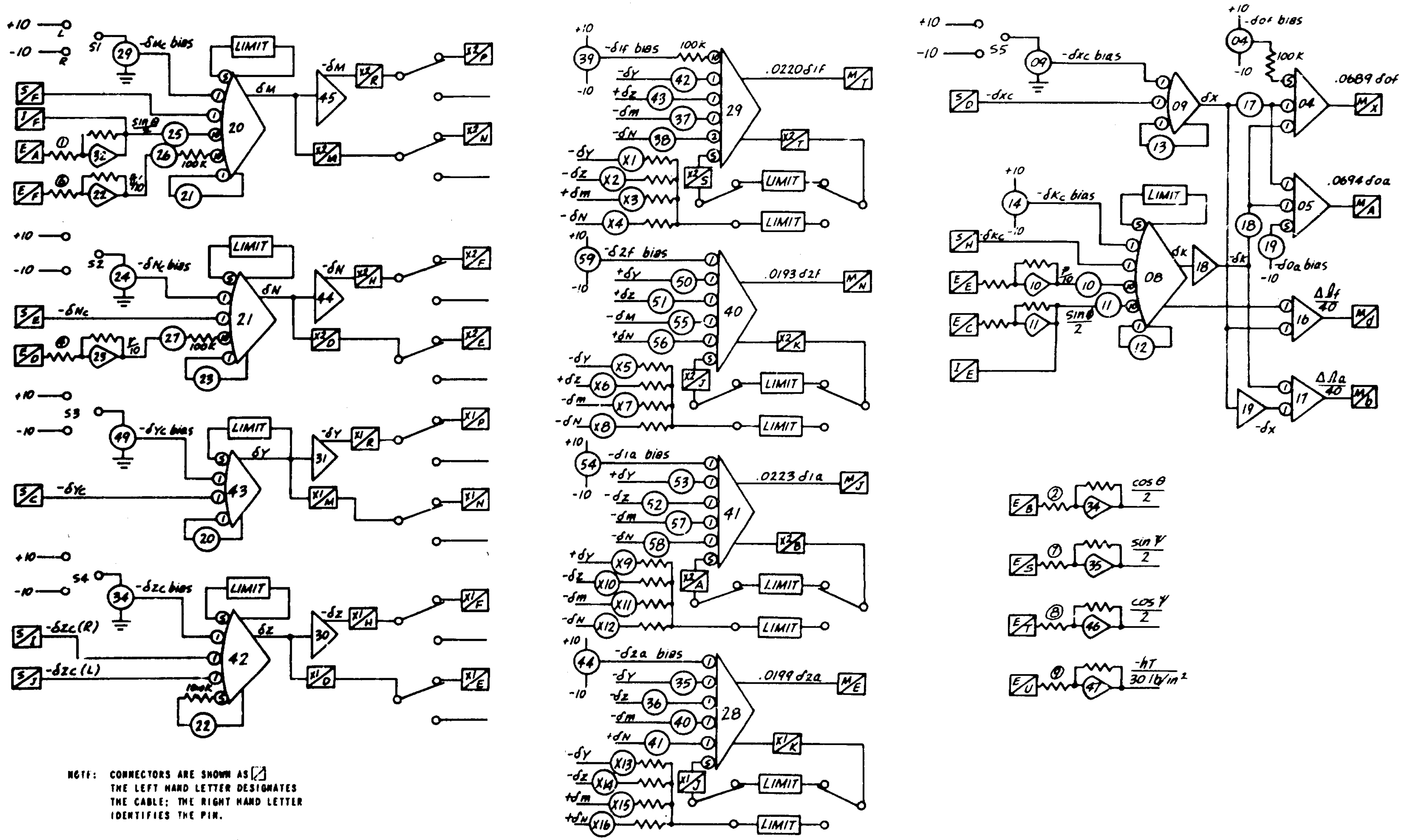

Figure A-5: COMPUTER MECHANIZATION - CONTROL SYSTEM

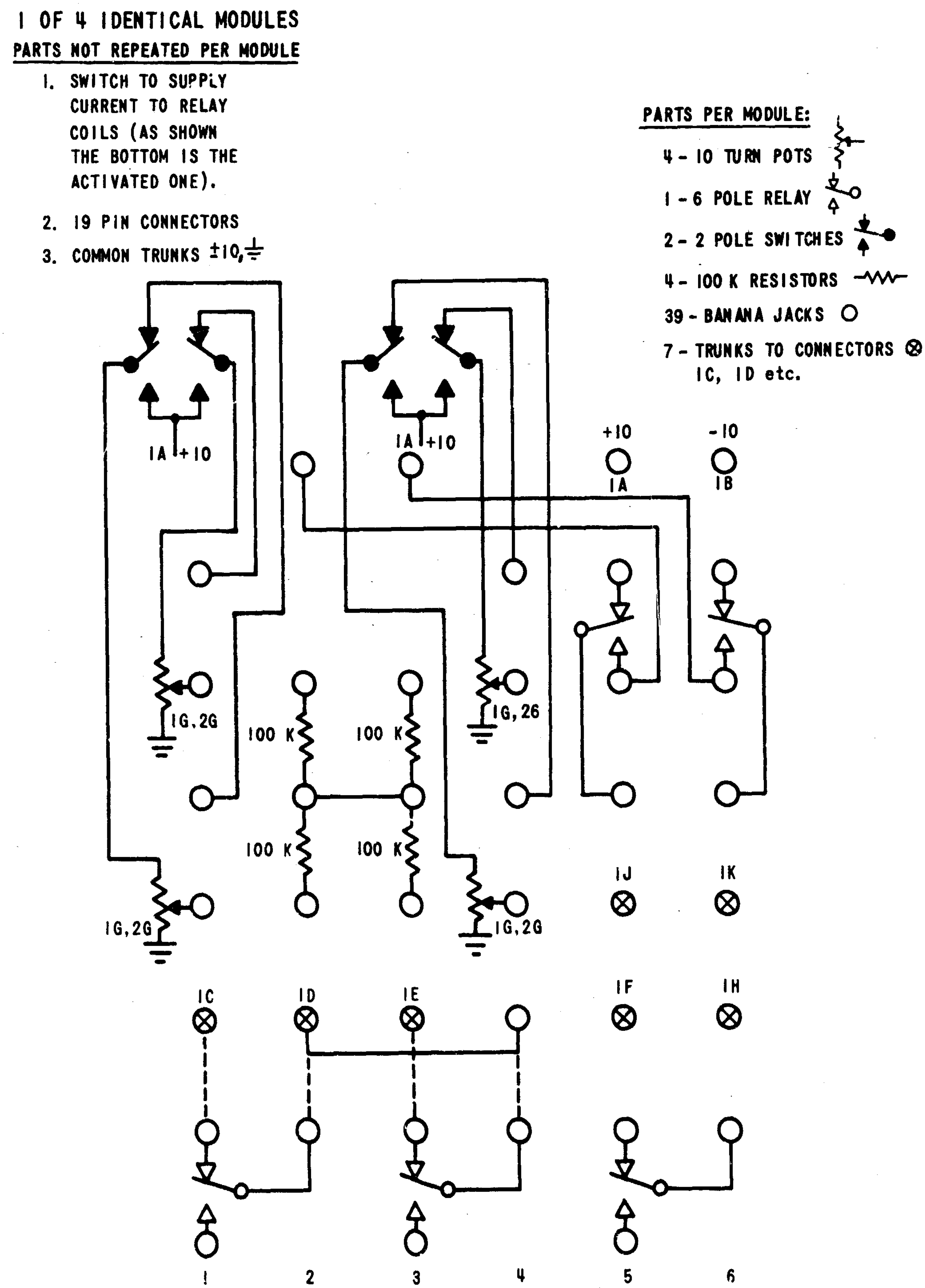

Figure A-6 MATRIX II PANEL INTERNAL WIRING

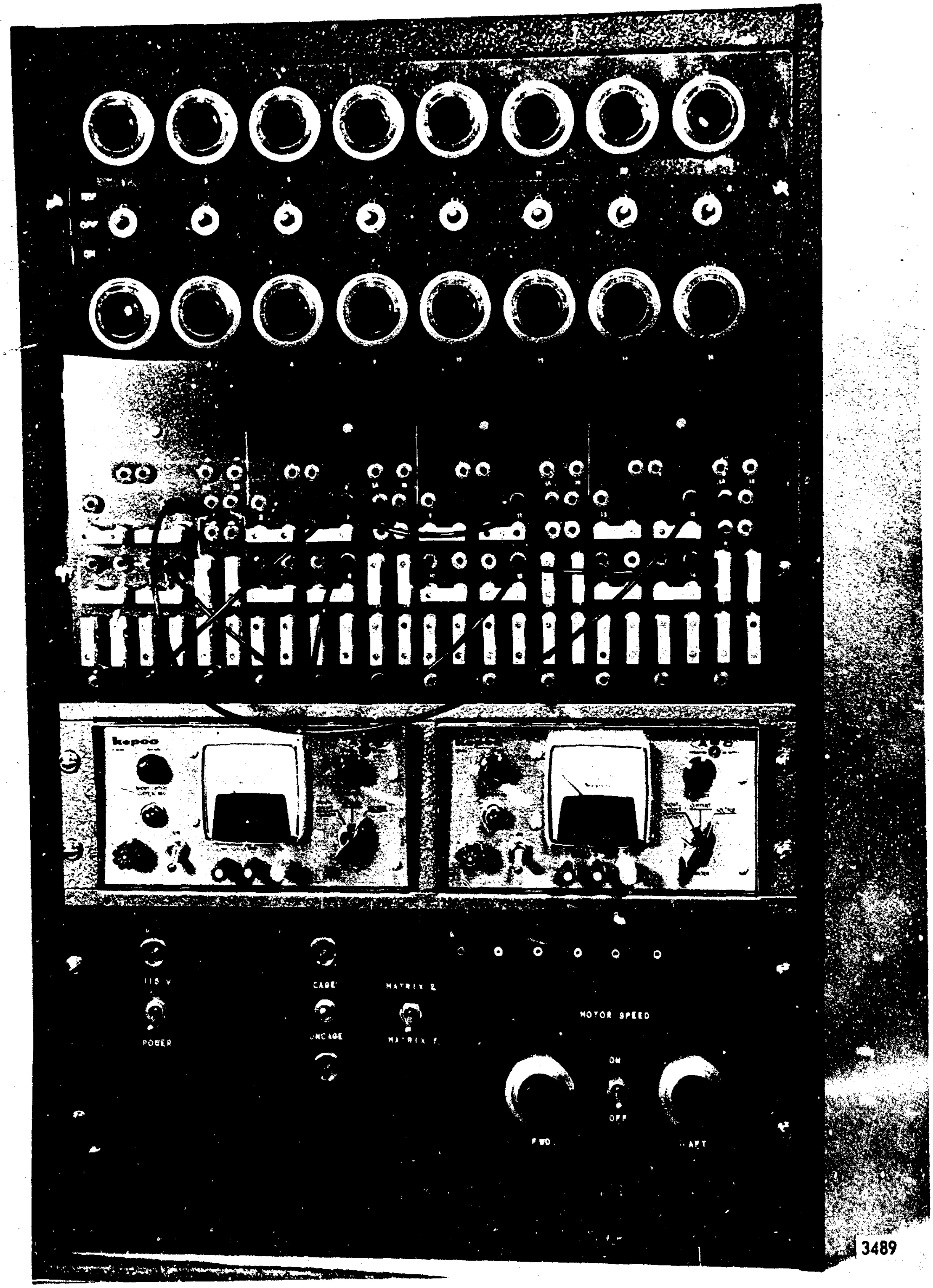

Figure A-7: GENERAL PURPOSE ELECTRONIC RACK - FRONT VIEW

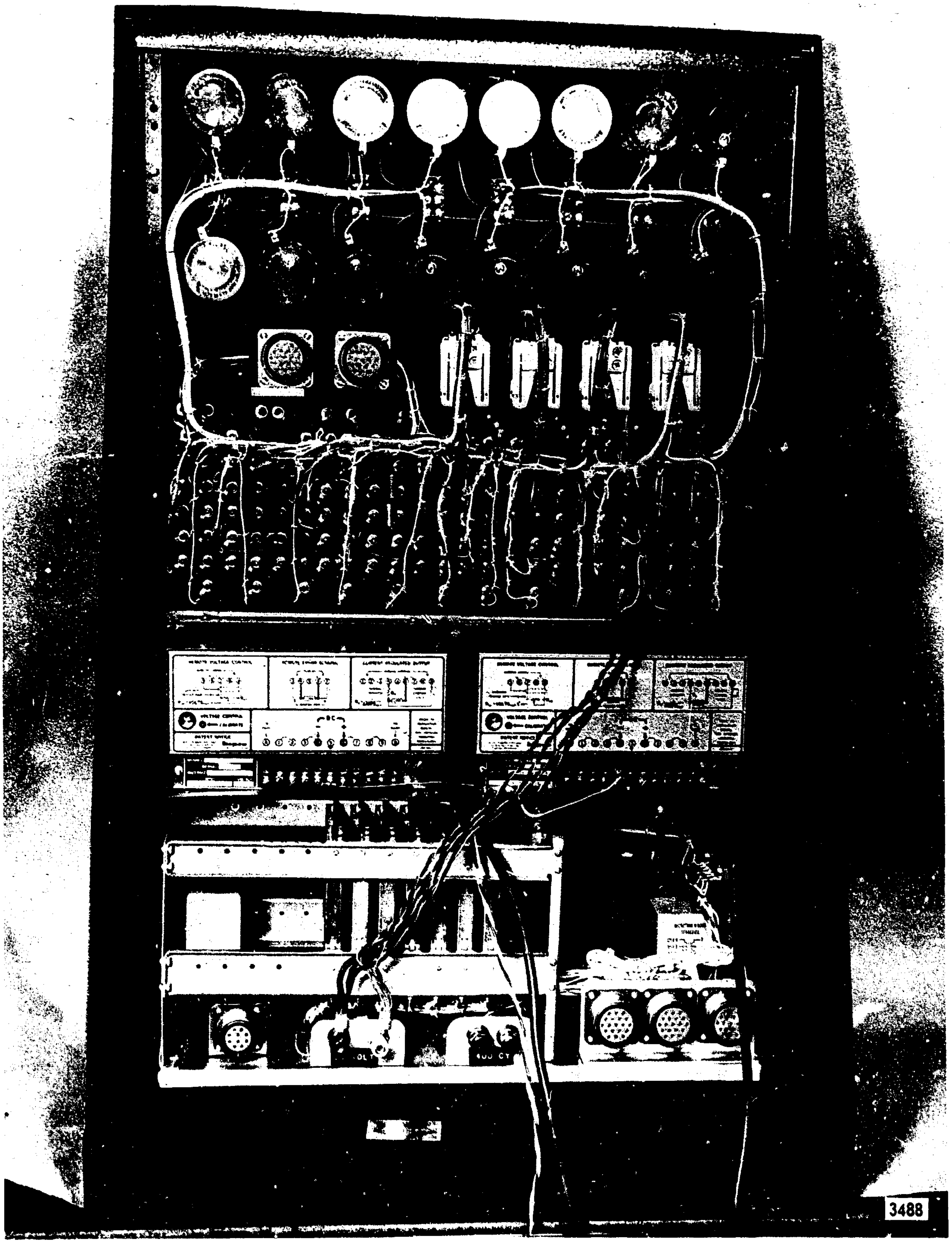

Figure A-8: GENERAL PURPOSE ELECTRONIC RACK - REAR VIEW

Additional feedback limiters were fabricated from purchased components because of the shortage of computer potentiometers and diodes. Plug-in limiter circuit schematic and assembly diagrams are shown in Figure A-9.

2.3.2 Position Location System Computations

The acoustic position location system computations were based on the following equations, derived from the geometry illustrated in Figure A-10. They are independent of model depth.

$$-R_X = \frac{1}{2d}\left(d_2^2 - d_1^2\right)$$
$$-R_Y = \frac{1}{2D}\left(d_2^2 - d_3^2\right) \qquad \text{(A-1)}$$

For use in the Circulating Water Channel, these equations were scaled as follows in order to obtain satisfactory computational accuracy:

$$-\frac{R_x}{30} = \frac{20}{2d}\left(\frac{d_2+d_1-70}{10}\right)\left(\frac{d_2-d_1}{60}\right) + \frac{20}{2d}\left(\frac{70}{10}\right)\left(\frac{d_2-d_1}{60}\right)$$
$$-\frac{R_Y}{10} = \frac{100}{2D}\left(\frac{d_2+d_3-70}{50}\right)\left(\frac{d_2-d_3}{20}\right) + \frac{100}{2D}\left(\frac{70}{50}\right)\left(\frac{d_2-d_3}{20}\right) \qquad \text{(A-2)}$$

Similar scaling techniques were used for operation in the Test Pond.

A computer mechanization diagram for Equations A-2 is shown in Figure A-11.

A range checkout computational sheet is shown in Table A-2. With the exception of the last two check points, where the range system apparently missed the initial pulse and picked up a reflection, the average error in Rx is .046 feet and the average error in Ry is .164 feet. These errors were considered to be quite satisfactory. It was decided that large errors due to missed pulses would be apparent should they exist during calibration runs.

