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MICRO SWITCH
PRODUCTS

TERMINATION REPORT
ON THE
DG6000 THREE AXIS REPEATER
FOR THE
ASTRA VERTICAL AND HEADING REFERENCE
SYSTEM
OF THE
CF-105 AVRO ARROW AIRCRAFT

CR-ED 1041 June 4/59

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TERMINATION REPORT

ON THE

EG6000 THREE AXIS REPEATER

FOR THE

ASTRA VERTICAL AND HEADING REFERENCE SYSTEM

OF THE

CF-105 AVRO ARROW AIRCRAFT.

HONEYWELL CONTROLS
MILITARY PRODUCTS DOCUMENT CR-ED 1041.

JUNE 4, 1959

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Honeywell Controls Limited
Military Products
and
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Toronto, Ontario.

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FOREWORD

This represents one of four documents related to the Astra Vertical and Heading Reference System as prepared by Honeywell Controls Limited in accordance with the requirements of Section 2(a) of Contract CD/DRB 819009/0013/719-16-30-601, D.D.P. Serial Number 2-PF-8-13.

It is recommended that this report be read in conjunction with the following Honeywell Controls Documents:-

CR-ED 1065 - Termination Report on the Stable Platform for the Astra Vertical and Heading Reference System of the CF 105 Avro Arrow Aircraft.

CR-ED 1066 - Termination Report on the Stabilization Repeater for the Astra Vertical and Heading Reference System of the CF 105 Avro Arrow Aircraft.

CR-ED 1067 - Termination Report on the Platform Computer for the Astra Vertical and Heading Reference System of the CF 105 Avro Arrow Aircraft.

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TERMINATION REPORT ON THE DG6000 THREE AXIS REPEATER FOR THE ASTRA VERTICAL AND HEADING REFERENCE SYSTEM OF THE CF 105 AVRO ARROW AIRCRAFT.

1 GENERAL DESCRIPTION

1.1 Vertical and Heading Reference System

The 3 Axis Repeater is an integral part of the Vertical and Heading Reference portion of the Astra I Electronics System. The repeater is built with variations to suit system requirements as follows:

a) Interim System comprising:

J-4 Compass	Directional Gyro
GG48B-3	Vertical Gyro
BG121A-1	Power Supply
D-DG6000A-1	3 Axis Repeater

b) Developmental System D-YG709A-1 comprising:

D-GG63A-1	Stable Platform
D-EG151A-1	Platform Amplifier Assembly
D-DG6000B-1	3 Axis Repeater

c) Pre-Production System YG709A-2 comprising:

D-GG63C-1	Stable Platform
D-EG151B-1	Platform Amplifier Assembly
D-DG6000C-1	3 Axis Repeater

1.2 Function in System

The 3 Axis Repeater repeats angular position, to specified accuracies, of the elevation, roll and heading axes of the Stable Platform portion of the VHRS. It supersedes and renders obsolete the Stabilization Repeater and Platform Computer as described in CR-ED 1066 and 1067 respectively.

Figure 1.2 shows the parts of the Astra Electronics System which receive information on the platform position from one or more of the repeater servos.

1.3 History of Development

In the original planning for the ASTRA system it was intended that each sub-system requiring Vertical and Heading Reference data would receive this data directly from the synchro transmitters on the gimbals of the Miniature Stable Platform. Any specific functions of the reference angles (roll,

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elevation & heading) would be generated within the particular sub-system.

The ASTRA system logically comprised two main groups of sub-systems. One group was associated with combat duties and consisted of the following:

The Data Link, Radar, Fire Control Computer and Weapons. The second group was associated with Automatic Flight Control and Navigation and consisted of: The Automatic Flight Control System, Navigation Computer, Vertical and Heading Reference System and Flight Instruments. The Doppler radar was grouped with the former, although its function is equally associated with the second group. Thus, two main groups of sub-systems emerge, each with several requirements for specific functions of the Platform outputs.

R.C.A. decided to generate the required functions of roll and elevation angles at a central point in the first sub-system group and designed a servo repeater for this purpose, to be located in the Aft Nose Bay of the aircraft.

Minneapolis-Honeywell in effect, took similar action, and provided servo repeaters to supply roll, elevation and heading information to the Automatic Flight Control System. The Flight Director-Attitude Indicator would obtain from these AFCS servos attitude or heading inputs other than those directly obtainable from the platform.

Analysis of the miniature stable platform revealed a need for azimuth (heading) resolution to provide the necessary co-ordinate transformation from Earth to Aircraft co-ordinates. In addition, stability of the outer roll gimbal could be improved by scheduling the gain of the gimbal servo. One suitable gain scheduling function is the secant of the elevation angle. Ideally these two functions would be provided by a resolver and secant potentiometer directly driven by the respective gimbals. However, the gimbal design was not ready for such a solution although this was the final design aim. A need was then expressed for a separate azimuth axis repeater of high dynamic performance. Requirements were so severe that the AFCS heading servo would not provide adequate response.

Concern was expressed that the parallel connection of several synchro control transformers would degrade the accuracy of the gimbal synchro transmitters to an unacceptable degree, and the requirement was formulated for a central 3 axis repeater from which all sub-systems would receive their reference inputs.

Because of the large number of output devices required, it was felt that the central repeater could not provide the dynamic response necessary for the miniature stable platform, hence the 2 axis, high performance platform repeater was left as a separate unit. This resulted in a maximum number of 3 paralleled repeaters in the Elevation axis and 2 in each of the Roll and Azimuth axes.

Responsibility for the central 3-Axis Repeater was for a time ill-defined, but finally rested with Minneapolis-Honeywell on the grounds that they would need such a repeater for initial platform testing.

By this time the available space in the forward electronics bay was limited to approximately 6" x 9" x 15", thus defining the envelope size of the repeater. A design study was then commenced using this envelope size, and an arbitrary choice was made to provide 12 output devices on the Roll and Elevation axes and 6 on the Azimuth axis.

In the initial design phase a basic 6 output modular repeater was designed. Two such units were to be used in cascade for the Roll and Elevation axes and one for the Azimuth axis. Figure 1.3a shows a mockup of one module.

Analysis showed that the second of the cascaded repeaters would have inadequate response. It was then proposed to parallel the two modules. This would have degraded the accuracy of the platform synchro transmitters and left little permissible error in the repeaters. At this time the number of required azimuth outputs rose to 7, so the design was changed to a basic 12 output module shown in figure 1.3b.

Three such modules could not be accommodated within the given envelope, and additional installation space was requested from R.C.A.

The final design envelope was, excluding shockmounts, 7" x 10" x 15 1/2" with a maximum height of 6" at the rear of the unit. The 12 output module not only improved the system accuracy by eliminating one paralleled control transformer, but also eliminated four electronic amplifiers and two servo motors.

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2 APPLICABLE SPECIFICATIONS

Design was predicated upon the following detail specifications and the various military specific-ations as referenced therein.

a) Technical Design Specification (T.D.S. 12269-05 as subsequently modified by Component Specification sheets.

b) Minneapolis-Honeywell Restricted Engineering Document (R-ED 876).

c) T.D.S. 12257

d) T.D.S. 12269-03

e) MIL-E-7894A

f) Astra I Environmental Spec. #1, Revision A (as amended by R-ED 932).

g) R.C.A. Spec. 895055

h) R-ED 930

i) R.C.A. - Astra Standard Parts List

j) DND-RCAF Spec. Proc-100-11 (as modified by R-ED 938)

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3 DESCRIPTION OF UNIT - GENERAL

3.1 Physical

The D-DG6000 Repeater consists of three similar modular servo repeaters mounted in a rack frame. The rack frame contains an integral junction box from which run the cables to the Astra I sub-systems. The Repeater is mounted on a shock and vibration isolating base D-QG6000A-1. The overall dimensions of the two together are 11.7 x 15.7 x 8.74 inches. The weight of the 3 axis repeater including shock mount base is 30 lb. maximum.

The rack frame and modules are painted a fine crinkle black with the amplifiers and chassis in flat black. The shockmount base has a clear anodized finish. All hardware is passivated stainless steel.

3.2 Electrical

3.2.1 Inputs

3.2.1.1 Power Supplies

A single phase, 115 volts ± 10% at 400 ± 20 cycles per second supply is applied at connector J6 as shown in schematic, Figure 3.2.1.1. The maximum A.C. power drain does not exceed 35 watts.

A D.C. supply of 27.5 ± 1.0 volts is also applied at connector J6. The maximum D.C. current drain does not exceed 2.0 amperes.

3.2.1.2 Signal Inputs

Each of the three repeater modules requires a three terminal output from the platform (or equivalent) synchro control transmitters. These transmitters are excited from a 400 cycle per second voltage, in-phase with the A.C. power supplied to the repeater. The error sensing control transformer used is a Clifton Precision Products ETC-11-F-2 (equivalent to a Bendix AY-935-A2). This requires maximum input voltages of 11.8 volts line-to-line from the external control transmitter.

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3.2.1.3 Fuse Protection

A design requirement stipulated absence of fuse or circuit breaker protection in this equipment.

3.2.2 Outputs

The output devices consist of synchros (control and torque transmitters, control transformers and resolvers), potentiometers and sector switches: These are listed in Table 1 and Table 2 for the D-DG6000A-1 and D-DG6000B-1 repeaters respectively.

The specifications of the non-standard outputs are listed in the following sections:

3.2.2.1 Roll Control Transformer (BR4)

Connected to the rotor of BR4 is a temperature compensating network. The requirements of the thermistor and resistor are as follows:

Thermistor - Keystone Carbon Company part number LA-300-390-S2
300 ohms ± 5% at 37.8°C,
and maximum rating of 1 watt.

Resistor - M-H part number 455755EKKA.
499 ohms ± 1.0%, 1/4 watt.

To function effectively, the thermistor is located near BR4.

3.2.2.2 Roll Sector Switch (SR7)

Normally closed over a range of -63° ± 2° thru 0° to +63° ± 2° and open over the balance of 360°. Rating of the switch was 1/4 ampere, 28 volts D.C. inductive load of 1/2 henry.

3.2.2.3 Roll Sector Switch (SR8)

Normally closed over a range of +7.5 ± 1° thru 0° to -7.5 ± 1°, and open over the balance of 360°. The rating of the switch was 1/4 ampere, 28 volts D.C., 1/2 henry inductive load.

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3.2.2.4 Roll Potentiometer (RR6)

This potentiometer was characterized to provide a secant minus one function and will conform to the following:

a) Active range from $+(60^\circ {}^{+4^\circ}_{-0^\circ})$ thru 0° to $-(60^\circ {}^{+4^\circ}_{-0^\circ})$. Output to be constant from $+60^\circ$ to $+70^\circ$ ($\pm 4^\circ$) and from -60° to -70° ($\pm 4^\circ$). Further rotation of the wiper beyond $+70^\circ$ or -70° shall provide a linear decrease in output over a $20^\circ {}^{+4^\circ}_{-0^\circ}$) range. Balance of the potentiometer to be a short circuit and connected to the centre tap. The potentiometer must work into a 50K load to maintain this linearity.

b) Deviation from secant minus one function will be $\pm$ 5% proportional or *0.1% independent, whichever is greater. *(existing potentiometers can only supply 2% independent tolerance).

c) Centre tap width not to exceed 2°.

d) Resolution not greater than 1% proportional.

e) Resistance measured between the centre tap and the shorted sector between 1000 and 1500 ohms.

f) The potentiometer capable of 5 volt, 400 cycle excitation between the shorted sectors and the centre tap.