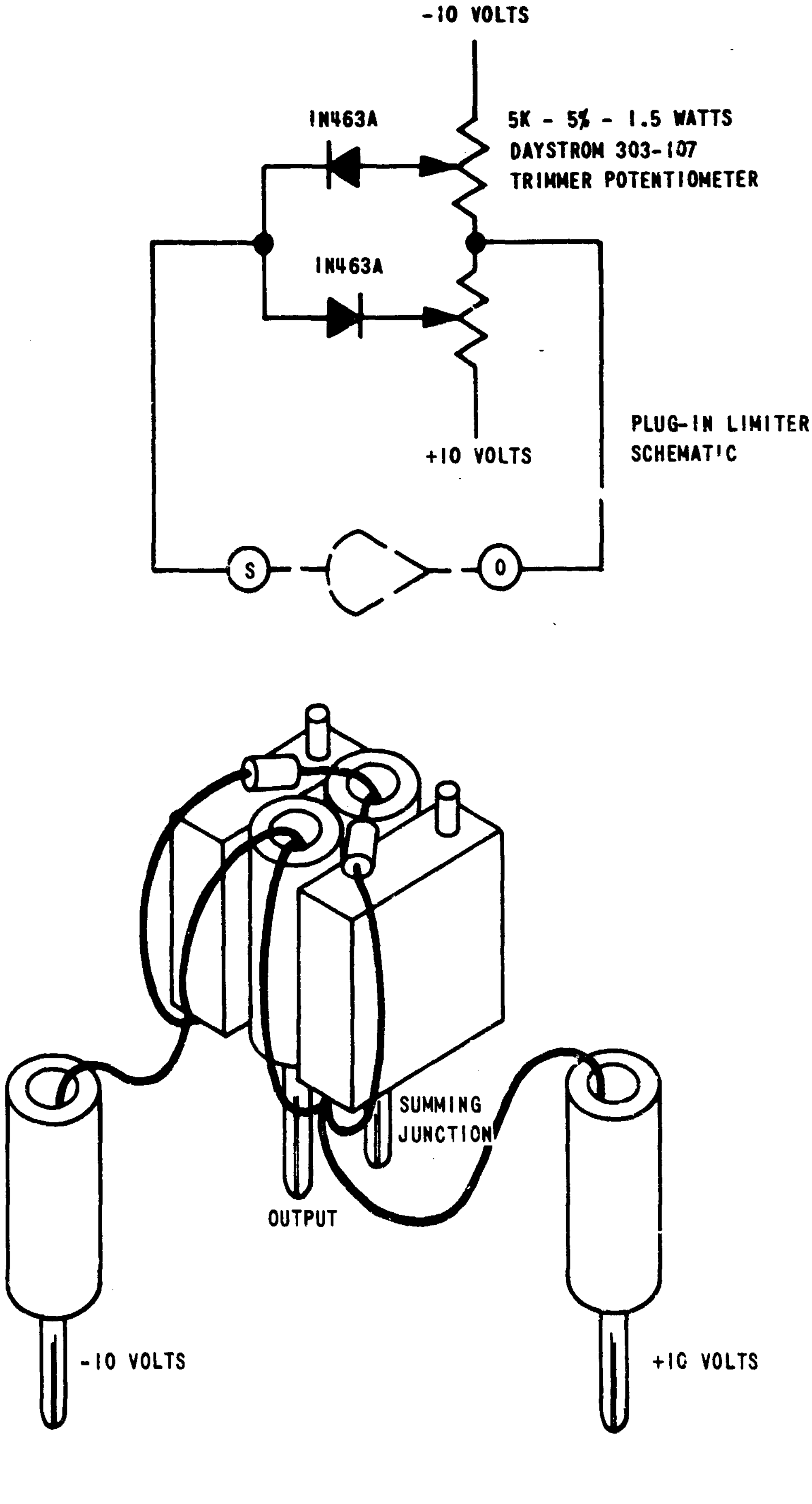

Figure A-9: PLUG-IN LIMITER ASSEMBLY

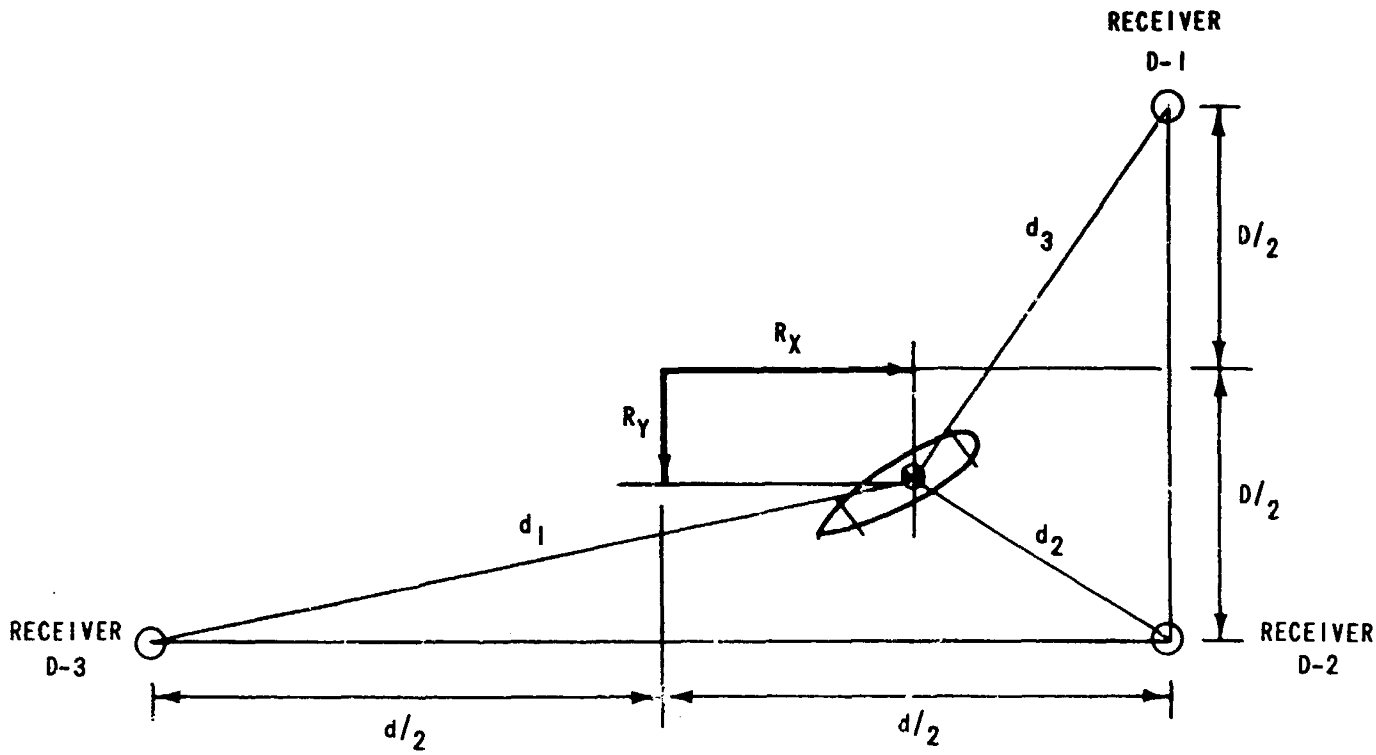

Figure A-10 POSITION LOCATION SYSTEM GEOMETRY

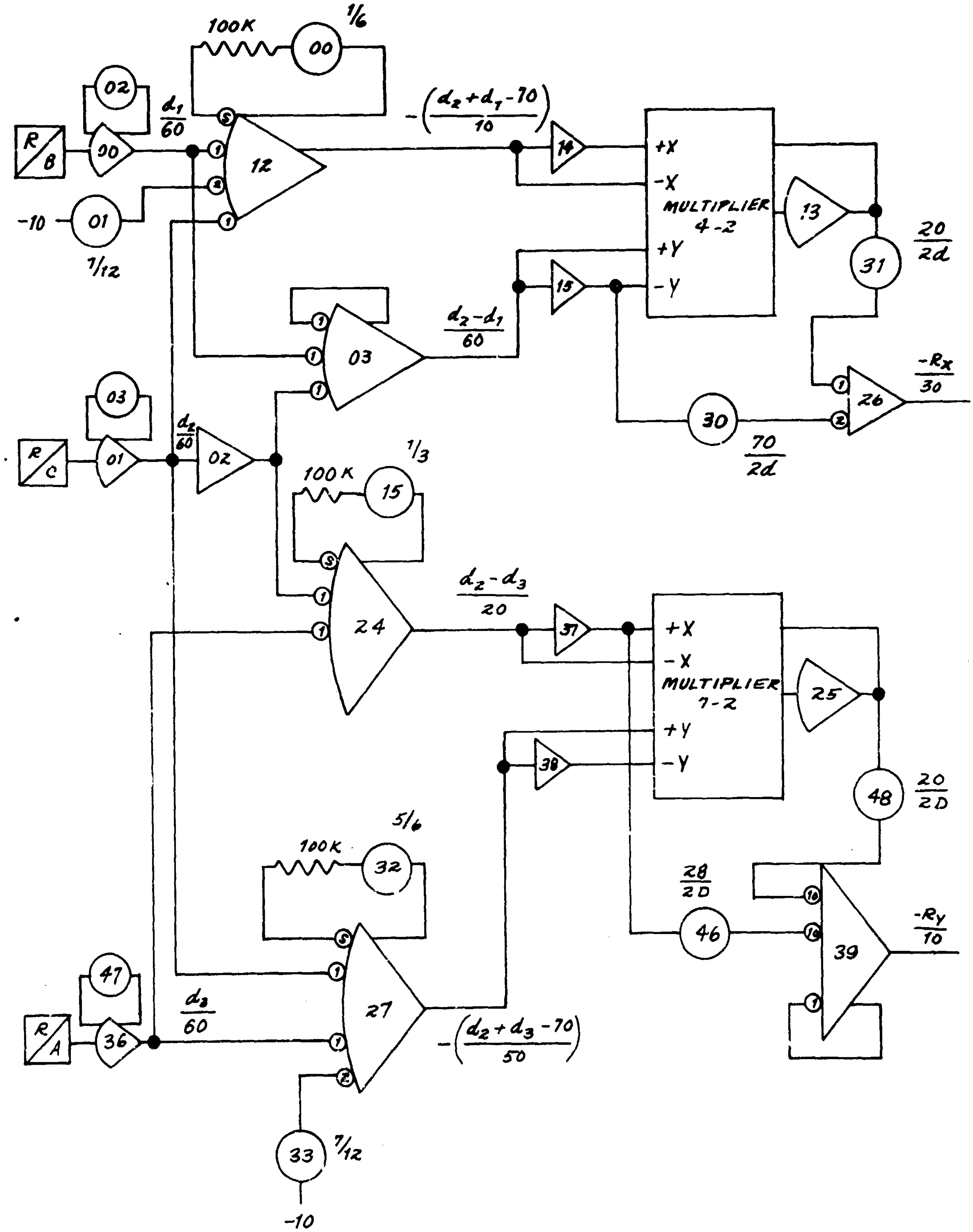

Figure A-11: COMPUTER MECHANIZATION - HORIZONTAL POSITION LOCATION COMPUTATIONS

	MEASURED		MEASURED DECIMAL		COMPUTED SCALED		COMPUTED DECIMAL		ERROR (MEAS-COMP)		D/DC CONVERTER OUTPUT 1.000= 10 VOLTS (60 FT)		
	-Rx	-Ry	-Rx FT.	-Ry FT.	-Rx/30 A26	-Ry/10 A39	-Rx FT.	-Ry FT.	Rxe FT.	Rye FT.	d1 A00	d2 A01	d3 A36
1	15'1¾"	-6'0"	+15.15	-6.00	+.507	-.578	15.21	-5.78	-.06	-.22	.239	.735	.781
2	15'1¾"	0	+15.15	-0.00	+.504	-.002 .026	15.12	-.02 -.26	+.03	+.02 +.26	.288 MEAS. 17'3"	.750	.752
3	15'1¾"	+6'0"	+15.15	+6.00	+.505	+.629	+15.15	+6.29	+.00	-.29	.360	.781	.732
4	0'3"	+6'0"	+0.25	+6.00	+.006	.607	+.18	6.07	+.07	-.07	.551	.556	.485
5	0'3"	0.0	+0.25	-0.00	+.008	.029	+.24	0.29	+.01	-.29	.508 MEAS. 30'4"	.515	.511
6	0'3"	-6'0"	+0.25	-6.00	+.007	-.589	+.21	-5.89	+.04	-.11	.480	.490	.549
7	-19'3"	-5¾"	-19.25	-0.47	-.638	-.052	-19.14	-0.52	-.11	+.05	.813 MEAS. 48'11"	.234 14'0"	.244 14'9-1/2"
8	-20'9½	+5'9"	-20.79	+5.75	-.726	+.585	-21.78	5.85	+.99	-.10	.884	.307	.151
9	-20'9½"	-6'3½"	-20.79	-6.29	-.727 -.800	-.622	-21.81 -24.00	-6.22	+1.02	-.07	.846*	.151 MEAS. 9'1½"	.315 18'10"

AMPLIFIER SETTINGS

	INPUT	OUTPUT
B	MAX	MAX
A	MAX	MAX
C	MAX	X100

*SHOULD HAVE BEEN .825.
PROBABLY MISSED FIRST CYCLE.

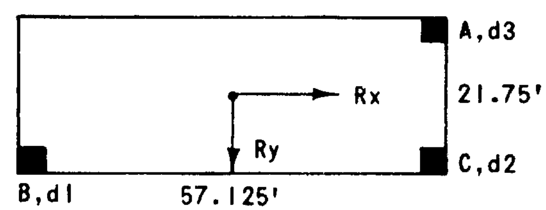

Table A-2 RANGE CHECKOUT COMPUTATION SHEET

2.3.3 Conalog Input Conditioning

Conalog input conditioning computations consisted of (1) transforming the sensor information into the appropriate coordinate system and scaling the information for use with the Conalog* and (2) adding rate and acceleration terms to the sensor signals for operation in a quickened** mode. Compromises were made in satisfying both functions in order to restrict computer circuitry to that available on one TR-48 computer.

A computer mechanization diagram for Conalog conditioning is shown in Figure A-12. This particular mechanization is suitable for all-azimuth vehicle orientations. Programming changes are required in which all-azimuth capability is sacrificed for satisfactory operation at large pitch angles. In the mechanization diagram, sectors labeled (1) show circuitry for differentiating signals from the position location system and the depth sensor. The differentiated signals are required for both Conalog velocity inputs and quickening. Sectors (2) show circuitry for transforming stick inputs, which were used to approximate accelerations for quickening, from body-fixed to earth-fixed coordinates. As noted above, the transformation is valid only in the horizontal plane. Sectors (3) show signals being added for quickening. Sector (4) shows a transformation from the earth-fixed coordinate system of the position location system to the earth-fixed coordinate system of the Conalog commanded path. Sectors (5) show switching, scaling, and the addition of nonlinearities required for the Conalog inputs. Sector (6) shows the inverse trigonometric transformation from the sine and cosine components of heading, which are the gyro outputs, to heading angle. Sector (7) shows the addition of heading quickening; and Sector (8) shows the all-quadrant transformation of quickened heading angle back to sine and cosine components, which are required for the Conalog inputs. Sector (9) shows the generation of heading error, required by the Conalog, according

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* A Contact Analog Display Input Chart is given in Table 7, Reference A3.

** Honeywell's reports, References A3 and A4, describe the characteristics of quickened displays.

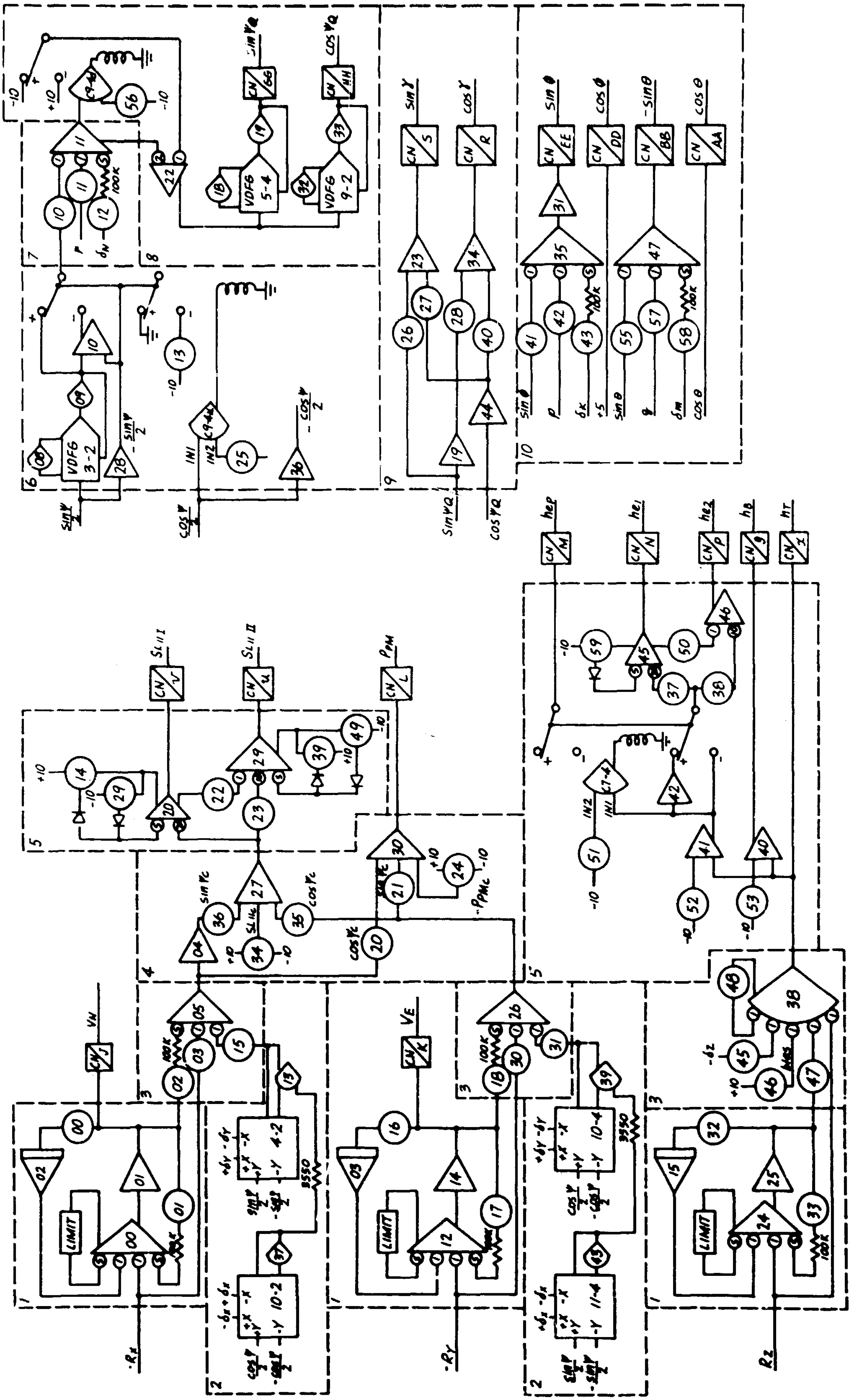

Figure A-12: COMPUTER MECHANIZATION - CONALOG CONDITIONING to the trigonometric identities:

$$\sin \gamma' = \sin(\psi_c - \psi) = \sin\psi_c \cos\psi - \cos\psi_c \sin\psi$$

$$\cos \gamma' = \cos(\psi_c - \psi) = \cos\psi_c \cos\psi + \sin\psi_c \sin\psi$$

Sector (10) shows the quickening of linearized roll and pitch angles.

2.4 Junction Box

The junction box identified in Figure A-1 is the main shore-based distribution center for transferring signals and power to and from the model. Its original wiring is described in Reference A1, pages 27-35. For purposes of the free-running test program, the internal connections were modified to those shown in Figure A-13. Only those connections which were utilized in the free-running tests are identified.

2.5 Umbilical Cable

All power for operation of the model - propeller drives, blade angle control, and instrumentation - was supplied through an umbilical cable having connections, as shown in Figure A-14. The complete cable contained 72 leads in 37 single wires, 23 paired wires, 8 three wire leads, and 4 coaxial lines. Total usable length of the cable was about 160 feet.

The cable was connected to the model through the floodable sail and sealed access cover plate. Sealing at the junction with the hull was particularly difficult because of inability to provide suitable bonding of the sealant to teflon-coated wires. Although a completely leak-tight seal was not achieved, a satisfactorily low leakage rate of the air used for model pressurization was obtained.