3.2.2.5 Elevation Potentiometer (RE7)

This potentiometer is characterized to provide a one minus cosine function and will conform to the following:

a) Active range from $+(90^\circ {}^{+4^\circ}_{-0^\circ})$ to $-(90^\circ {}^{+4^\circ}_{-0^\circ})$ and the balance of the potentiometer will be a short circuit.

b) Deviation from the one minus cosine function will not exceed $\pm$ 5% proportional or 0.1%* of maximum output, whichever is greater.
(*existing potentiometers can only supply 2% independent tolerance.)

c) Centre tap width will not exceed 5°.

d) Resolution will not exceed 1% proportional.

e) Resistance measured between centre tap and the shorted segment will be 5000 ohms ± 5%.

f) The potentiometer is capable of excitation of 2 volts, 400 cycles between centre tap and the shorted segment.

3.2.2.6 Elevation Sector Switch (SE8)

Normally closed over a range of -55° ± 4° to +55° ± 4° and open over the balance of 360°. Switch rating will be 1/4 amperes, 28 volts, 1/2 Henry inductive load.

3.2.2.7 Elevation Potentiometer (RE10)

This potentiometer will be characterized to provide a secant minus one function and will conform to the following:

a) Active range from -(87° ± 1°) to +(87° ± 1°), balance of 360° to be a short circuit.

b) Conformity to the function will be 0° to 55.6° - ± 0.75% absolute, 55.6° to 80.9° - ± 1.25 abs., 80.9° to 82.6° - 5% abs., 82.6° to 83.5° - ± 10% abs., 83.5° to 87° - ± 20% abs.

c) Centre tap width not to exceed 2°.

d) Resistance between centre tap and shorted segment will be 500 ohms ± 5%.

e) Resolution will not be greater than 1.0% proportional.

f) The potentiometer will be capable of 10 volt, 400 cycle excitation between the shorted segment and center tap.

3.2.3 User Abbreviations

RPTR	Repeater, Three Axis
AFCS	Automatic Flight Control System
FC	Fire Control

NC	Navigation Computer
DOP	Doppler Radar
FD/AI	Flight Director/Attitude Indicator
DL	Data Link
IDI	Integrated Destination Indicator
INST	Instrumentation- Flight Test
SDC	Signal Data Converter
VHRS	Vertical and Heading Reference System (Platform Stabilization)

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TABLE 1

D-DG6000A-1 FUNCTION INDEX TYPE PC CONNECTORS

	Mtg Pos	Aero Ref	Honeywell Aero No.	Unit Ref	Vendor No	Mpls Ref	Mpls Mfr No.	User
01A-5	1	B2	AD-480584	CT1	ETC-11-F-2	BHCT+	AY-935-A2	-
	2	-	480722-1	PLUG	-	-	-	-
TH	3	B5	480590	CX3	EGC-11-F-9	BH7-	7RS-910-5E	DL + NC
	4	B6	480590	CX1	EGC-11-F-9	BH1-	7RS-910-5E	AFCS
	5	-	480722-1	PLUG	-	-	-	-
	6	B4	480645	TX2	EGC-11-F-6	BH3-	CG-11-B-6	NC
	7	B3	480645	TX1	EGC-11-F-6	BH2-	CG-11-B-6	NC
	8	-	480722-1	PLUG	-	-	-	-
	9	B10	480645	TX3	EGC-11-F-6	BH4-	CG-11-B-6	NC
R	10	-	480722-1	PLUG	-	-	-	-
	11	B9	480584	CT2	ETC-11-F-2	BH9+	AY-935-A2	INST
	12	B11	480645	TX4	EGC-11-F-6	BH5+	CG-11-B-6	IDI
	13	-	480722-1	PLUG	-	-	-	-
	14	B8	480591	CX4	EGC-11-F-2	BH8+	7RS-910-7E	FDAI
	15	B12	480588	CX2	EGC-11-F-4	BH6+	7RS-910-1E	DL
NT	16	B1	481269	MOTOR	15-1M-460-3	-	-	-
01A-3	1	B2	AD-480584	CT1	ETC-11-F-2	BECT+	AY-935-A2	-
	2	-	480722-1	PLUG	-	-	-	-
ION	3	B5	480650	B3	ESC-11-F-1	BE3-	CS-11-B-2	NC
	4	B9	480585	B2	ESC-11-F-3	BE1-	7RS-930-3E	FC
	5	-	480722-1	PLUG	-	-	-	-
	6	B3	480591	CX4	EGC-11-F-2	BE6-	7RS-910-7E	FDAI
	7	B4	480590	CX3	EGC-11-F-9	BE5-	7RS-910-5E	AFCS
	8	S1	480592	SEC SW	C.I.C. 115	SE8+	55° SECTOR	AFCS
	9	B6	480589	CX1	EGC-11-F-3	BE2-	7RS-910-4E	SDC
EAR	10	-	480722-1	PLUG	-	-	-	-
	11	R4	480780	1-COS POT	SNT 597	RE7+	T.D.S	AFCS
	12	B7	480588	CX2	EGC-11-F-4	BE4+	7RS-910-1E	DOP
	13	-	480722-1	PLUG	-	-	-	-
	14	-	480722-1	PLUG	-	-	-	-
	15	B8	480584	CT2	ETC-11-F-2	BE9+	AY-935-A2	INST
RONT	16	B1	481269	MOTOR	15-1M-460-3	-	-	-
01A-1	1	B2	AD-480584	CT1	ETC-11-F-2	BRCT+	AY-935-A2	-
L	2	-	480722-1	PLUG	-	-	-	-
	3	B5	480585	B3	ESC-11-F-3	BR2-	7RS-930-3E	FC
	4	B4	480585	B2	ESC-11-F-3	BR1-	7RS-930-3E	FC
	5	-	480722-1	PLUG	-	-	-	-
	6	R4	480661	SEC.POT	SNT 601	RR6-	T.D.S.	AFCS
	7	B3	480585	B4	ESC-11-F-3	BR3-	7RS-930-3E	SDC
	8	S1	480829	SEC SW2	C.I.C. 115	SR7+ SR8+	63° SECTOR 7.5° "	AFCS
EAR	9	B7	480591	CX1	EGC-11-F-2	BR5-	7RS-910-7E	FDAI
	10	-	481020	-	NETWORK	-	-	-
	11	B6	480587	CT2	ETC-11-F-8	BR4+	7RS-900-2E	AFCS
	12	-	480722-1	PLUG	-	-	-	-
	13	B8	480584	CT3	ETC-11-F-2	BR9+	AY-935-A2	INST
	14	-	480722-1	PLUG	-	-	-	-
	15	S2	481071	SEC SW	C.I.C. 115	SR10+	5° SECTOR	NC
RONT	16	B1	481269	MOTOR	15-1M-460-3	-	-	-