Styrofoam blocks were placed at intervals along the entire length of the cable to provide positive buoyancy for prevention of entanglement of the cable with the propellers. A balance between the slight positive buoyancy of the cable and the slight negative buoyancy of the model was

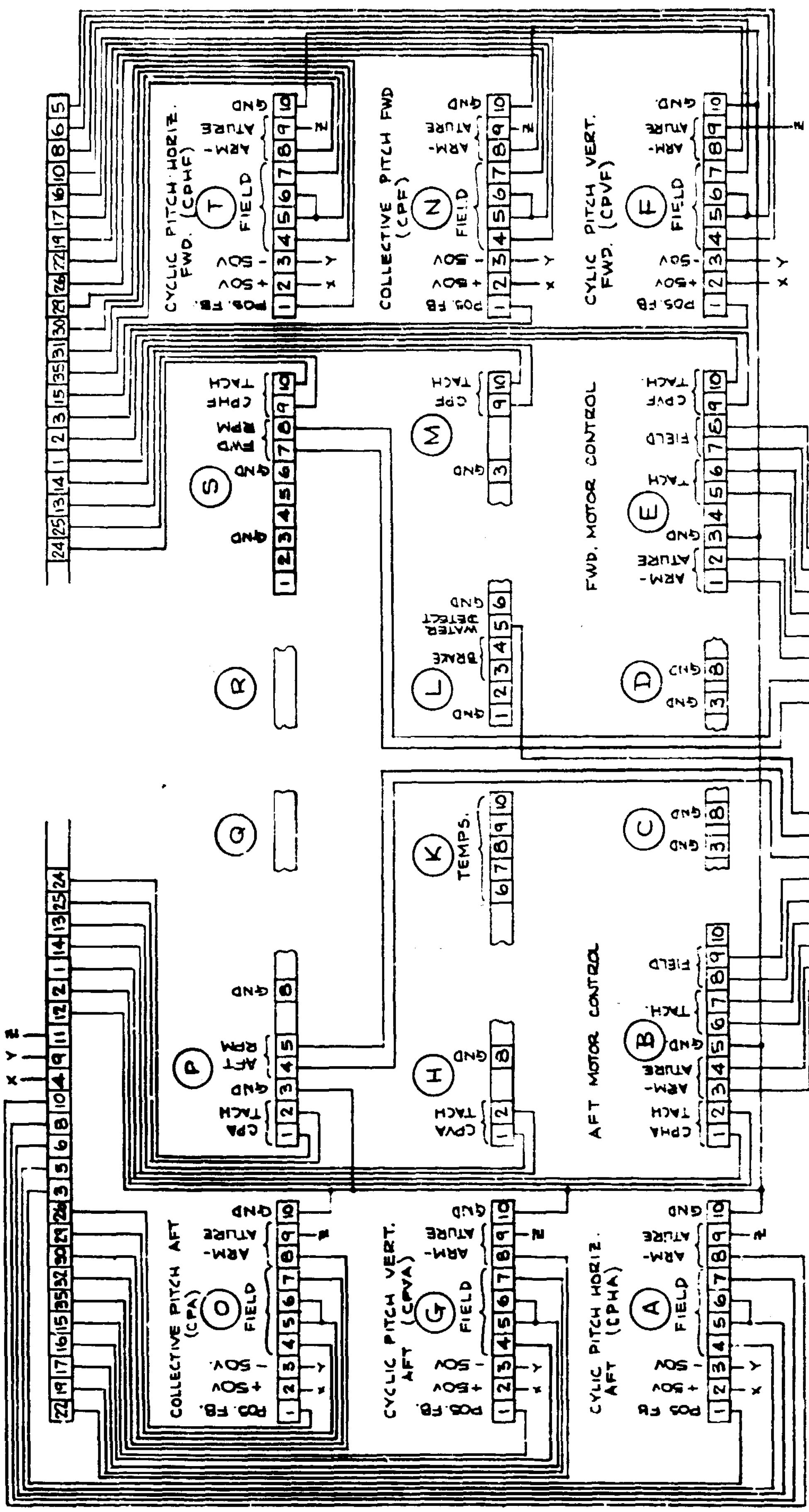

Figure A-13: JUNCTION BOX CONNECTIONS

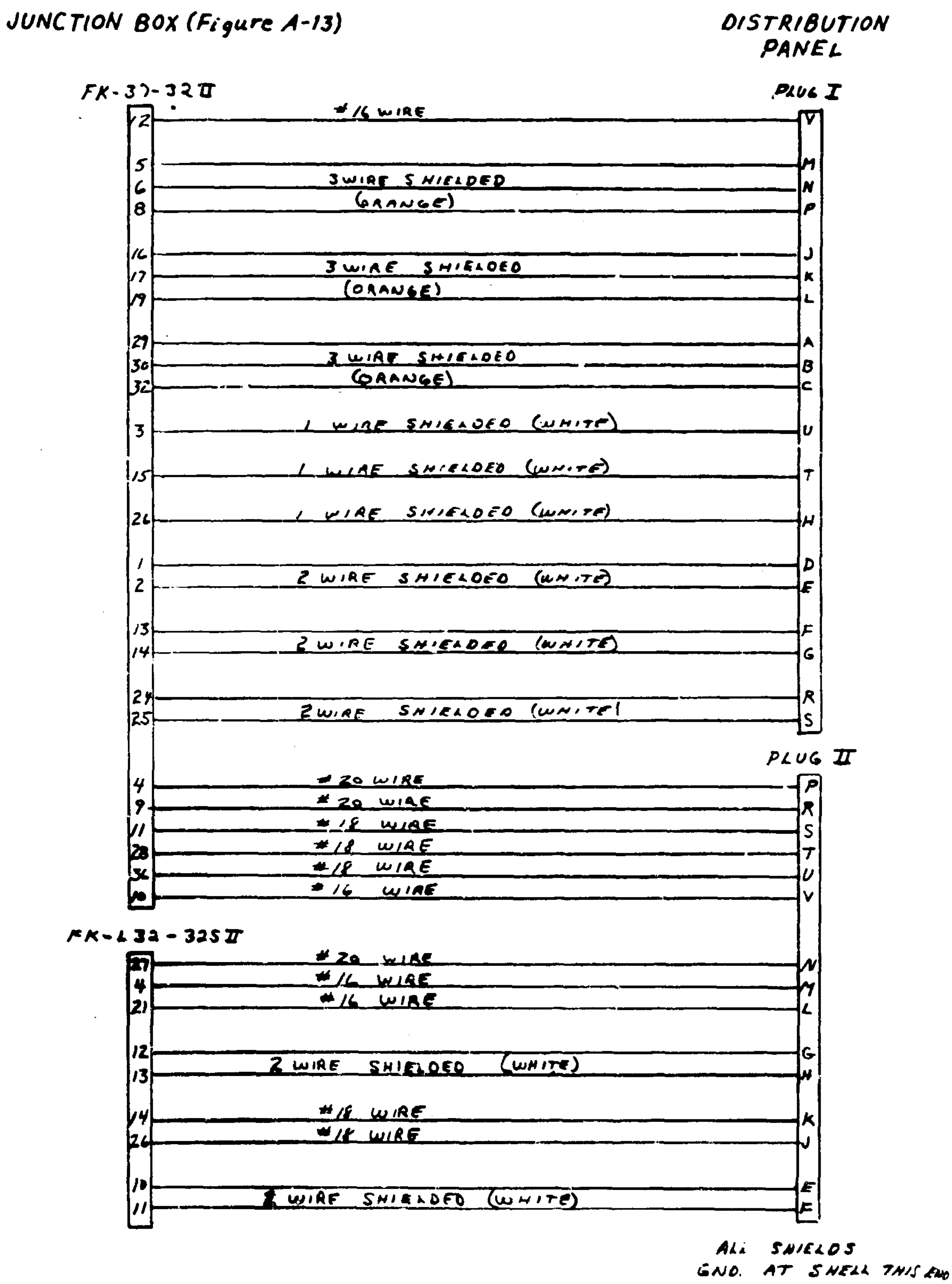

Figure A-14a: UMBILICAL CABLE - AFT PROPELLER SECTION OF CABLE

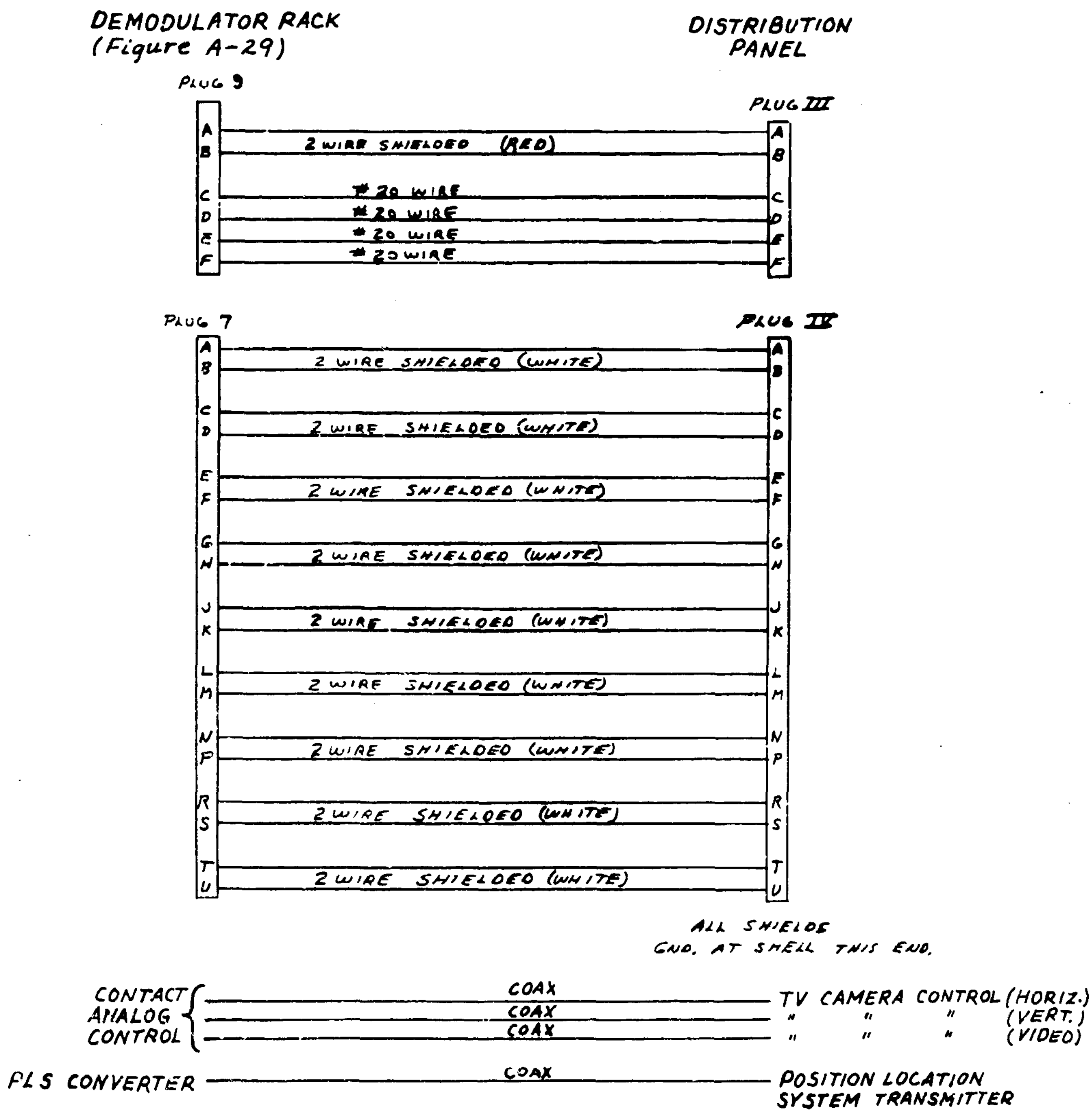

Figure A-14b: UMBILICAL CABLE SENSING SECTION

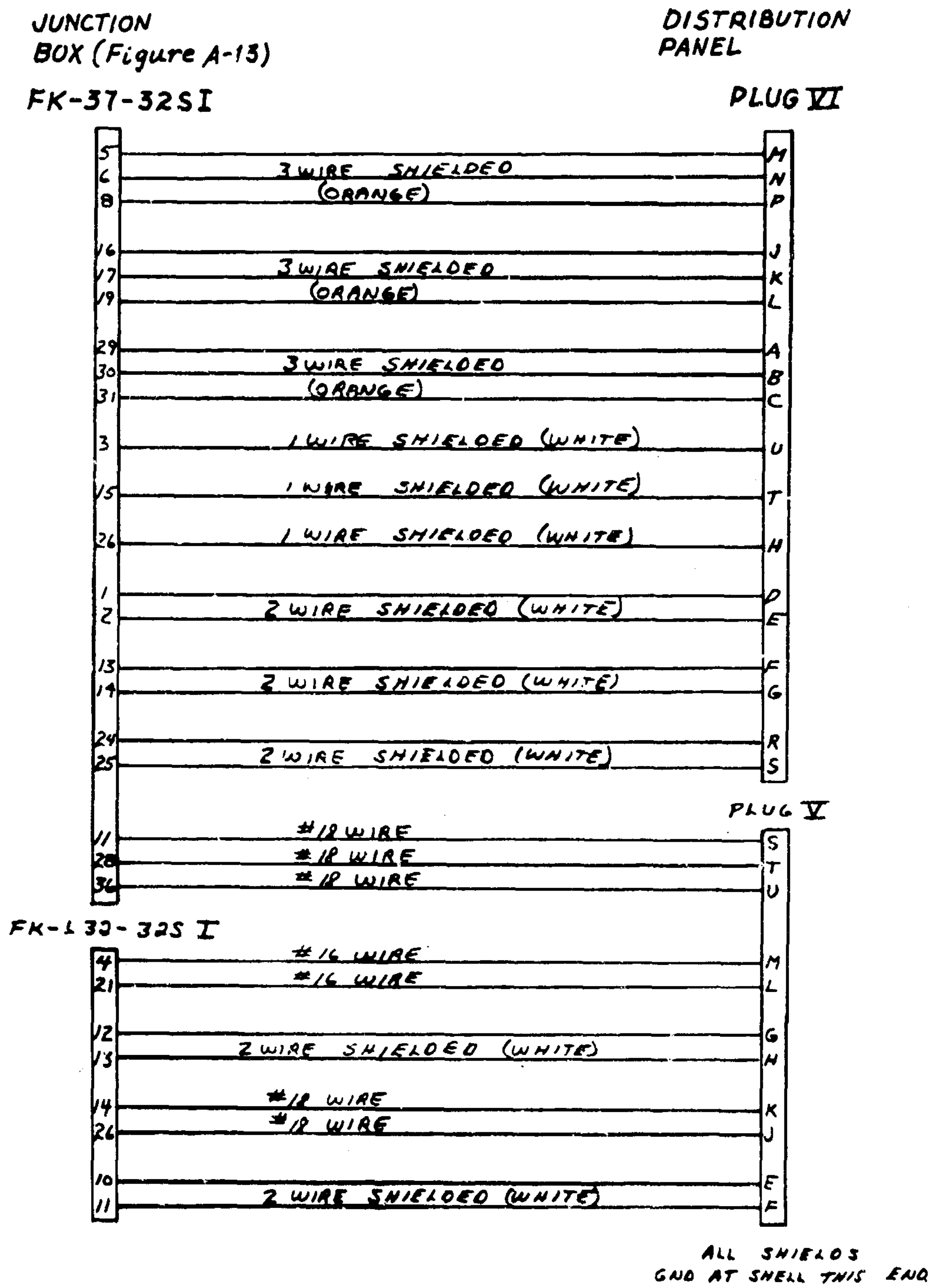

Figure A-14c: UMBILICAL CABLE -FORWARD PROPELLER SECTION established to produce an equilibrium point at about four feet submergence for tests in the Circulating Water Channel and 10 feet submergence for demonstrations in the Test Pond. Cable flexibility appeared to have little influence on test results but cable drag, due primarily to the flotation blocks, prevented the accumulation of useful quantitative information at high model speeds.

Connections from the umbilical cable terminals in the model to the distribution panel are shown in Section 2. 13.

2. 6 Model

The model as used in the free-running test series was essentially that used in the earlier captive model tests. NSMB drawings S3481-1 through 73 give a complete description of its mechanical design details. Additional descriptions are provided in Reference A5 and in the main body of this report. Several minor modifications made to improve compatibility of the basic model with the purpose of and the equipment used in the free-running tests are discussed below.

A simplified inboard profile of the model as adapted for these tests is shown in Figure A-15. The addition of the fore and aft sensor packages and of the electrical distribution panel are the most noteworthy modifications to the original design. The ballasting system and the propeller and blade drive mechanisms are unchanged except for the removal of a brake unit from the forward propeller.

For all operations in the free-running model program, the model was internally pressurized with air. Initially, the model was merely filled with air to a pressure of 6 psi above the ambient air pressure and operated until the internal pressure fell below the pressure associated with the deepest submergence (9 feet) encountered in the tests. Later, when submergence depths increased to 20-25 feet, it was found that continuous pressurization to 15 psi above the ambient air pressure was required because of the relief valve action of the rotating seals at the propellers. This technique proved to be quite satisfactory.

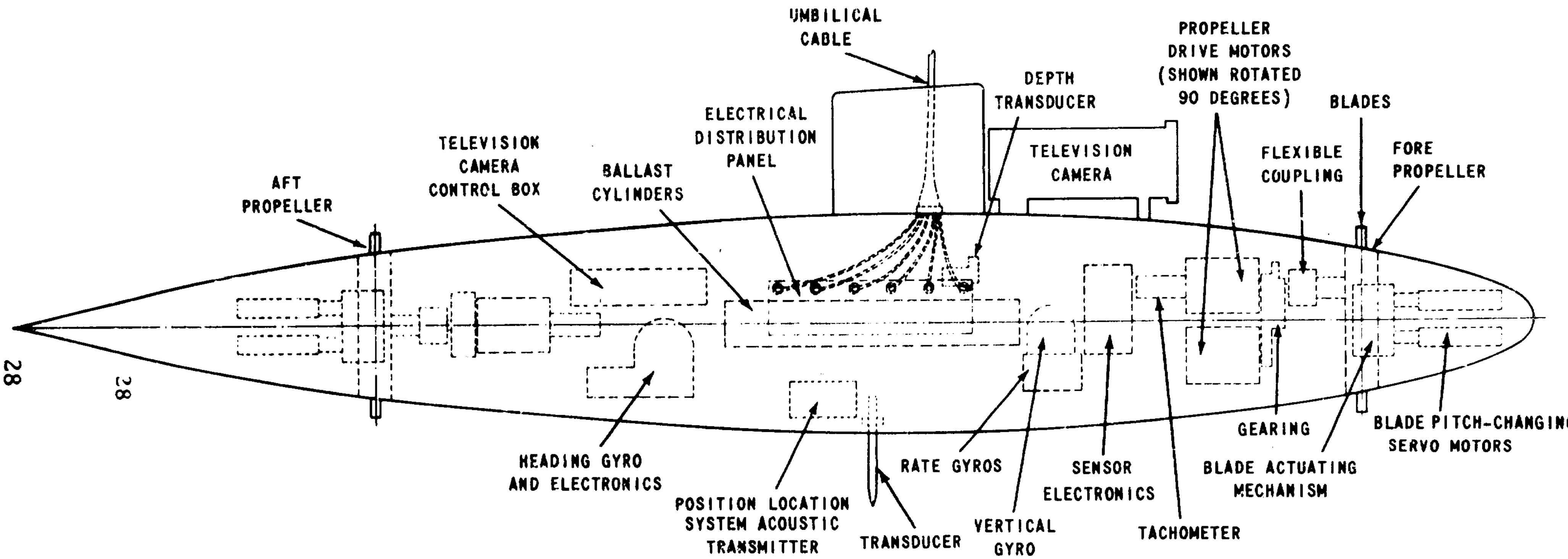

Figure A-15: SIMPLIFIED INBOARD PROFILE OF THE TPS MODEL

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Ballasting and balancing of the model for neutral buoyancy and zero metacentric height were accomplished with negligible errors utilizing the ballasting arrangement provided, plus some additional weights forward of the center-of-gravity. Calculations indicate that a weight/displacement match to within one pound and a negative metacentric height of less than 0.1 inch were achieved.

In addition to these adaptations, minor modifications, as listed below, were made.

1. For convenience of installation of the umbilical cable, the sail was located about nine inches forward of its location on the captive models and its height was reduced by about 5%. No effects from these changes were evident.

2. Radial spines were attached to the hull near each of the propellers to provide protection for the blades in case of impact with test basin structure. Since the total frontal area of these spines was only a small fraction of the propeller annular flow area, it is unlikely that they affected model hydrodynamics.

3. All position servo feedback potentiometers received their excitation voltages in parallel from a single supply; all water detectors were wired in parallel; and none of the potentiometers supplied in the NSMB design for blade angle instrumentation purposes were used. (Blade angle information was obtained from the servo feedback signal.) These changes were made solely to minimize the size of the umbilical cable.

4. The torsion springs on the propeller blade drive rods, used initially to provide constant loading against the wobble-plate mechanism, were disconnected.

General reliability of the model-borne equipment was excellent. Some early difficulties caused by slippage in mechanical connections (e.g., blade drive clutch mechanisms and feedback tachometer attachments) were encountered and, toward the end of the test program, a number of electrical problems appeared (e.g., open-circuited servomotor armatures); but, in some 200 hours of in-water test time, equipment operation was quite satisfactory.