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NOTE: B2 turns C.W. for positive gimbal angle.
+ same direction of rotation as B2
- opposite direction of rotation as B2.

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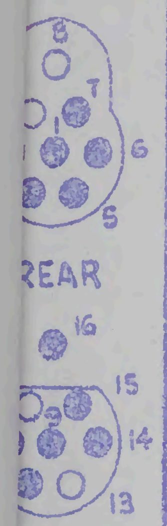
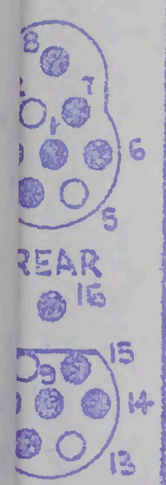
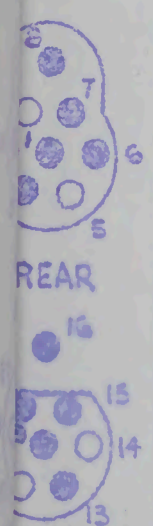
TABLE 2

-DG6000B-1 FUNCTION INDEX TYPE PT CONNECTORS

	Mtg Pos	Aero Ref	Honeywell Aero No	Unit Ref	Vendor No.	Mpls Ref	Mpls Mfr No.	User
001B-2	1	B2	AD-480584	CT1	ETC-11-F-2	BHCT+	AY-935-A2	-
TH	2	-	480722-1	PLUG	-	-	-	-
	3	B5	480590	CX3	EGC-11-F-9	BH7-	7RS-910-5E	DL + NC
	4	B6	480590	CX1	EGC-11-F-9	BH1-	7RS-910-5E	AFCS
	5	B7	480650	B2	ESC-11-F-1	BH10-	CS-11-B-2	VHRS
	6	B4	480645	TX2	EGC-11-F-6	BH3-	CG-11-B-6	NC
	7	B3	480645	TX1	EGC-11-F-6	BH2-	CG-11-B-6	NC
	8	-	480722-1	PLUG	-	-	-	-
REAR	9	B10	480645	TX3	EGC-11-F-6	BH4-	CG-11-B-6	NC
	10	-	480722-1	PLUG	-	-	-	-
	11	B9	480584	CT2	ETC-11-F-2	BH9+	AY-935-A2	INST
	12	B11	480645	TX4	EGC-11-F-6	BH5+	CG-11-B-6	IDI
	13	-	480722-1	PLUG	-	-	-	-
	14	B8	480591	CX4	EGC-11-F-2	BH8+	7RS-910-7E	FDAI
	15	B12	480588	CX2	EGC-11-F-4	BH6+	7RS-910-1E	DL
RONT	16	B1	481269	MOTOR	15-1M-460-3	-	-	-
001B-3	1	B2	AD-480584	CT1	ETC-11-F-2	BECT+	AY-935-A2	-
TION	2	-	480722-1	PLUG	-	-	-	-
	3	B5	480650	B3	ESC-11-F-1	BE3	CS-11-B-2	NC
	4	R5	480651	SEC 1 POT	SNT 593	RE10+	T.D.S.	VHRS
	5	-	480722-1	PLUG	-	-	-	-
	6	B3	480591	CX4	EGC-11-F-2	BE6-	7RS-910-7E	FDAI
	7	B4	480590	CX3	EGC-11-F-9	BE5-	7RS-910-5E	AFCS
	8	S1	480592	SEC SW	C.I.C. 115	SE8+	55° SECTOR	AFCS
REAR	9	B6	480589	CX1	EGC-11-F-3	BE2-	7RS-910-4E	SDC
	10	-	480722-1	PLUG	-	-	-	-
	11	R4	480780	1-COS POT	SNT 597	RE7+	T.D.S.	AFCS
	12	B9	480585	B2	ESC-11-F-3	BE1+	7RS-930-3E	FC
	13	-	480722-1	PLUG	-	-	-	-
	14	B7	480588	CX2	EGC-11-F-4	BE4+	7RS-910-1E	DOP
RONT	15	B8	480584	CT2	ETC-11-F-2	BE9+	AY-935-A2	INST
	16	B1	481269	MOTOR	15-1M-460-3	-	-	-
001B-1	1	B2	AD-480584	CT1	ETC-11-F-2	BRCT+	AY-935-A2	-
LL	2	-	480722-1	PLUG	-	-	-	-
	3	B5	480585	B3	ESC-11-F-3	BR2-	7RS-930-3E	FC
	4	B4	480585	B2	ESC-11-F-3	BR1-	7RS-930-3E	FC
	5	-	480722-1	PLUG	-	-	-	-
	6	R4	480661	SEC POT	SNT 601	RR6-	T.D.S.	AFCS
	7	B3	480585	B4	ESC-11-F-3	BR3-	7RS-930-3E	SDC
REAR	8	S1	480829	S1A S1B	C.I.C. 115	SR7+ SR8+	63° SECTOR 7.5°SECTOR	AFCS
	9	B7	480591	CX1	EGC-11-F-2	BR5-	7RS-910-7E	FDAI
	10	-	481020	-	NETWORK	-	-	-
	11	B6	480587	CT2	ETC-11-F-8	BR4+	7RS-900-2E	AFCS
	12	-	480722-1	PLUG	-	-	-	-
	13	B8	480584	CT3	ETC-11-F-2	BR9+	AY-935-A2	INST
	14	-	480722-1	PLUG	-	-	-	-
RONT	15	S2	481071	SEC SW	C.I.C. 115	SR10+	5° SECTOR	NC
	16	B1	481269	MOTOR	15-1M-460-3	-	-	-

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NOTE: B2 turn C.W. for positive gimbal angle
+ same direction of rotation as B2
- opposite direction of rotation as B2.

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4 DESCRIPTION OF PARTS

4.1 Repeater 3 Axis, D-DG6000A-1 and D-DG6000B, General

Three similar modular servo repeaters were mounted on a common rack, which in turn was mounted on a vibration isolating base.

External views of the 3 Axis Repeater are given in Figures 4.1.a and 4.1.b

Since most sub-systems required data from each of the three axes it was decided to provide a junction box on the front panel of the repeater. A total of some 30 output devices required approximately 120 leadwires. Since the repeater was connected to several sub-systems, the cabling was arranged so that each connector on the repeater was connected to only one other component of a particular sub-system. Seven Bendix Pygmy Connectors on the front of the junction box led to the aircraft cabling, and six connectors on the rear of the box led in pairs to the three modules.

It was decided that the three modules should differ only in quantity and type of output devices and the shell polarization of the electrical connectors. The modules were assigned the basic type symbol D-DG6001 and the three variations designated by suffixes A-1, A-3, and A-5. (The numbers were assigned at the stage when there were 5 six-output modules).

The D-DG6000A-1 series repeaters had Bendix Pygmy PC02A connectors; the D-DG6000B-1 repeaters had PT02A and D-DG6000C-1 had PT00P wall mount, bayonet lock, potted connectors.

4.1.1 Description of Mounting Rack DD480821

The mounting rack consisted of a riveted sheet metal tray suitably reinforced to mount the three modular repeaters, and an integral front panel and junction box. The junction box rear section was hinged, allowing the electrical connectors to be wired as a separate assembly and offered up to the rack. A rear view of the rack with the junction box opened is shown in Figure 4.1.1.a.

The rack was mounted on the D-QG6000A-1 shockmount base (Figure 4.1.1.b) by means of the conical pins located at the rear corners and by hooks at the front engaging with cup washers on the shockmount base.

Four captive socket head screws secured each module to the rack by engaging with self locking clinch nuts mounted on the module chassis.

An additional stiffening member was found necessary at the rear edge of the rack. This is shown in Figure 4.1.1.c.

4.1.2 Repeater, Servo Modular

The design aim was to provide an easily interchangeable modular assembly to facilitate servicing of the 3 Axis Repeater. It was further decided to group the Electrical and Mechanical components into separate sub-assemblies, since the mechanical assembly was to be carried out in a dust-free clean room, and the nature of the electrical wiring-up operation is such as to leave small clippings of wire and insulation.

The amplifiers and motor phasing and tuning capacitors were mounted on the chassis together with a terminal board. All electrical connections between the chassis and the mechanical assembly were brought to screw terminals on this terminal board. Figure 4.1.2 shows the terminal board and the gain setting resistors.

4.1.3 Description of Repeater Servo Module

Each Repeater module consisted of the following items mounted on a suitable cast frame and sheet metal chassis.

a) Two phase 400 cycle inertia damped servo motor

b) A synchro control transformer for error sensing.

c) A voltage amplifier

d) A power amplifier

e) A gear train for coupling the motor to the control transformer.

f) A gear train for coupling the control transformer to the output devices.

g) Output devices as specified

A possible total of fourteen output positions were available on each module, though it was desirable to have a blank position where the cable entered the front and rear covers to allow more room for the wiring to fan out to the various devices. Figure 4.1.3.a illustrates this point.

All outputs were of BuOrd size 11 servo mount type with 0.1200 +0000 / -0005 diameter shafts extending 0.625 +015 / -010 inches from the mounting face.

All the mechanism was housed in an aluminum alloy casting secured to the chassis by six screws.