2.7 Control Input Device

The six degree-of-freedom control input device used in the free-running model tests is shown in Figure A-16 and an illustration of the control input motions is given as Figure A-17. The mechanisms used in the rotational degrees of freedom are essentially the same; an exploded view of a typical unit is shown in Figure A-18. The primary features of this design are:

1. Convenient adjustability of force-gradient, breakout force, and damping force.
2. Axial loading of compression springs for constant force-gradient.
3. Essentially constant damping force through use of face-loaded teflon disks producing coulomb friction.

Spring force for motions about the base element is obtained with torsion bar restraint as shown in Figure A-19. Damping is provided by teflon disks as with the upper structure mechanisms.

The design force gradients and angular ranges for the various motions of the device are as listed below

	Range (deg.)	Gradient (lbs./deg.)
Pitch	±30	.3
Roll	±30	.3
Yaw	±30	.3
Longitudinal	± 7.5	1.0
Lateral	± 7.5	1.0
Vertical	±80	---

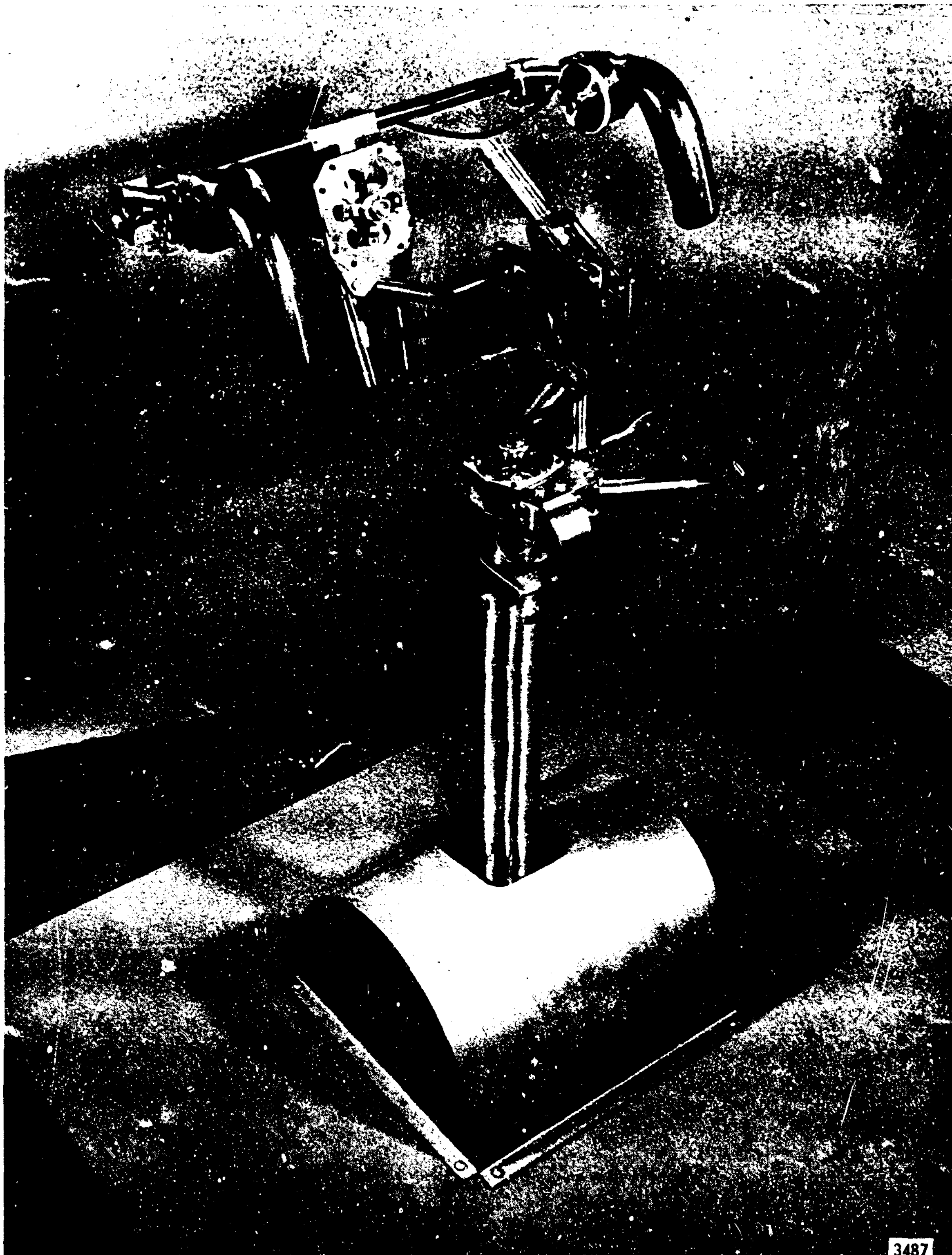

Figure A-16: CONTROL INPUT DEVICE

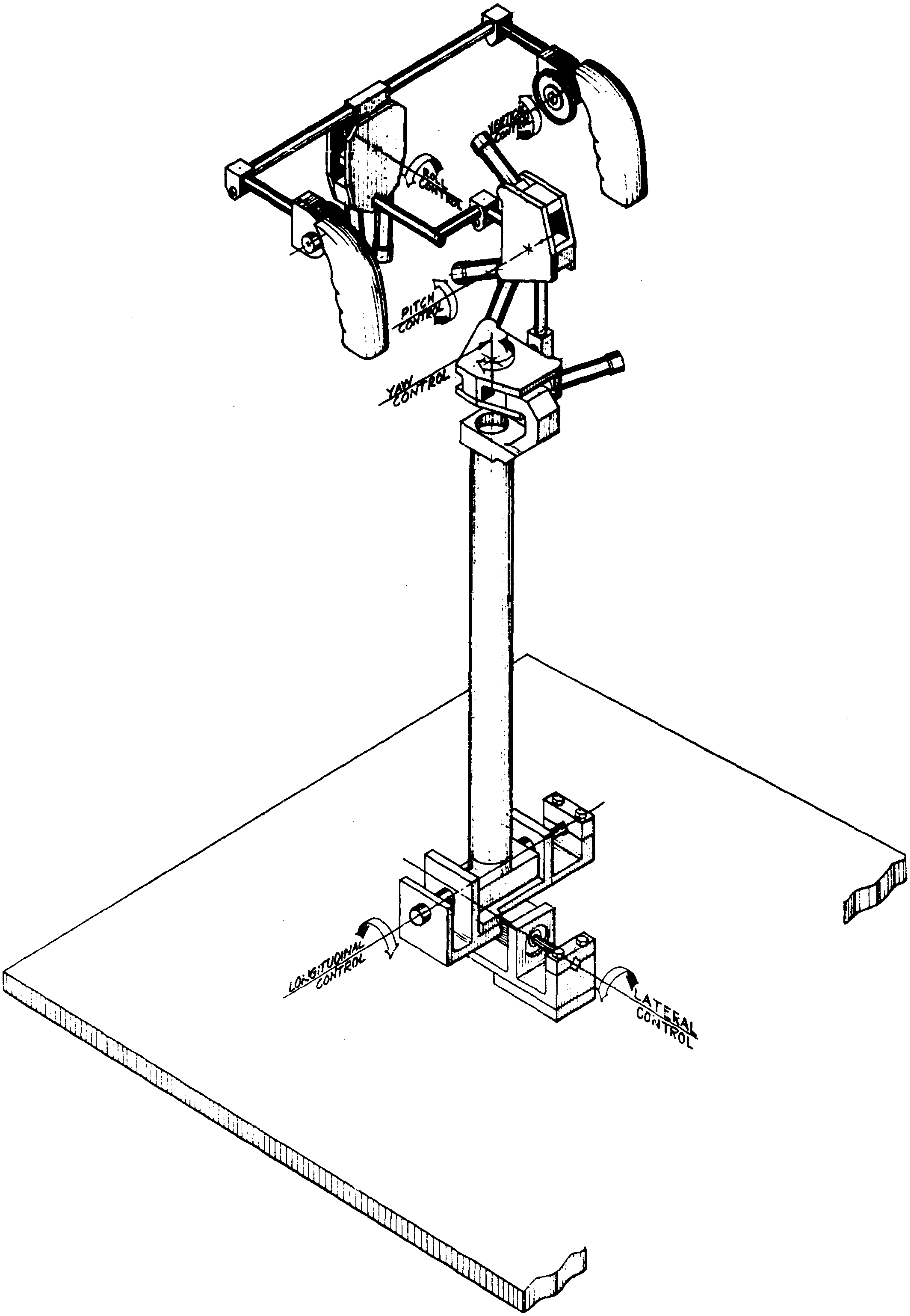

Figure A-17 CONTROL INPUT DEVICE - MOTION COMMANDS

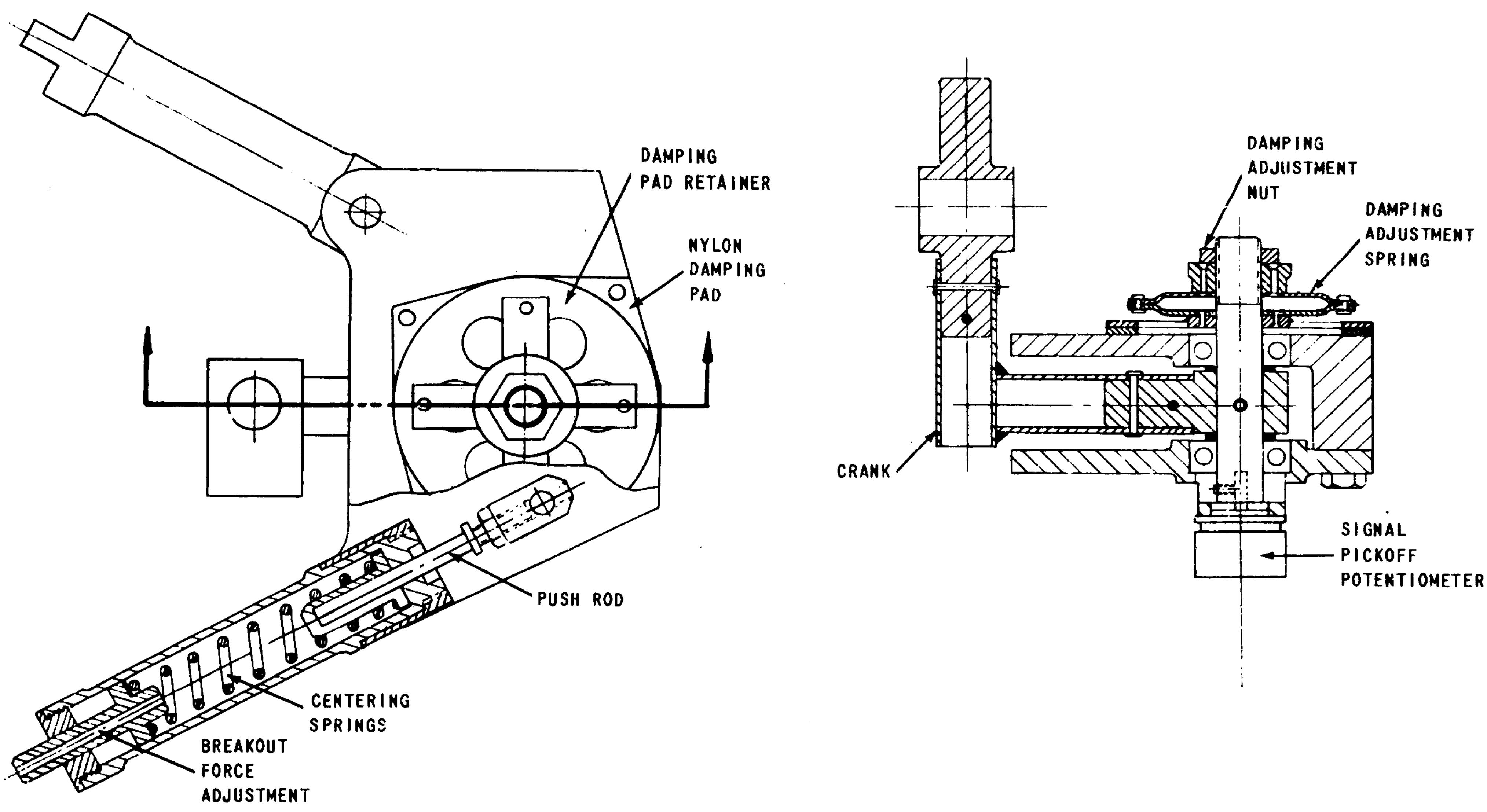

Figure A-18: CONTROL INPUT DEVICE - UPPER STRUCTURE MECHANISM

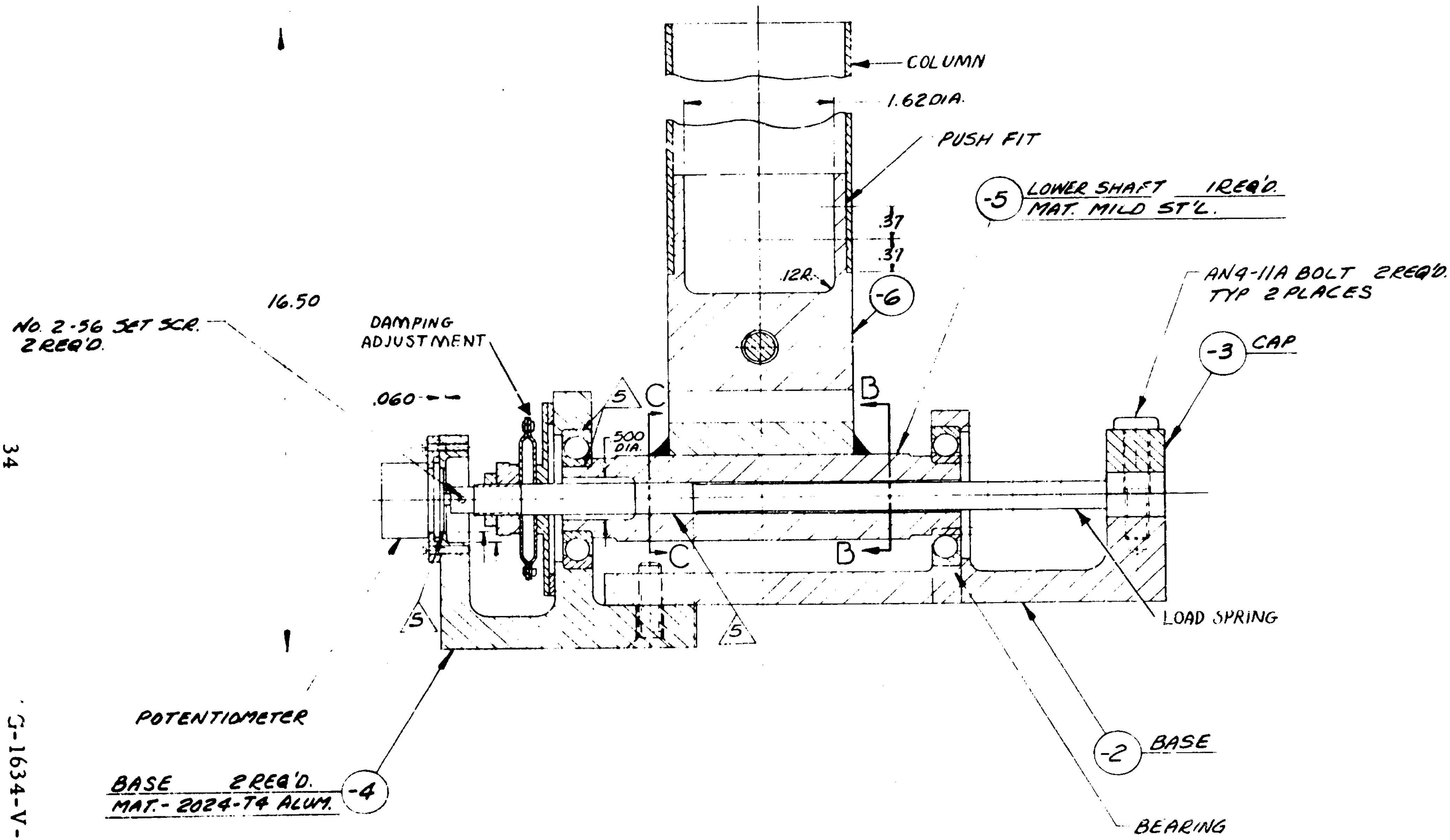

Figure A-19 CONTROL INPUT DEVICE - LOWER STRUCTURE MECHANISM

A separate set of springs for the rotational motion control units was available for reducing the gradients to 90% of those shown.

An electrical schematic diagram of the motion pickoff connections is given in Figure A-20. All potentiometers are of the infinite resolution, deposited carbon film-type with resistance of 1000 ohms and active length of 320 degrees. Each is center-tapped to provide a zero reference voltage at zero input command.

2.8 Sensors

Instrumentation to provide data with which to evaluate model performance and from which to secure the necessary information for use in the feedback control systems were installed specifically for the free-running test program. These functions are discussed in the main body of this report. In this appendix, some of the design characteristics of the sensor systems will be described and pertinent diagrams will be presented.

A generalized block diagram of the complete sensor system, as mounted in the model, is shown in Figure A-21. As indicated, all instruments are operated on 400 cycle power supplied through the umbilical cable. Information signals, after amplification, are demodulated for use in the DC control system and for recording. Physical mountings of the instrument packages, before installation in the model, are shown in the photograph, Figure A-22.

Rate Gyros

Angular rate information about each of the three orthogonal body axes is obtained from one of three similar rate gyroscopes whose input axis is appropriately oriented. The principal characteristics of these gyros are:

Manufacturer:	U. S. Time Corp.
Range:	40 degrees/second (max.)
Threshold:	.01 degrees/second
Pickoff:	synchro

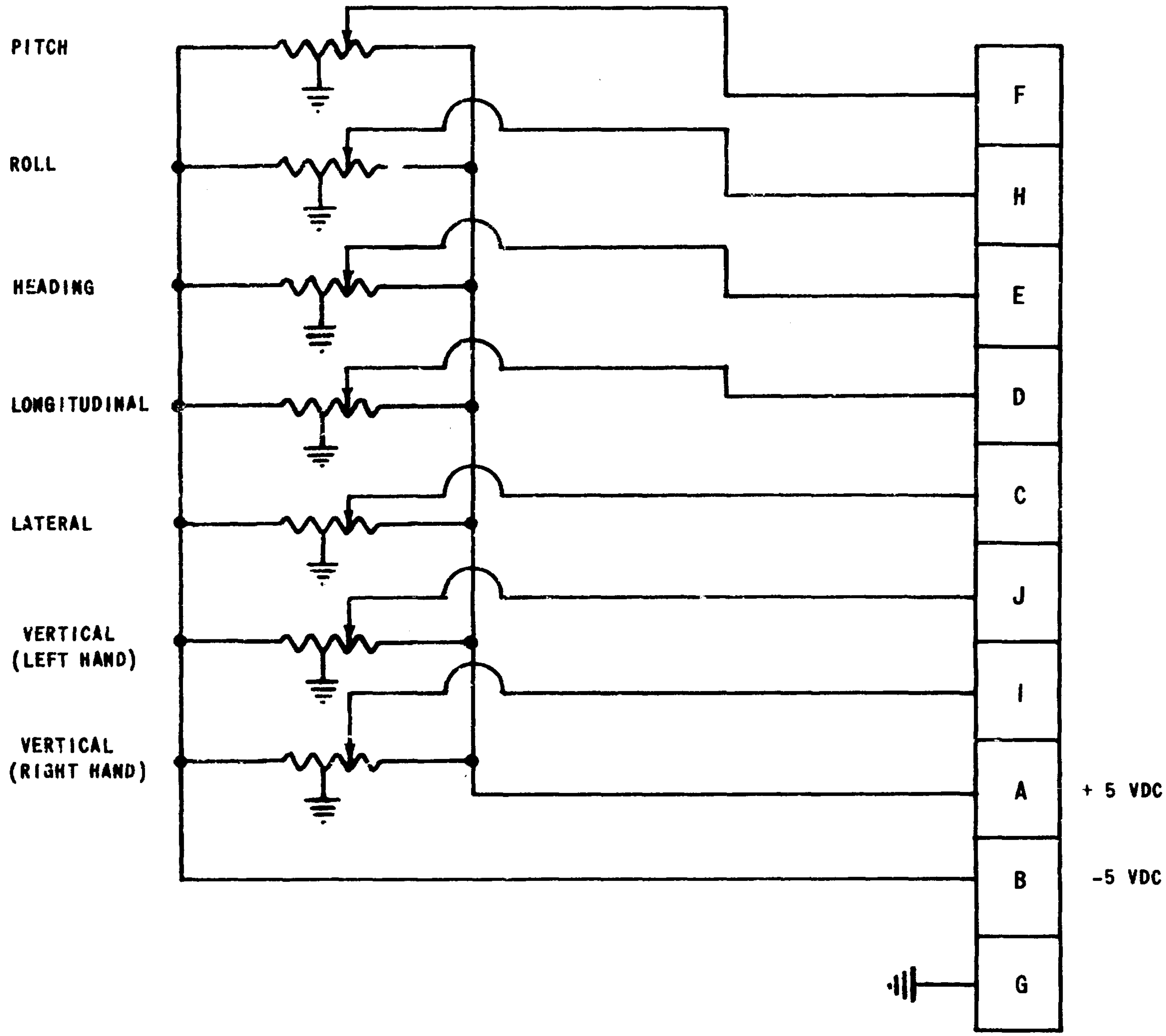

Figure A-20 CONTROL INPUT DEVICE - ELECTRICAL SCHEMATIC

11 FRAMES

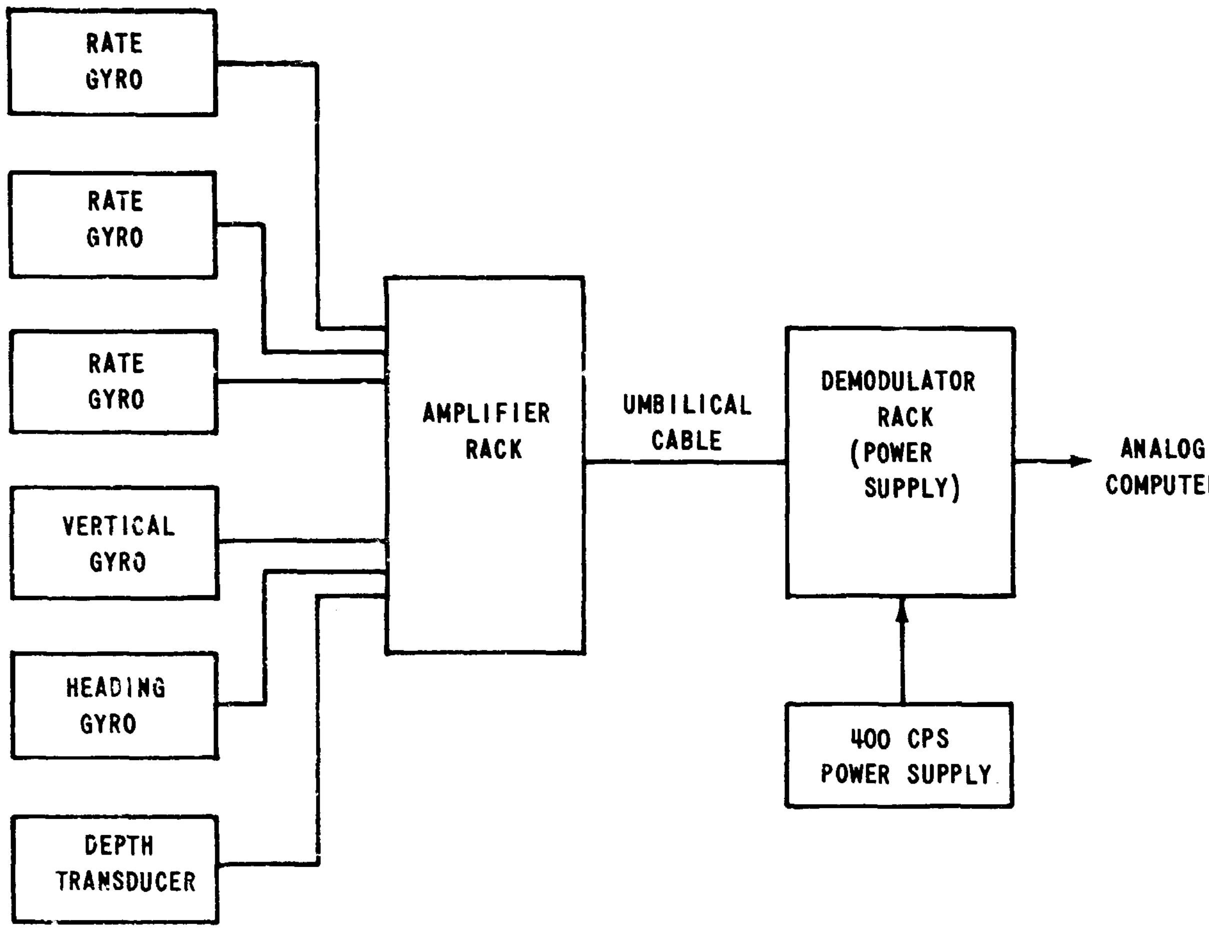

Figure A-21 SENSOR SYSTEM BLOCK DIAGRAM

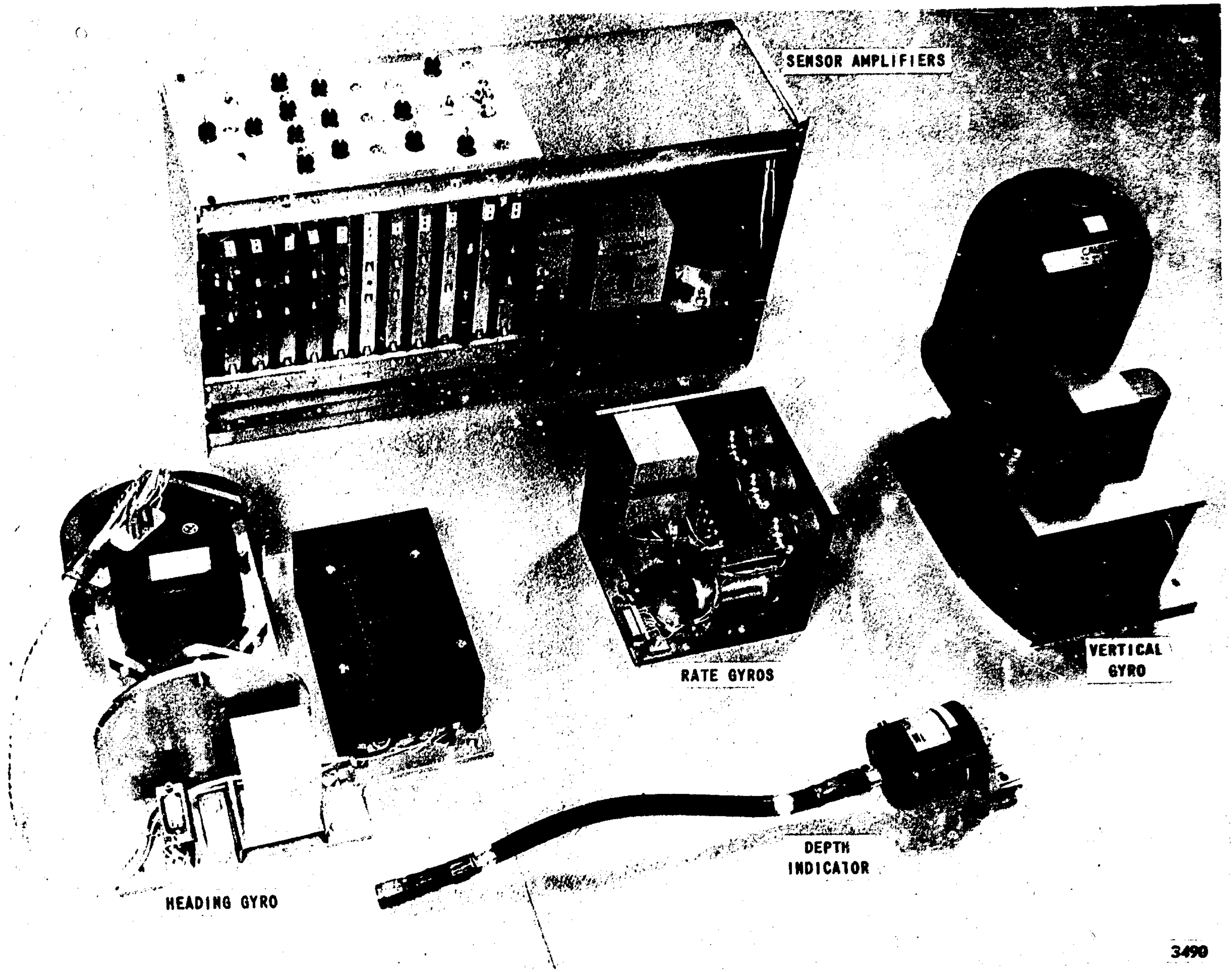

Figure A-22: SENSOR EQUIPMENT

Sensitivity:	110 millivolts/degree/second
Excitation:	26 volts, 400 cps
Model:	40

Figure A-23 shows the signal pickoff and spin motor connections for these units.

Vertical Gyro

Roll and pitch attitude angles with respect to a horizontal plane are obtained from the vertical gyro. Its pertinent characteristics are:

Manufacturer:	Kearfott
Model:	423305
Range:	85° inner axis; 360° outer axis
Pickoff:	synchro
Sensitivity:	.206 volts/degree
Excitation:	26 volts, 400 cps
Spin Motor:	400 cps; 115 v, 3Ø, (40 watts, starting)

The unit was mounted in the model so that roll angle was measured on the inner gimbal pickoff and pitch angle on the outer gimbal pickoff to a[illegible]d gimbal lock during large magnitude pitch maneuvers. Provision for fast erection is included in the design. A schematic diagram of its electrical connections is shown in Figure A-24. The gyro was used throughout the free-running test program without difficulty.

Heading Gyro

A two-degree-of-freedom cageable free gyro was utilized to obtain heading angle information with respect to a reference line established at the instant of uncaging. The important characteristics of this unit are:

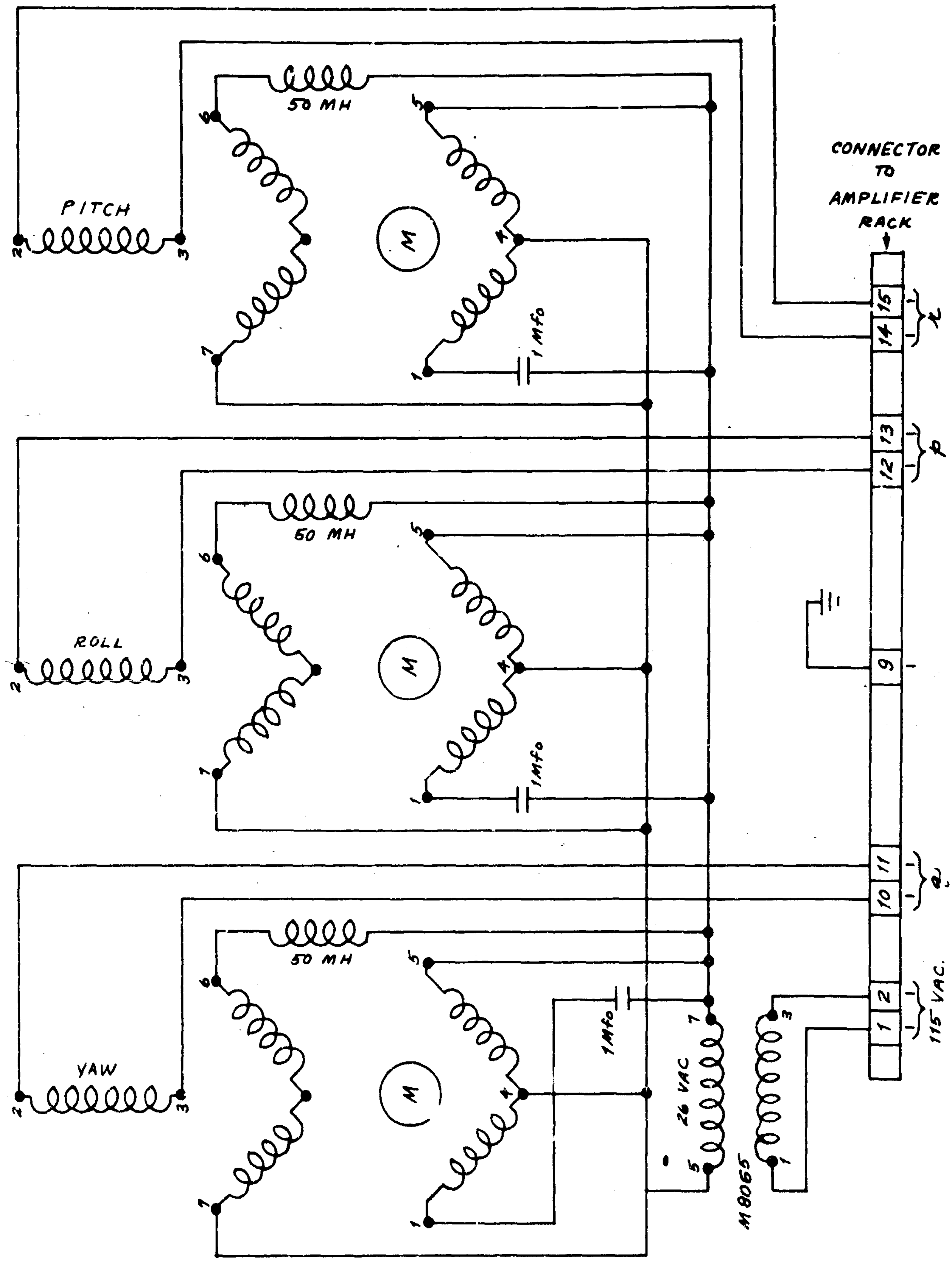

Figure A-23 RATE GYRO CONNECTIONS

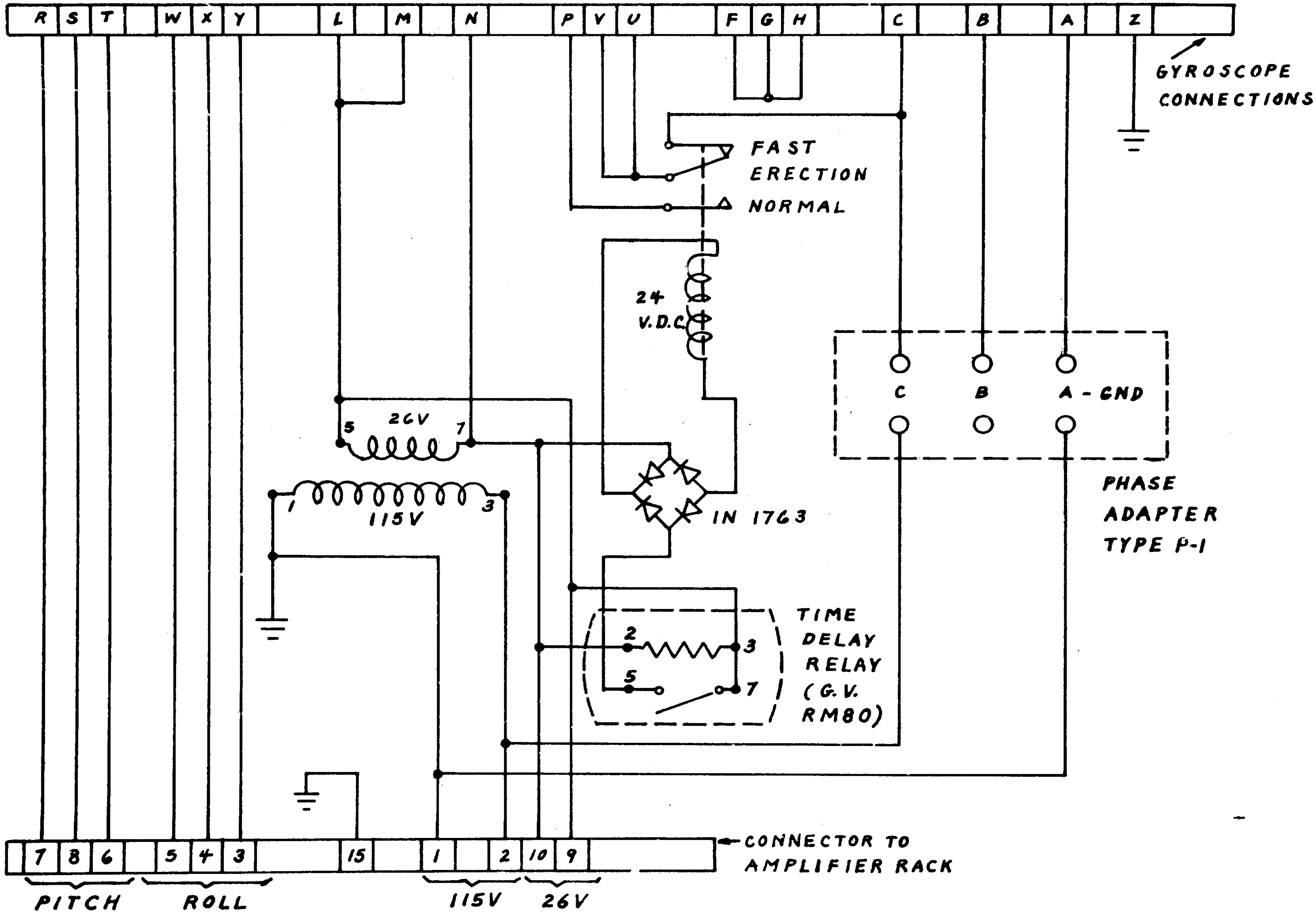

Figure A-24: VERTICAL GYRO CONNECTIONS

Manufacturer:	Iron Fireman
Model:	4100A
Range:	360 degrees on outer gimbal
Pickoff:	synchro
Drift Rate:	.25 degree/minute

In order to maintain heading reference even though the model might be pitched to 90 degrees, the gyro case was pendulously mounted about an athwartship axis which coincided with the spin axis of the gyro. (See Figure 6.2-1 in the main body of the report.) An electrical schematic diagram of the gyro connections is shown in Figure A-25.