The output devices and wiring were protected by molded fiberglas covers secured to three hexagonal pillars which together with 3 screws also served to secure the synchro plates to the body.

The wiring was arranged so that complete harness and plug assemblies could be prefabricated. The plugs were PC06E type on the D-DG 6000A-1 modules, PT06E on the D-DG6000B-1 modules and PT06P on the D-DG6000C-1 modules.

The cables were protected by plastic sleeving and suitably clamped to the body casting. Solderless crimp type lugs were used as wire terminations in all cases except the switches and potentiometers, which for the Development models had solder terminals.

Passivated stainless steel hardware was used throughout the mechanism to eliminate possible malfunction due to mechanical removal of plating.

The motor was secured by five BuOrd synchro clamps, and the output devices were secured by single and double clamps, the latter being necessitated by close spacing of the output devices. Figure 4.1.3.b shows the clamping arrangements.

4.1.3.1 Synchro and gear case assembly

The original intention was to make removal and replacement of any one output device possible without disturbing the setting of the remainder of the devices. For this the outside diameter of the gear on each output shaft had to be smaller than 1.000 inch diameter mounting hole in the plate. This gear had to mesh through an idler gear with a gear of the same size on the error sensing control transformer shaft in order to preserve the 1:1 angular correspondence between input and output angles. The stringent angular accuracy requirement, however, made this impossible and only one gear mesh was permissible between the control transformer gear and any one output gear. Further, the need for scissor type anti-backlash gears made straight replacement of outputs impossible.

A design was therefore prepared, having six, 80 tooth, 64 pitch output gears equally spaced around a similar central gear mounted on the control transformer shaft, as shown in Figure 4.1.3.1.a. The central gear was wide enough to allow staggering of the output gears to avoid locking and to accommodate the build-up of tolerances.

The maximum allowable overall dimensions of the module did not permit mounting the size 15 motor in either a central position or in any one output position, therefore, an idler shaft with a compound cluster gear was introduced. A 144 tooth, 64 pitch gear, integral with the control transformer gear, meshed with an 88 tooth, 64 pitch gear on the cluster. A 147 tooth, 97 pitch gear on the cluster meshed with the 15 tooth, 96 pitch motor pinion directly.

These two stages of gearing gave the ratio of 16:1 which was originally intended. It was later found that inadequate resolution was obtained and an additional 3.42:1 ratio was introduced by the use of an integral size 15 gearhead on the motor.

The combination of load inertia due to the large centre gear, and the large amount of backlash in the drive train, led to instability at gains sufficient to give the required resolution. The second gear of the cluster gear was then replaced by a scissor type anti-backlash gear, which allowed the gain to be increased to achieve the desired resolution.

The idler shaft also carried a 22 tooth, 64 pitch pinion meshing with a 72 tooth, 64 pitch anti-backlash gear fitted to the shaft of an additional output device mounted opposite the motor. This output shaft had a 1:2 angular correspondence with the input. Sector switches were mounted at this position, since their torque was expected to be relatively high, but the required angular accuracy was not unduly high. The torque reflected at the motor due to the switch was thus half its normal value. The angular switching function was repeated twice per full revolution of the output, or once per input revolution.

Assembly of the gear train was simplified. One plate covered the whole of the rear face of the casting and carried the control transformer, up to six equally spaced output devices a bridge supporting the cluster gear, and the half-speed output device. This plate could be fully assembled prior to being offered up to the body casting.

A similar but smaller plate on the front side of the casting carried one central, and up to six equally spaced output devices.

The two plates were secured to the casting by screws and dowels, while the motor was mounted in a precision bore in the casting.

When a full complement of devices was not required, care was taken in grouping to provide equalisation of mechanical loads on the central device. Vacant positions were closed by plugs. The drive was transmitted from the control transformer gear to the opposite centre gear by means of a flexible bellows type coupling, allowing small misalignments, both radial and angular, but maintaining freedom from backlash.

Figure 4.1.3.1.b is an exploded view of a synchro and gear case assembly, and clearly shows the large centre gear and bellows coupling. The rectangular opening in the base of the casting provided access to the bellows coupling during the final assembly. Assembly Pins can also be seen in the anti-backlash gears. These pins were withdrawn prior to final assembly.

Figure 4.1.3.1.c shows the synchro and gear body assembly less covers and wiring.

4.1.3.2 Servo Motor

The servo motor was chosen on the strength of rather limited knowledge of the output load characteristics. A size 15 motor with torque characteristics similar to a BuOrd MK7 motor was considered to provide an adequate torque safety margin.

Originally the usual form of an A.C. servo system using tachometric feedback was planned. The parallel development of the Two Axis Repeater did, in fact, employ rate generators on the model constructed. About that time, however, a following rate specification was received which required a constant slewing rate of 1200 degrees per second for a maximum output lag of 5 degrees. Such a requirement was incompatible with the other system parameters (resolution, damping ratio) were rate feedback compensation to be used.

Analyses using the newly introduced inertial damped servo motors showed that high following rates presented no problem. The damping portion of such motors consists of a drag cup that is attached to the rear of the motor shaft and rotates in the field of a bearing mounted permanent magnet. This magnet being itself free to rotate provides a damping force only under conditions of relative magnet-drag cup motion. The mass inertia of the magnet ensures such relative motion only when the motor shaft is accelerating. Thus a damping force does not occur under conditions of constant input velocity and a high following rate is available.

Experiments carried out with such units showed that equal, and in some cases superior frequency response and transient response characteristics of the servo loop were obtained.

Inertial damping also offered benefits in the form of:

1. increased reliability of a mechanical system.