Depth Indicator (See Figure A-22)

Measurements of model submergence were obtained with a differential pressure transducer mounted in the model. The application was straightforward and no special design problems were encountered. In operation, a tendency for the Bourdon tube-driven potentiometer wiper to stick resulted in nonlinearities in the transducer output but maximum errors did not exceed one-half foot. The pertinent characteristics of the transducer and the associated circuitry are:

Manufacturer:	Transonics
Model:	1430
Range:	0-50 psia (0-115 ft)
Pickoff:	Wirewound potentiometer - 10K ohms

Sensor Signal Amplifiers

A schematic diagram of one of nine similar feedback amplifiers used to amplify the output signals from the sensors is shown in Figure A-26. These units are transistorized, printed-circuit, rack-mounted cards built by the Cornell Aeronautical Laboratory. Amplifier gain is controllable by adjustment of the feedback resistance (R_F). All units

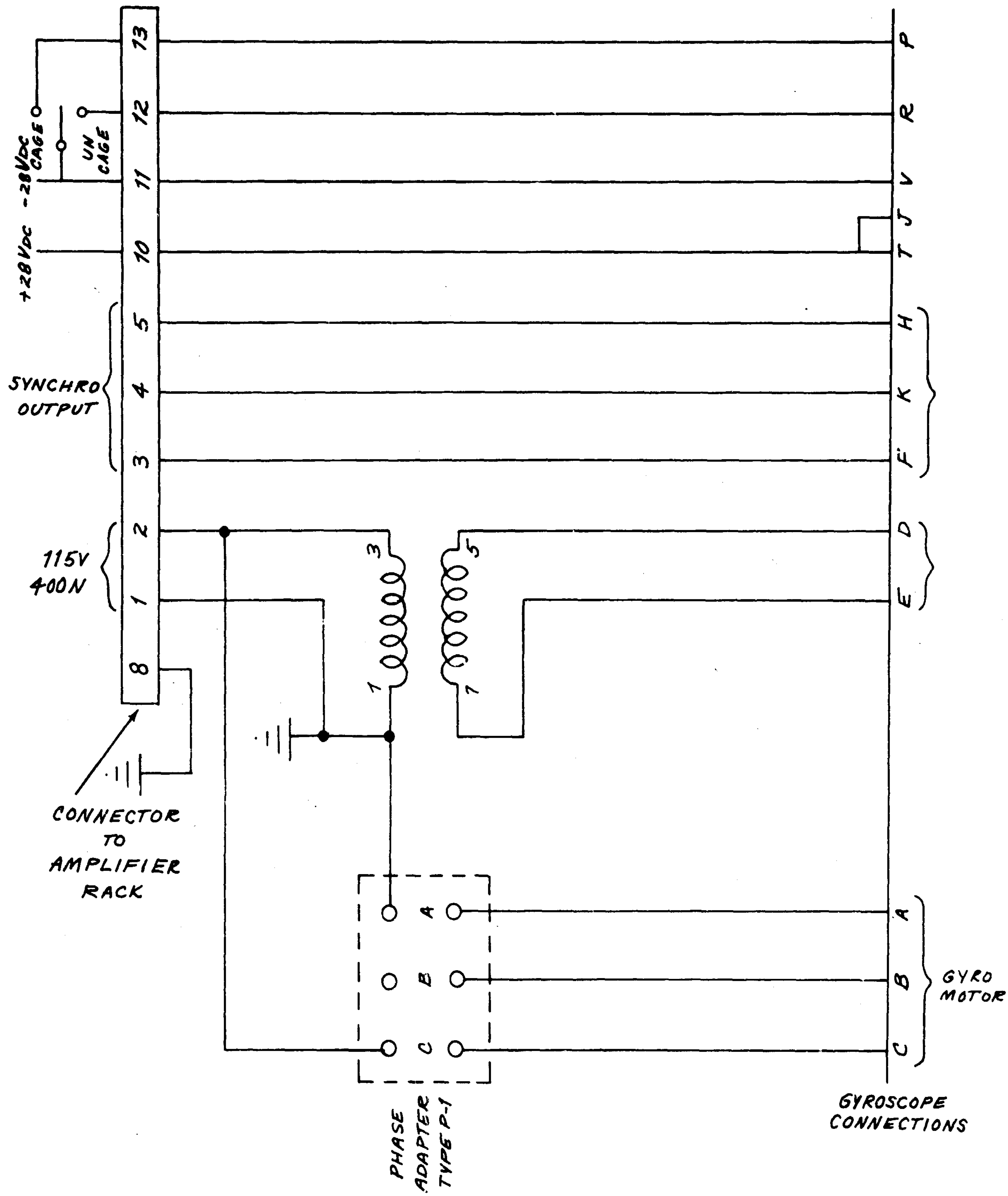

Figure A-25 HEADING GYRO CONNECTIONS

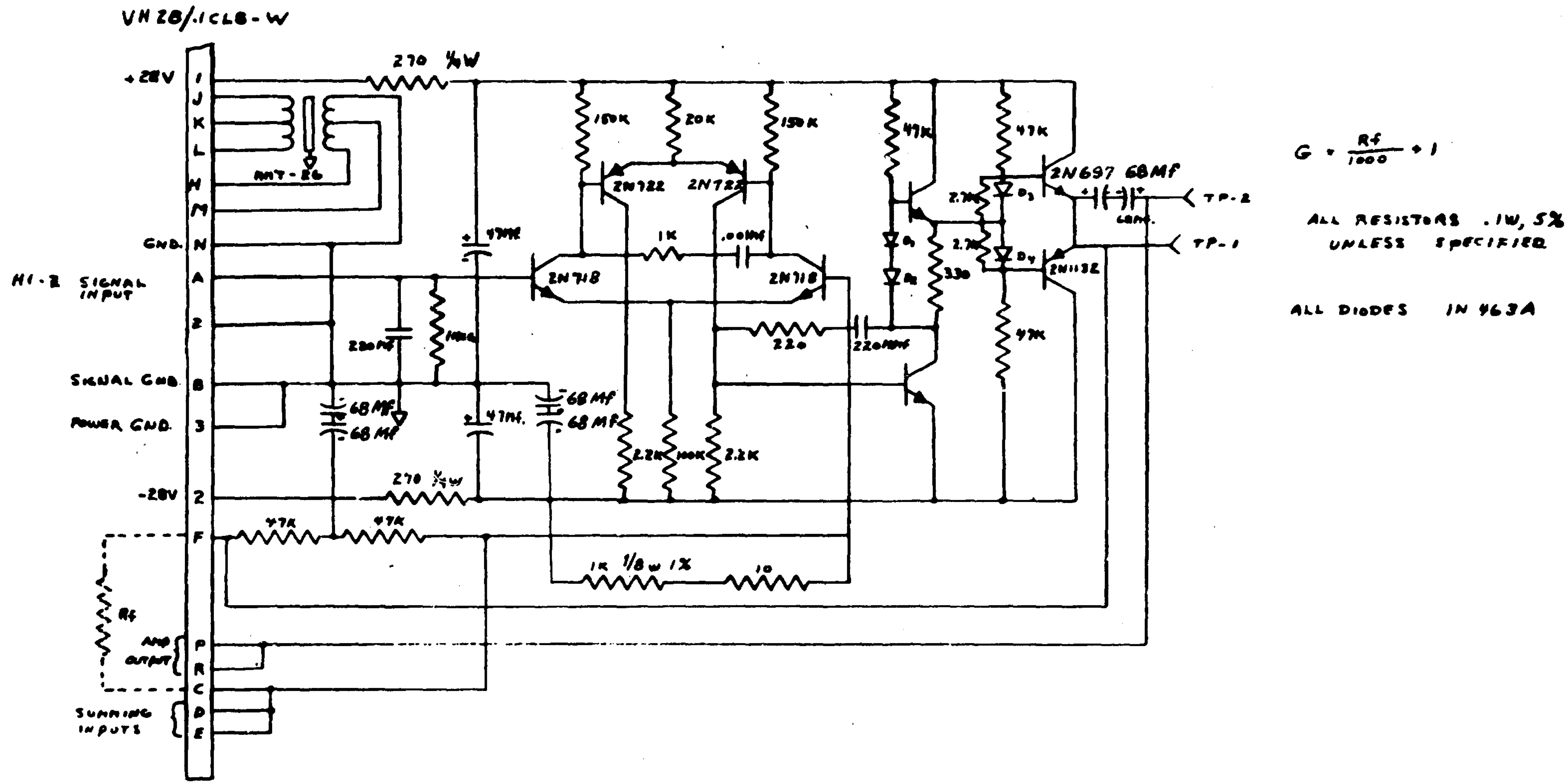

Figure A-26 SENSOR AMPLIFIER - SCHEMATIC DIAGRAM are mounted in a single chassis shown in Figure A-22 and schematically represented in Figure A-27. Note that provision is made for generating both the sine and cosine functions of pitch and yaw angles by utilization of dual-winding synchro transformers.

Sensor Signal Demodulator

Figure A-28 is an electrical schematic of one of five similar dual demodulating channels used to provide direct current signals from the synchro outputs of the sensing components for use in the analog computer. Two channels of demodulating circuitry are mounted on each card; these cards in turn fit into a chassis which is schematically diagrammed in Figure A-29. This chassis also contains the special power supply for the 28 volts DC used in the heading gyro cage/uncage circuit as shown. (See Figures A-7 and A-8 for photograph.)

Indicators (See Figure A-2)

The processed outputs of the vertical gyro and depth indicator (after demodulation and amplification) are displayed on DC galvanometers for use by the control operator. Thus, indications of pitch attitude, roll attitude (in actuality, the sines of these attitude angles), and depth were available to supplement the television monitor display in controllability demonstrations in which direct visual contact with the model was not utilized. The application was quite simple and no problems were encountered.

2.9 Contact Analog

The contact analog system used in the free-running tests was supplied as a single integral unit for the program and was employed without modification. The complete system was assembled by the Norden Division of United Aircraft Corporation and incorporates proprietary designs of a number of components. Detailed diagrams of the electronic circuitry are not available but a general layout of the system is illustrated in Figure A-30. Input requirements to the contact analog for an earlier