2. no generator excitation required (4.2 watts)

3. no adding network and simplified circuitry.

The possibility of using a size 11 unit was investigated. For the D-model configuration however, it was found that the torque characteristic of such a unit was inadequate. Following rates as high as 400 degrees per second were not obtainable with the Beckman 11-1M461 inertial damped motor.

The final choice of motor, therefore, became the Beckman 151M460-3 series. Such a unit requires 8.5 watts at 115 volts on the reference phase and 8.5 watts at 40 volts on the control phase. The stall torque, speed and acceleration characteristics for no load are 1.5 ounce-inches, 6000 r.p.m. and 53,000 rad/sec^2 respectively. A flywheel damping factor of 440 dyne-cm-seconds was originally specified; later considerations suggested that this be increased to a minimum of 600 dyne-cm-sec.

4.1.4 Back-up Design Effort in Minneapolis

About the time the preliminary design was completed, an alternative design was produced by Minneapolis Honeywell, which, it was claimed, had superior performance and was easier to manufacture.

This device, a model of which is shown in Figure 4.1.4 had the output devices driven by a connecting plate through crank arms clamped to the output shafts.

A magnetic amplifier with transistorized preamplifier stages was used to drive a size 11 motor and 80:1 gearhead.

The connecting plate could only be statically and dynamically balanced for a known fixed number of output devices. At that time the total number was not fully determined, and spare positions were required by specification.

The Minneapolis designed model accommodated only four outputs and occupied approximately the same volume as the D-DG6001 12 output module. Actual performance of the crank-arm model was somewhat below specifications for velocity constant and resolution. These shortcomings might have been eliminated by further design effort.

It was decided to continue with the geared designed on the grounds that the development of the special manufacturing techniques required for the crank-arm repeater would delay the program by an unacceptable period.

4.2 Servo Amplifiers - General

It was the original intention to use the Minneapolis-Honeywell D-EG129 transistorized magnetic amplifier to drive the repeater servos. This was desirable, as identical amplifiers were used in many other applications in the Minneapolis-Honeywell portions of the ASTRA system. This amplifier, however, was found to have a time constant which proved excessive for the repeater application. The D-EG129 measured approximately 2 3/8" x 2 3/8" x 2 3/8" and weighed 11.5 ounces.

It was then decided to use two transistor amplifiers in cascade. The preamplifier chosen was a Minneapolis-Honeywell D-EG113C, already specified for use in other parts of the ASTRA system, and a separate transistor power amplifier specifically designed for the repeater application.

4.2.1 D-EG113C Preamplifier

The D-EG113C silicon transistor amplifier consisted of a two stage preamplifier and a stage of push-pull discrimation. It was designed as a printed card unit in a hermetically sealed case measuring approximately 2 3/8" x 2 3/8" x 1" with a weight of 4 ounces. A single external 400 cycle a.c. power source was required. The input signal could be of sinusoidal or square wave form.

Three terminal outputs produced phase sensitive, full wave d.c. or a.c. current. The maximum gain ratio expressed in milliamperes per volt, (or volts per volt using 1000 ohm load resistors) was 20,000 with an associated input impedance greater than 1.5 kilohms. The gain ratio could be reduced by means of a specified external resistance to a minimum of 25 with a related increase of input impedance to a value exceeding 1 megohm.

The amplifier with push-pull a.c. output was capable of driving a small motor directly, or a power transistor output stage.

The full wave d.c. output was suitable for operating hydraulic valves, relays or magnetic amplifiers.

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Up to one watt output could be obtained with 1,000 ohm minimum load. The amplifier was provisioned to accept an additional a.c. signal as might be derived from a velocity signal generator.

The amplifier can be seen at the left rear of the chassis in Figure 1.3.b.

4.2.2 Experimental Silicon Transistor Power Amplifier

A design was prepared using four, Texas Instrument 970 n-p-n silicon power transistors in parallel push-pull. Transformer coupling was employed at input and output. In addition a 40 V B+ supply was required and was to be provided by a separately packaged power supply unit. The amplifier was built and tested in both breadboard and packaged form and performed well, although its size was somewhat excessive, approximating to a 2 3/8" cube. Schematic and typical section are shown in Figure 4.2.2.

4.2.3 Silicon Power Amplifier DD-480813

A new silicon power transistor, the Texas Instruments 2N389, became available, and enabled the amplifier design to be simplified.

The DD480813 power amplifier was a single stage transistorized unit in a hermetically sealed container. A single external d.c. power source was required. It was found that sufficient output was obtained using the aircraft 28V D.C. supply as B+, and the separate power supply package was eliminated.

Two Texas Instruments 2N389 n-p-n silicon power transistors operating in class B push-pull provided up to 6watts continuous a.c.output power into a double ended load of 50 ohms per side.

Designed for excitation from the D-EG113C amplifier the unit could be driven to full output by any single ended or push-pull 400 cycle, 1000 ohm input signal source capable of supplying 1/2 watt.

The amplifier fed directly into the tuned 40 volt centre tapped control phase winding of the servo motor of the module.

Transformer coupling was used at the input.

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A feedback transformer having a 1:1 ratio was connected across the push pull output, and had an output impedance of less than 3000 ohms. The amplifier was designed to work satisfactorily in an ambient temperature range of -30 degrees to +160 degrees F. Electrical connections were made to a solder type header on the base. The envelope size was 1 5/8 x 1 5/16 x 2 3/8 and the unit was mounted by four threaded studs on the base. The weight of the unit was 5 1/4 ounces.