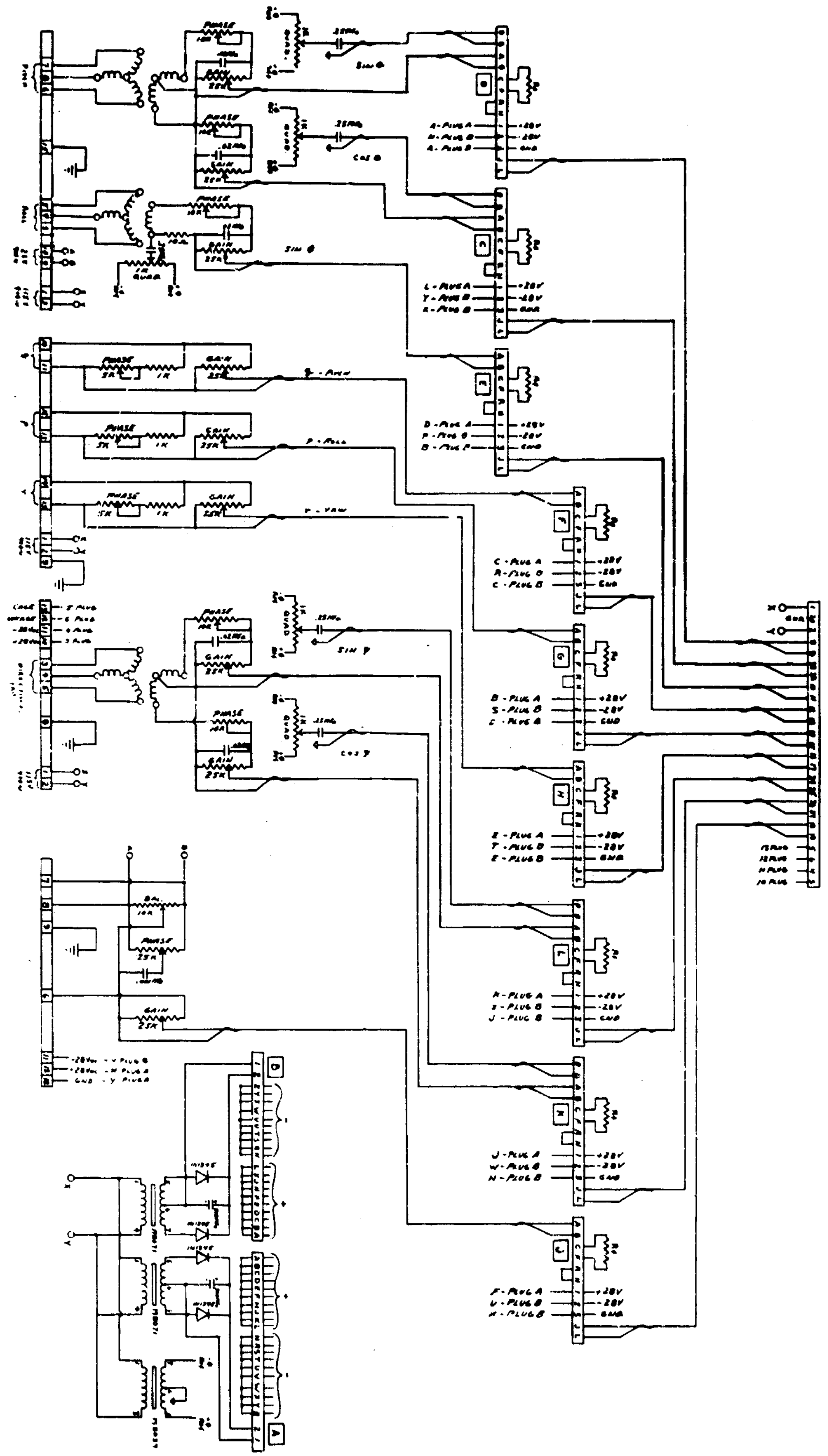

Figure A-27: AMPLIFIER RACK

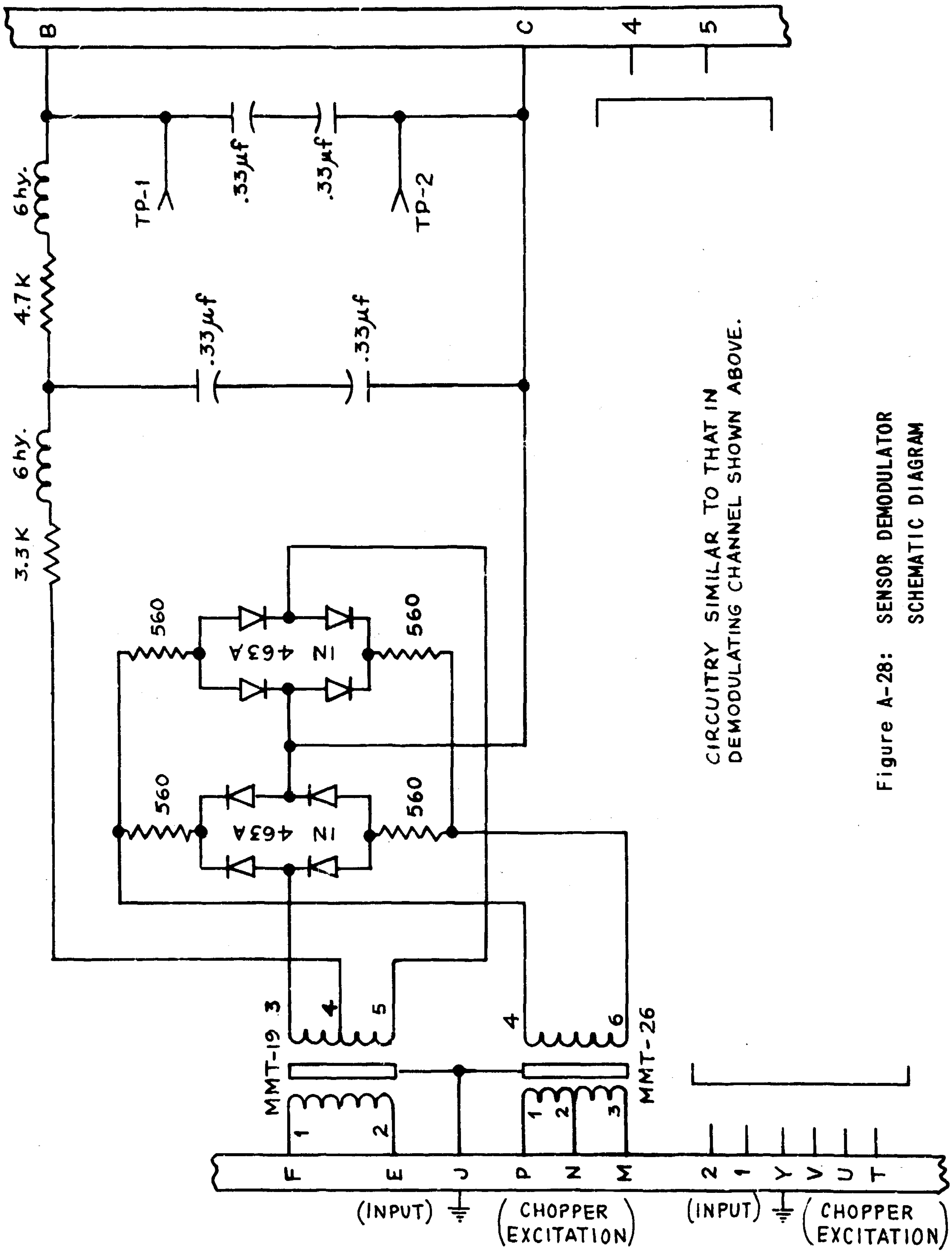

Figure A-28: SENSOR DEMODULATOR SCHEMATIC DIAGRAM

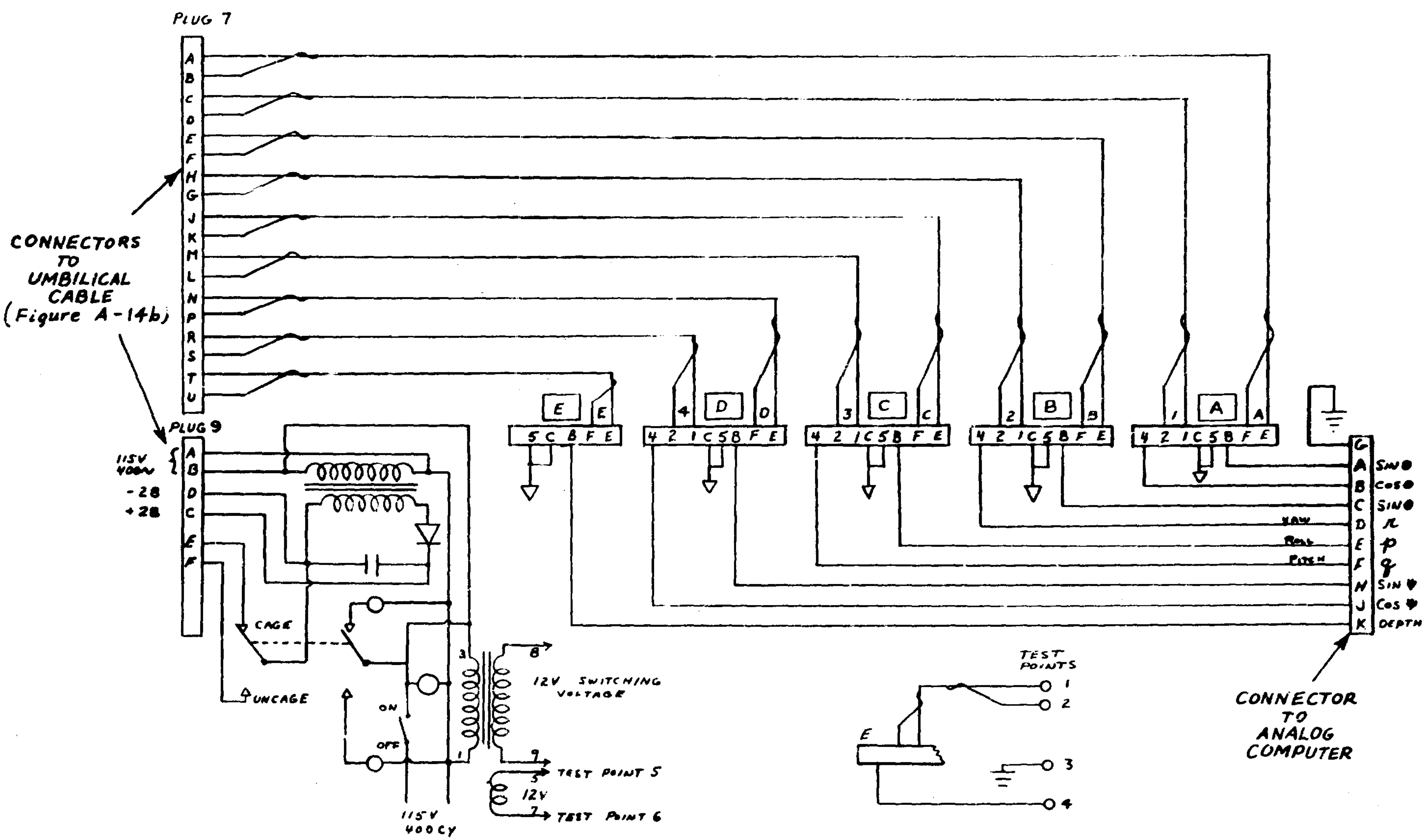

Figure A-29: DEMODULATOR AND POWER SUPPLY

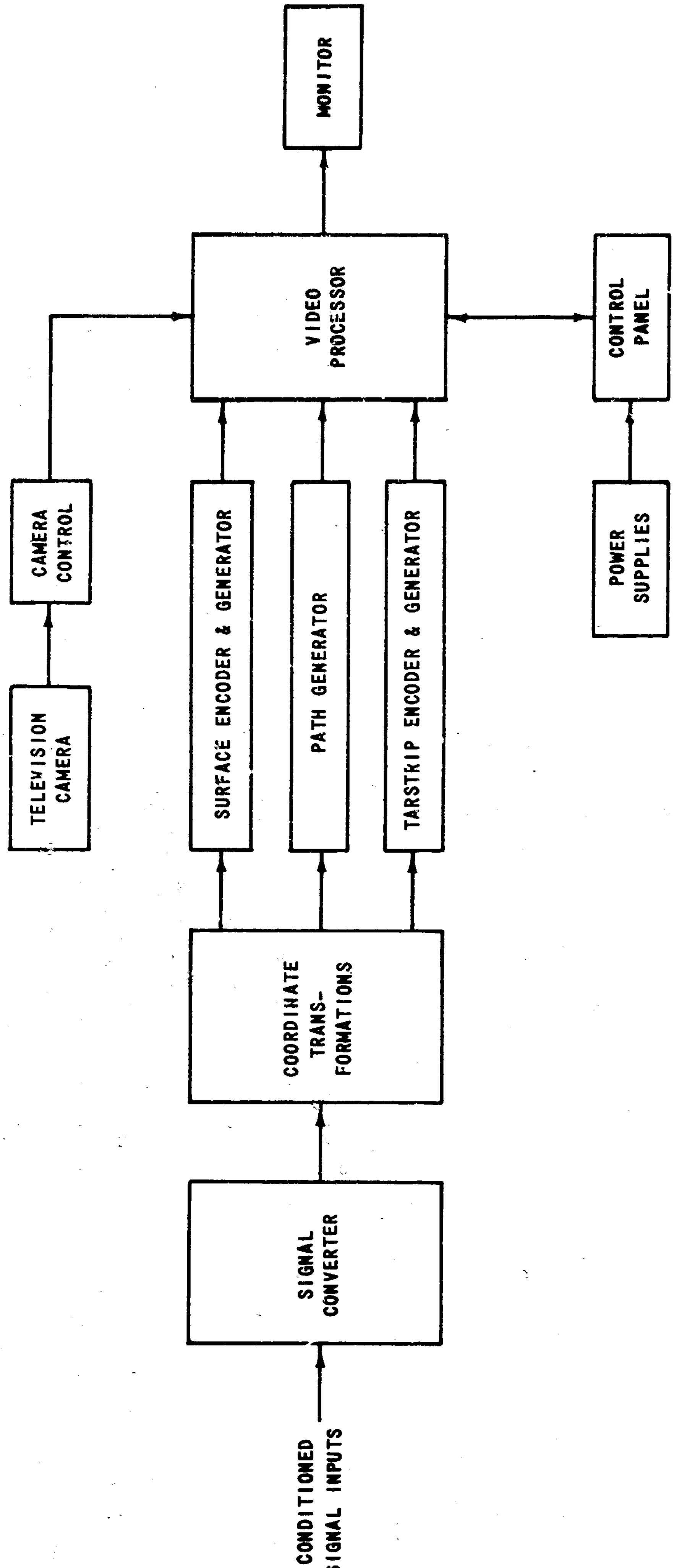

Figure A-30 CONTACT ANALOG BLOCK DIAGRAM study of TPS controllability are described in some detail in Reference A3; the section on the Central Analog Computer in this appendix (2.3) discusses the methods used for signal conditioning in this program.

2.10 Television Camera

The television camera, furnished for this phase of the program as part of the contact analog system, was used without further modification.* Its characteristics, together with complete information on its associated electronics, are described in Reference A6.

As shown in Figure A-15, the camera in its waterproof enclosure (DTMB Drawing E-2195-1) was mounted on the model forward of the sail and its control unit was installed inside the model. Only two lines to carry 110 vac, 60 cps, single-phase power to the unit (plus three coaxial signal lines) were therefore needed in the umbilical cable. To avoid disrupting the balance and weight of the model without the camera, the housing, including the camera, was carefully ballasted with styrofoam strips for neutral buoyancy. Underwater operation of the unit, once certain grounding problems were alleviated, was quite satisfactory.

2.11 Position Location System

In order to obtain information on the horizontal translational motions of the model, a position location system, incorporating an acoustic ranging section, a pulse counting and digital-to-analog conversion section, and an analog computing section was assembled. The equipment is schematically depicted in Figure A-31. As indicated in the figure, the method employs three receivers in a spherical-tracking arrangement. The spherical tracking system (in preference to hyperbolic tracking) is used to minimize computational problems.

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* It had previously been adapted for synchronization with the contact analog to allow simultaneous display of the two outputs.

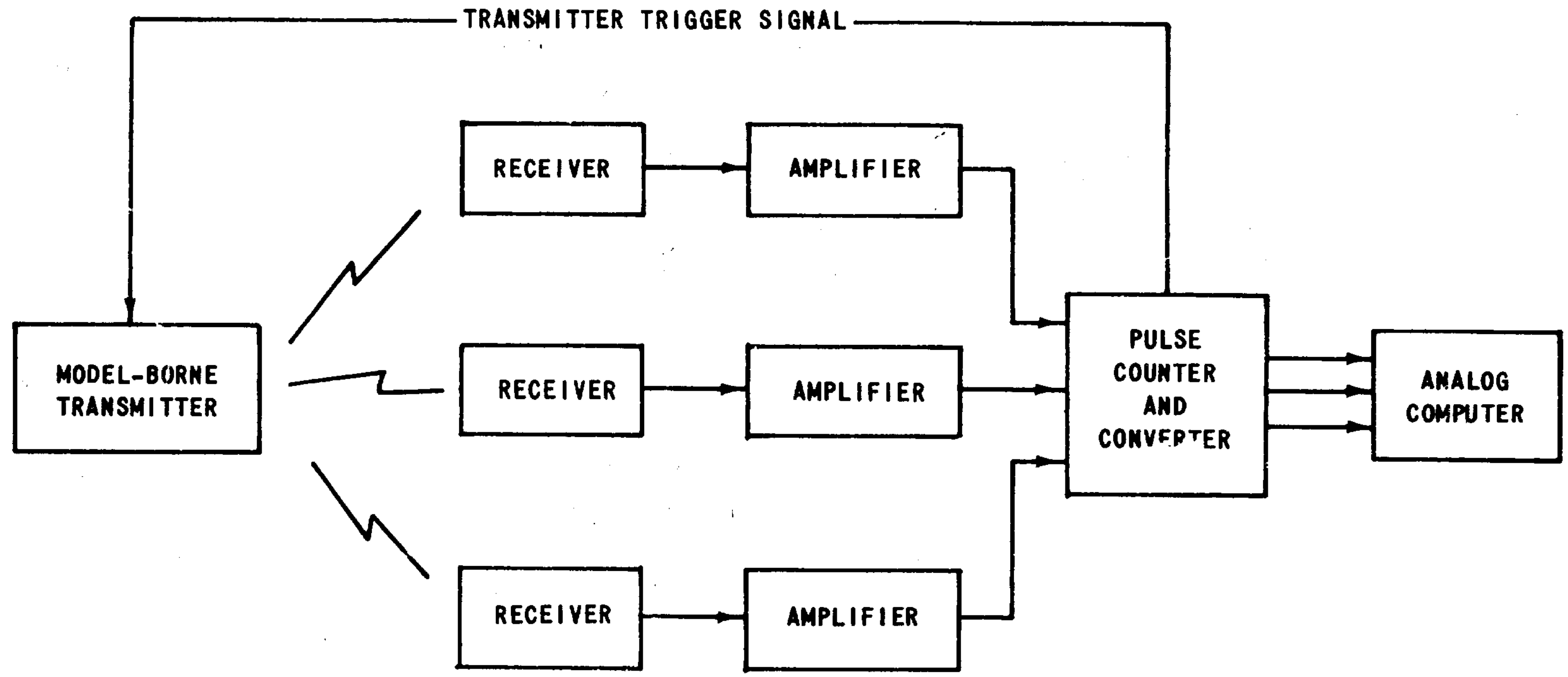

Figure A-31 POSITION LOCATION SYSTEM BLOCK DIAGRAM

Requirements for the system were determined to be:

1. Need for real-time position information (for use with the contact analog).

2. Minimization of the error associated with variable depth of submergence.

3. Location accuracy to better than one-half foot.

Approaches other than an acoustic ranging system (e.g., model-borne accelerometers) were briefly considered for application but rejected on cost and accuracy bases. The three-receiver system was chosen to satisfy the second requirement above and an error analysis indicated that the third requirement could be satisfied using components available with the analog computer selected for mechanization of the control system. (See Section 2.3 of this appendix for a description of the computing circuitry.)

Briefly, the system operates as follows. The lengths of perpendicular base lines d and D, as shown in Figure A-10, Section 2.3, are known. A noise-pulse emanating from the transmitter mounted in the model is received at each of the three receiver stations (D_1, D_2, D_3) at some later time governed by the distance between the transmitter and each receiver and the propagation velocity of sound in water. Since the instant at which the pulse is transmitted is known and the elapsed time until the pulse is received can be measured, distances d_1, d_2, and d_3 can be determined. From these distances, Rx and Ry can be computed, (see Section 2.3.2).

The acoustic ranging system utilized basic equipment employed by the David Taylor Model Basin in its own hyperbolic tracking system. This equipment included the transmitting and receiving transducers, the receiver amplifiers, and transmitter oscillator. These units are described in detail in Reference A-7.

The pulse counting circuitry and digital-to-analog converter were designed by CAL to provide real-time information on model location. This sub-system is thoroughly described in Reference A8 but some of the major components will be briefly discussed here.

The TPS Range-to-Volts Converter generates (1) the transmit trigger pulse at 2.6 pulses per second, and (2) three analog output voltages proportional to the propagation delays from the transmitter to each of three listening transducers.

The full scale voltage (-15 volts in series with 2500 ohms) corresponds to 48.2 milliseconds (about 240 feet) in channel D1, and 24.1 milliseconds (120 feet) in channels D2 and D3. Taper pin connections in each channel can change the full scale range to either value for each channel independently.

The block diagram (see Figure A-32) shows these major components.

1.	Clock,	operates at 170 Kc and provides a two-phase mutually exclusive clock structure for the counting, storage and control operations.
2.	Counter,	binary count sequence (2^{15} states) running continuously at 85 Kc. Bits are denoted by C-0 to C-14 inclusive.
3.	Transmit trigger generator,	trigger derived from the reset of C-14 (-6 to zero volts transition) occurring every 385 milliseconds.
4.	D1 channel,	includes a 12 bit storage register, control elements, a digital to analog converter (DAC), and reference supply.
5.	D2 and D3 channels,	operationally identical to D1 and completely independent of D1.

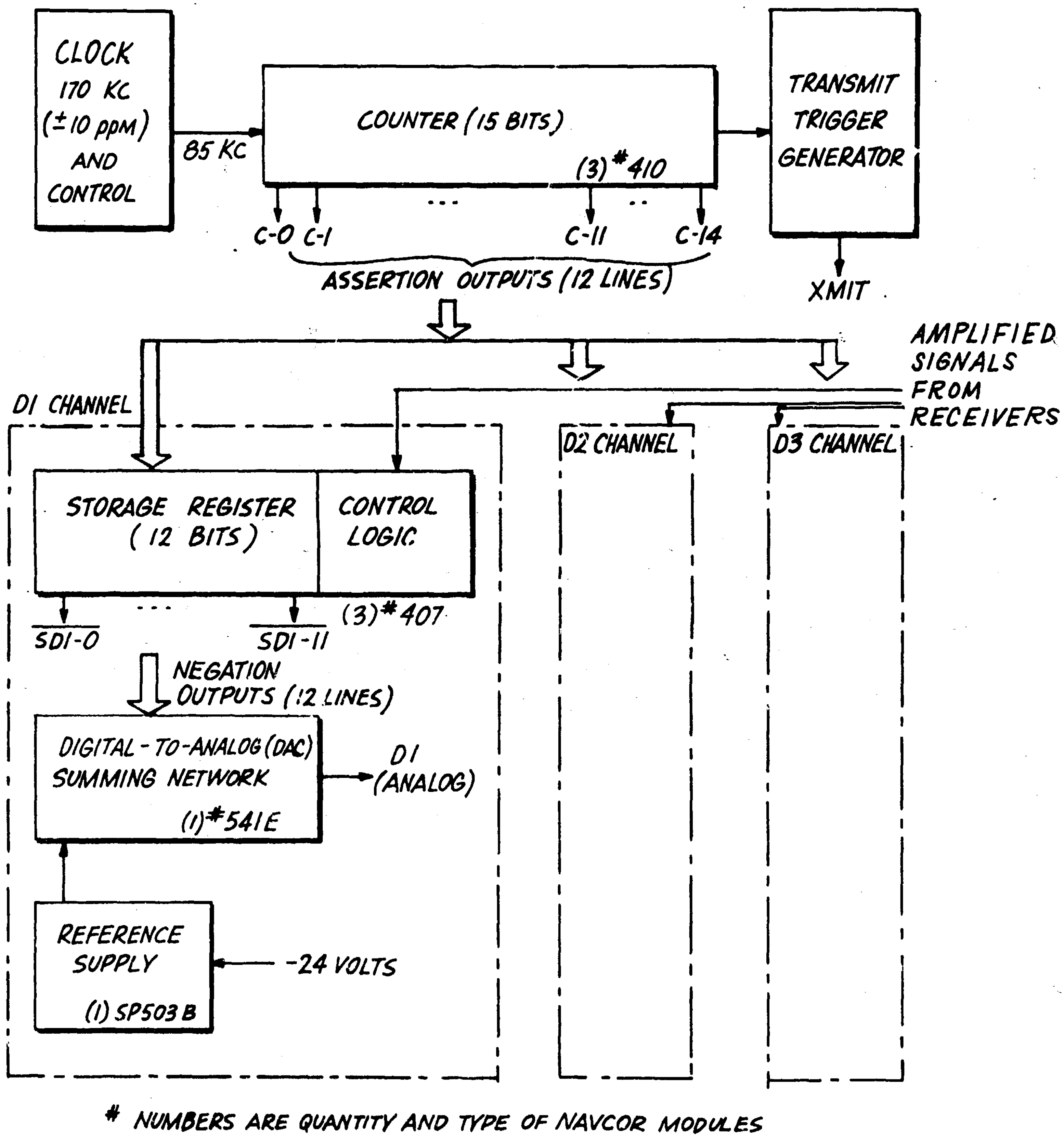

Figure A-32: RANGE-TO-VOLTS CONVERTER BLOCK DIAGRAM

NAVCOR* standard digital boards and power supplies, A-MP Series 53 taper pins and Amphenol connectors have been used with a few exceptions (e.g., the DTMB Pulse Shaper Amplifier and a -18 volt Zener regulator).

The number of distinct board types has been minimized to reduce the number of spares required. These NAVCOR boards are used:

Type	Quantity
Storage Flip Flop (#407)	9
Binary Counter (#410)	3
3 Input NAND/AND gates (#466)	5
Clock with Crystal Oven (#450 XH)	1
DAC Summing Network (#541E)	3
Reference Power Supply (#SP503B)	3

Two NAVCOR power supplies are used:

#4000 (-12 volts at 2.0 ampere)	1
#4005 (+12 volts at 0.3 ampere, -24 volts at 1.0 ampere, -100 volts at 0.02 ampere)	1

Figures A-33 through A-36 are photographs of the transmitter, transducers, and the conversion unit.

2.12 Instrumentation Recording

All data records were obtained with an 18-channel Consolidated Electronics Corporation oscillographic strip recorder. Direct current voltages representing the variables of interest were obtained from the central analog computer and fed through simple adjustable resistance networks for current compatibility with the recording galvonometers. The arrangement worked satisfactorily throughout the data-taking phase of the program.

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* Navigation Computer Corporation, Valley Forge Industrial Park, Norristown, Pa.

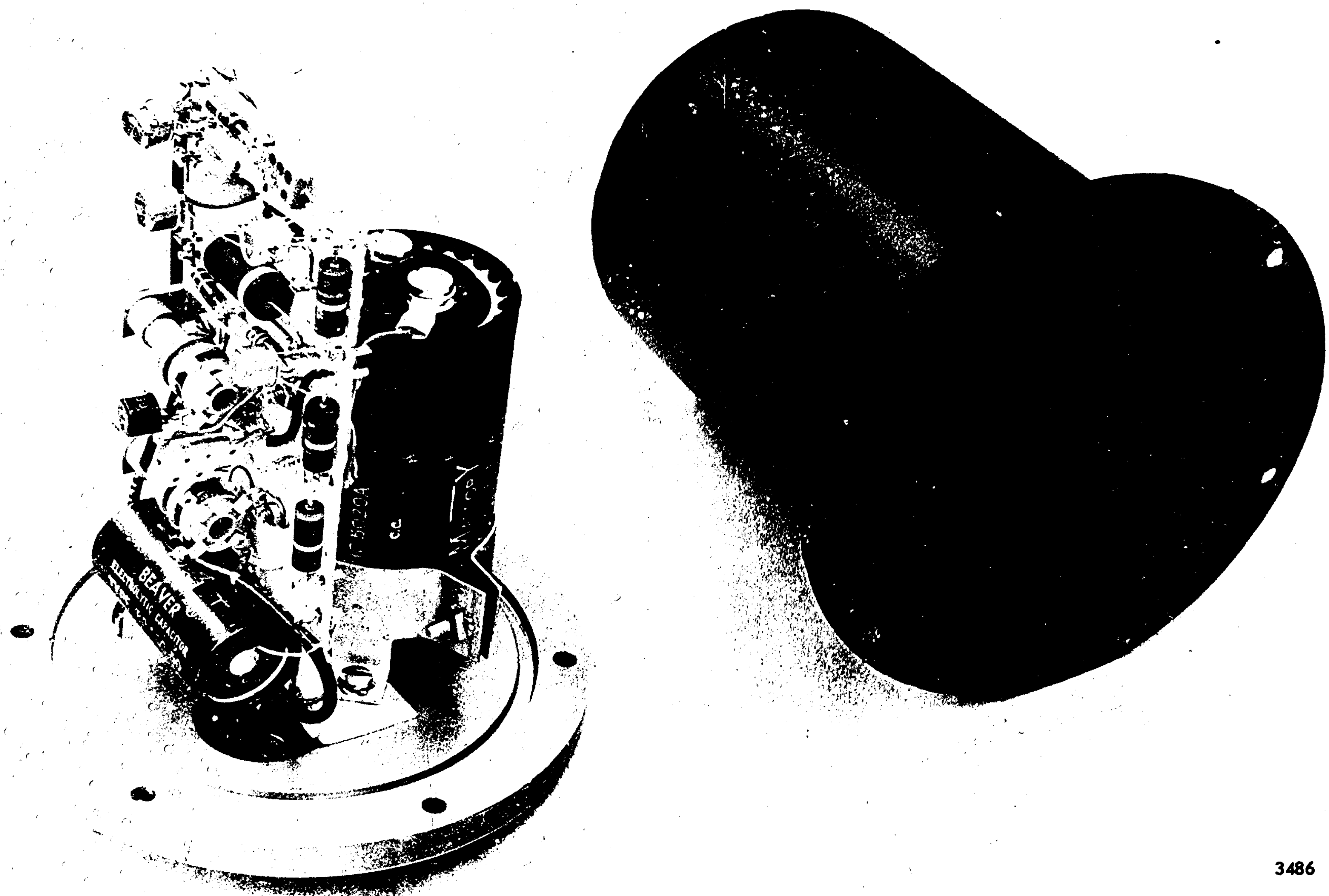

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Figure A-33: POSITION LOCATION SYSTEM TRANSMITTER

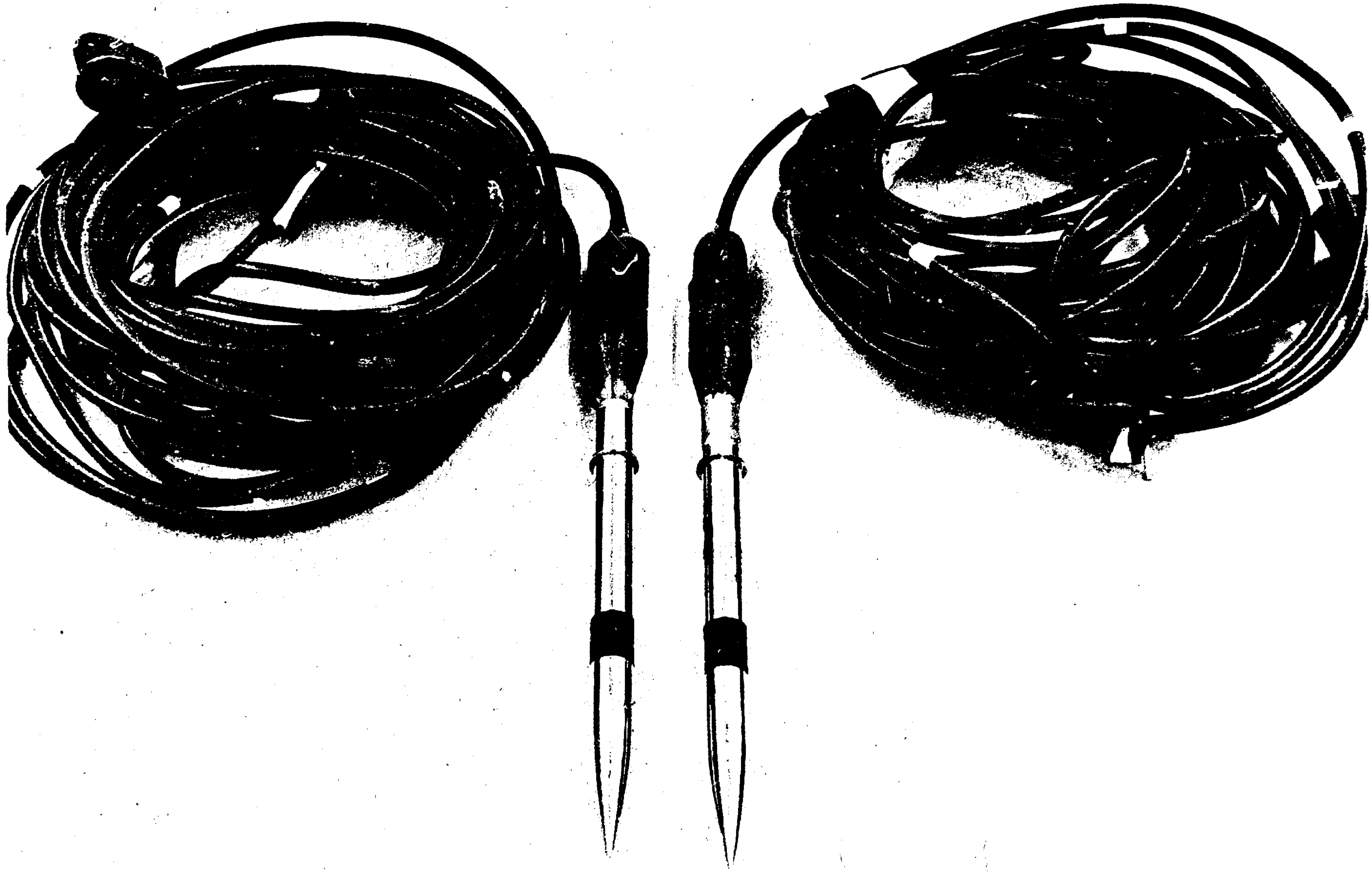

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Figure A-34: POSITION LOCATION SYSTEM TRANSMITTING AND RECEIVING TRANSDUCERS

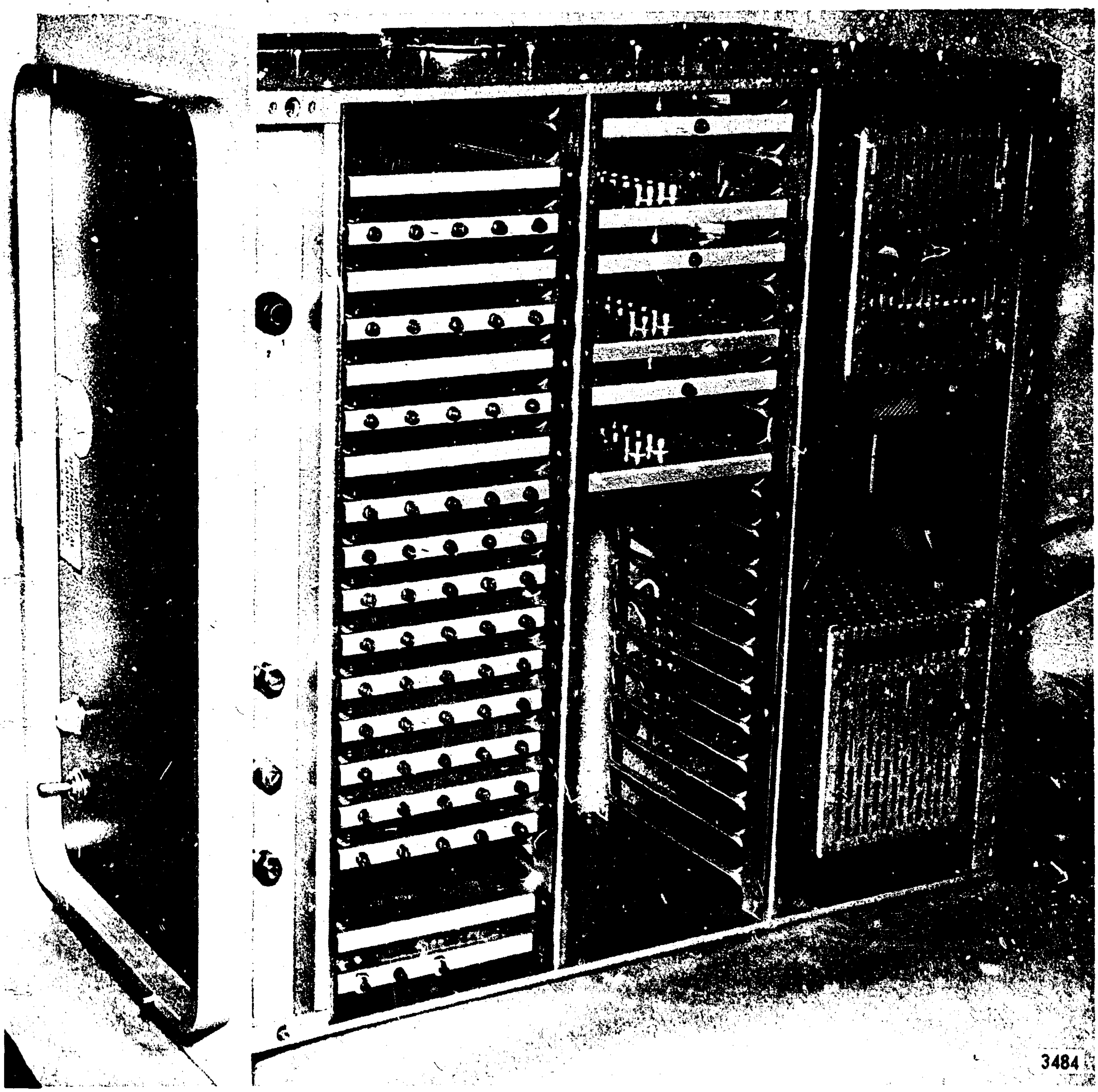

Figure A-35: POSITION LOCATION SYSTEM CONVERSION UNIT - EXTERNAL VIEW

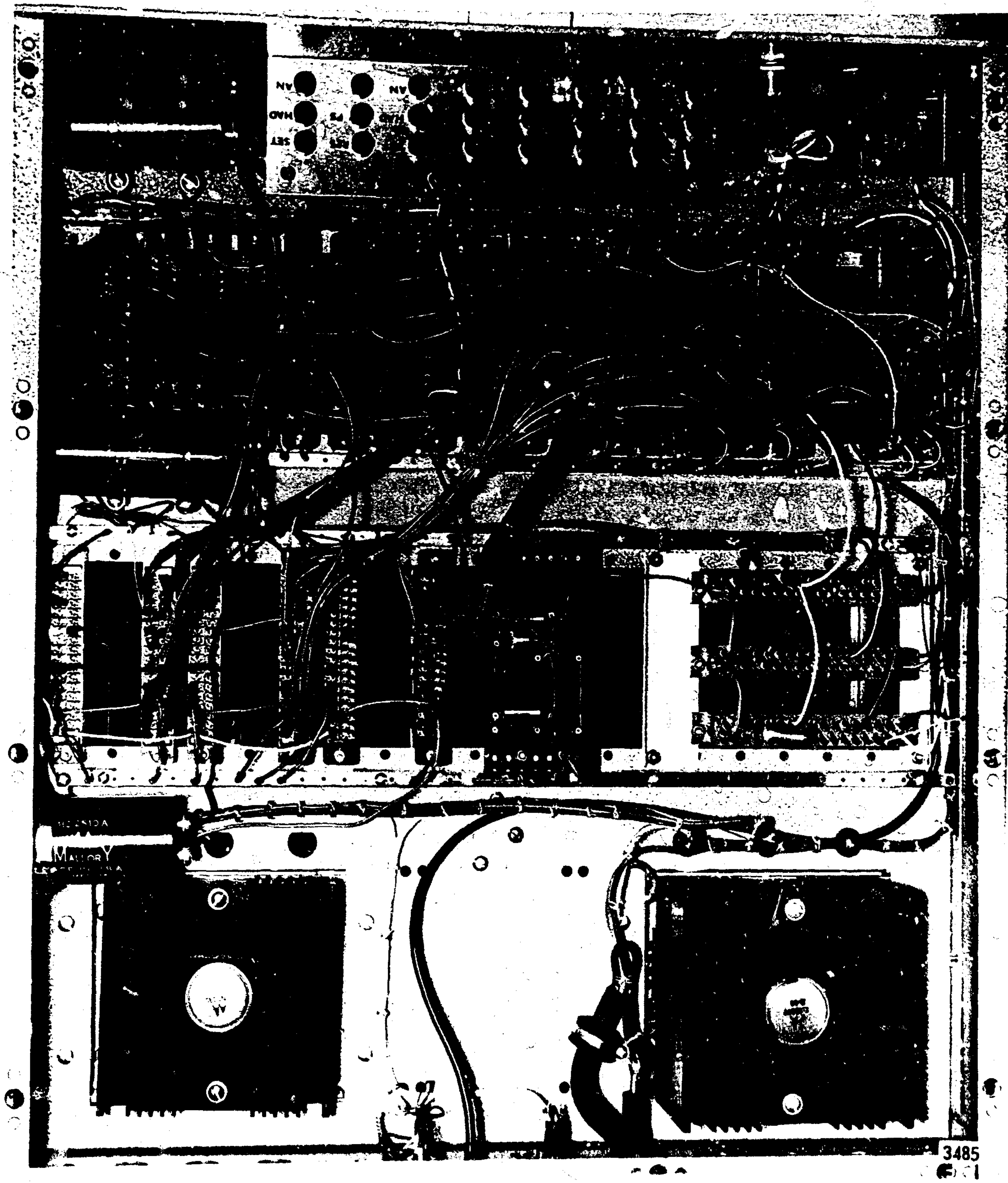

Figure A-36: POSITION LOCATION SYSTEM CONVERSION UNIT - INTERNAL VIEW

2.13 Miscellaneous Equipment and Cabling

In addition to the principal components and sub-systems of the TPS model system described above, a large number of auxiliary devices and interconnecting cables were built or assembled. These would include, for example, the water detector alarm, test and calibration units for the contact analog and gyroscopes, and adapter patch boards for use with the analog computer. No attempt will be made to describe these parts or the minor cables in detail because they are either so specialized that they are useful only in an identical arrangement or new units to perform the same functions can be easily built if required.

Cable connector pin designations for the major interconnect cables assembled by CAL are given in Tables A-3 through A-15. The cable code letters are as shown in Figure A-1, the overall free-running model system block diagram. Where code letters are not shown, the titles identify the termini and the connector designations can be correlated with sub-system descriptions given elsewhere in this report.

Table A-3 - Sensor Electronics to Analog Computer

Cable/Pin Designators	Signal
E/A	$\sin \theta$
E/B	$\cos \theta$
E/S	$\sin \psi$
E/T	$\cos \psi$
E/C	$\sin \phi$
E/U	h_T (depth)
E/G	ground
E/E	p
E/F	q
E/D	r

Table A-4 - Analog Computer to Indicators

Cable/Pin Designators	Signal	Indicator Location
I/E	ϕ	Left
I/F	θ	Right
I/D	h_T	Center
I/G	ground	

Table A-5 - Position Location System to Analog Computer

Cable/Pin Designators	Signal	Conversion Unit Code
R/C	d_1	D_2
R/B	d_2	D_3
R/A	d_3	D_1
R/G	ground	

Table A-6 - Analog Computer to Shore-Based Servo Electronics

Cable Designator	Pin Designators	Signal
M	X Y Z a	δ_{0f}
M	A B C D	δ_{0a}
M	T U V W	δ_{1f}
M	E F G H	δ_{2a}
M	N P R S	δ_{2f}
M	J K L M	δ_{1a}
M	d	$\Delta\Omega_f$
M	b	$\Delta\Omega_a$
M	shell	Ground

Table A-7 - Control Input Device to Analog Computer

Cable/Pin Designator	Signal	Input device wire colors
S/D	δ_{XC}	green
S/C	δ_{YC}	green
S/I	δ_{ZC} (R)	green
S/J	δ_{ZC} (L)	green
S/H	δ_{KC}	green
S/F	δ_{MC}	green
S/E	δ_{NC}	green
S/A	+5 volts	red
S/B	-5 volts	white
S/G	ground	black

Table A-8 - Matrix II to Analog Computer

Cable/Pin Designators	Computer Trunk	Signal
X1/A	13	+10 volts
X1/B	14	-10 volts
X1/C	15	SPARE
X1/D	12	+ δ_z arm
X1/E	9	+ δ_z up
X1/F	11	- δ_z up
X1/G	6	Ground
X1/H	8	- δ_z arm
X1/J	3	δ_{2a} SJ
X1/K	5	δ_{2a} OUT
X1/L	1	SPARE
X1/M	2	+ δ_Y arm
X1/N	10	+ δ_Y up
X1/P	7	- δ_Y up
X1/R	4	- δ_Y arm

Table A-9 - Matrix II to Analog Computer (Continued)

Cable/Pin Designators	Signal
X2/A	δ_{1a}SJ
X2/B	δ_{1a}OUT
X2/C	SPARE
X2/D	+ $\hat{\delta}_N$ arm
X2/E	+ $\hat{\delta}_N$ up
X2/F	- $\hat{\delta}_N$ up
X2/G	Ground
X2/H	- δ_N arm
X2/J	δ_{2f} SJ
X2/K	δ_{2f} OUT
X2/L	SPARE
X2/M	+ δ_M arm
X2/N	+ $\hat{\delta}_M$ up
X2/P	- δ_M up
X2/R	- δ_M arm
X2/S	$\hat{\delta}_{1f}$ SJ
X2/T	δ_{1f} OUT

Table A-10 - Umbilical Cable to Distribution Panel to Aft Propeller Connectors

Plug I	Distribution Panel Terminal Strips	Aft Propeller Connector (FK-37-32S-II)
V	A-1	12, 23, 34
M	A-7	5
N	A-6	6, 7
P	A-5	8
J	A-10	16
K	A-9	17, 18
L	A-8	19
A	B-9	29
B	B-8	30, 31
C	B-7	32
U	A-2	3
T	A-3	15
H	A-4	26
D	B-6	1
E	B-5	2
F	B-4	13
G	B-3	14
R	B-2	24
S	B-1	25

Table A-11 - Umbilical Cable to Distribution Panel to Aft Propeller Connectors

Plug II	Distribution Panel Terminal Strips	Aft Propeller Connectors (FK-37-32S-II)
P	C-5	4, 20, 33
R	C-6	9, 21, 37
S	C-4	10
T	C-3	22
U	C-2	35
V	C-1	11, 28, 36
		(FK-32L-32S-II)
N	C-7	27
M	C-8	4
L	C-9	21
G	D-3	12
H	D-2	13
K	C-10	14
J	D-1	26
E	D-5	10
F	D-4	11
	A-1	32, 25, 31

Table A-12 - Umbilical Cable to Distribution Panel to Sensor System

Plug III	Distribution Panel Terminal Strips	Amplifier Rack
A	F-9	1
B	F-10	2
C	D-10	3
D	D-9	4
E	D-8	5
F	D-7	6

Table A-13 - Umbilical Cable to Distribution Panel to Sensor System

Plug IV	Distribution Panel Terminal Strips	Amplifier Rack
A	E-1	8
B	E-2	9
C	E-3	32
D	E-4	33
E	E-5	10
F	E-6	11
G	E-7	12
H	E-8	13
J	E-9	14
K	E-10	15
L	F-1	16
M	F-2	17
N	F-3	34
P	F-4	35
R	F-5	36
S	F-6	37
T	F-7	18
U	F-8	19

Table A-14 - Umbilical Cable to Distribution Panel to Fore Propeller Connectors

Plug V	Distribution Panel Terminal Strips	Fore Propeller Connector (FK-37-32S-I)
S	H-4	11
T	H-3	28
U	H-2	36
P	H-5, C-5	4, 20, 33
R	H-6, C-6	9, 21, 37
V	H-1, C-1	10, 22, 35
		(FK-32L-32S-I)
G	G-3	12
H	G-2	13
K	H-10	14
J	G-1	26
E	G-5	10
F	G-4	1
N	H-7, C-7	27
M	H-8	4
L	H-9	21
	K-1 (Ground)	25, 31, 32

Table A-15 - Umbilical Cable to Distribution Panel to Fore Propeller Connectors

Plug VI	Distribution Panel Terminal Strips	Fore Propeller Connector (FK-37-32S-I)
M	K-7	5
N	K-6	6, 7
P	K-5	8
J	K-10	16
K	K-9	17, 18
L	K-8	19
A	J-9	29
B	J-8	30, 31
C	J-7	32
U	K-2	3
T	K-3	15
H	K-4	26
D	J-6	1
E	J-5	2
F	J-4	13
G	J-3	14
R	J-2	24
S	J-1	25
	K-1) A-1) Ground	12, 23, 34

3

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