The DD 480813 amplifier can be seen to the right rear of the chassis in Figure 1.3.b and a sectional view is given in Figure 4.2.3.

4.2.4 DD 481313 Capacitor Assembly

To obtain a 90° voltage phase shift on the motor fixed phase winding a combination of series and shunt capacitors was used. In addition, the control phase winding was tuned by a shunt capacitor. The required values of capacitance were non-standard and had to be made up of pairs of standard values of capacitors. These were mounted on a terminal board and enclosed in an epoxy foam-filled can. The assembly measured 2 5/8" x 1 1/4" x 1 3/4" and weighed 5 ounces.

Electrical connections were made to a solder type header and the unit was mounted by four threaded studs on the base. The capacitor assembly can be seen centrally mounted on the front of the chassis in Figure 1.3.b.

4.2.5 Back-up Design Effort in Minneapolis

An independent, but parallel, effort was made in Minneapolis to design a transistor power amplifier for the repeater application. A sample amplifier, using two Honeywell germanium power transistors in class B push-pull, with positive feedback, was received for evaluation in Toronto. The unit was approximately the same size as the DD 480813 amplifier, but was filled with magnesium oxide and silicone oil to aid heat dissipation.

A test specification was received with the unit, but unfortunately the amplifier would not function with the recommended circuit and no comparative tests were possible.

A second design, employing silicon power transistors was understood to be in progress in Minneapolis. The status of this design at termination is not known.

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5 STATIC AND DYNAMIC PERFORMANCE

5.1 Theoretical Analysis

In the initial servo-loop analysis the following simplifying assumptions have been made.

a) The system behaves according to linear theory. This excludes any effect on performance due to gear train backlash, amplifier saturation, imperfect waveforms, etc.

b) No significant electrical time constants exist in the amplifier system or in the amplifier-motor coupling.

5.1.1 System Transfer Functions

Consider a system as shown in Figure 5.1.1

θ_i, θ_m, θ_o = input, motor shaft and output angle, in radians.

θ_d = Damper mass angle, radians

S = the Laplace operator

N = gear ratio, control transformer to motor shaft.

K_A = amplifier gain, volts/volt

K_B = control transformer sensitivity, volts/radian

K_T = motor torque constant, dyne-cm/volt

J_1 = effective inertia at motor shaft, gm cm^2

J_r = rotor inertia, gm cm^2

J_o = output load inertia, gm cm^2

J_2 = damper flywheel inertia, gm cm^2

f_1 = effective damping at motor shaft, dyne-cm/rad/sec.

f_r = motor damping constant, dyne-cm/rad/sec.

f_o = output damping, dyne-cm/rad/sec.

f_2 = damping constant due to coupling between the motor shaft and the damper inertia, dyne-cm/rad/sec.

F = effective frictional torques at motor shaft, dyne-cm.

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$T_{c.o}$ = output coulomb friction, dyne-cm

$T_{s.o}$ = output starting friction, dyne-cm.

Note that $J_1 = J_r + \dfrac{J_o}{N^2}$ ------------------------(1)

$f_1 = f_r + \dfrac{f_o}{N^2}$ ------------------------(2)

At any instant the motor torque equals the load torque.

Motor torque = $K_A K_B K_T \theta_i$

Load torque = $J_1 S^2 \theta_m + f_1 S \theta_m + f_2 S (\theta_m - \theta_d) + F$

Thus equating:

$K_A K_B K_T \theta_i = J_1 S^2 \theta_m + f_1 S \theta_m + f_2 S (\theta_m - \theta_d) + F$ ---(3)

The torque term due to the damper is

$f_2 S (\theta_m - \theta_d) = J_2 S^2 \theta_d$

$\therefore \theta_d = \dfrac{\theta_m}{1 + \dfrac{J_2}{f_2} S}$ ------------------------(4)

Since: $\theta_m = N\theta_o$ and ------------------------(5)

$F = \dfrac{T_{so} + T_{co}}{N}$ ------------------------(6)

Then equation (3) becomes: $K_A K_B K_T \theta_i$ =

$N J_1 S^2 \theta_o + N(f_1 + f_2) S\theta_o - \dfrac{N f_2 S \theta_o}{1 + \dfrac{J_2}{f_2} S} + \dfrac{T_{so} + T_{co}}{N}$

This reduces to the open loop transfer function

$$\left.\frac{\theta_o}{\theta_i}\right|_{O.L.} = \frac{K_A K_B K_T}{N f_1} \times \frac{\left(1 + \frac{J_2}{f_2} S\right)}{S\left\{\frac{J_1 J_2}{f_1 f_2} S^2 + \frac{J_1 f_2 + (f_1 + f_2) J_2}{f_1 f_2} S + 1 + \frac{J_2 (T_{so} + T_{co})}{f_2 N^2 f_1 \theta_o} + \frac{T_{so} + T_{co}}{N^2 f_1 \theta_o S}\right\}} \quad \text{--(7)}$$

For most purposes the output torque terms can be neglected giving as the open loop transfer function.

$$\left.\frac{\theta_o}{\theta_i}\right|_{O.L} = \frac{K_A K_B K_T}{N f_1} \times \frac{\left(1 + \frac{J_2}{f_2}S\right)}{S\left\{\frac{J_1 J_2}{f_1 f_2}S^2 + \frac{J_1 f_2 + (f_1 + f_2) J_2}{f_1 f_2}S + 1\right\}} \quad \text{---(8)}$$

Closing this loop using a feedback factor of (-1) gives:

$$\left.\frac{\theta_o}{\theta_i}\right|_{C.L} = \frac{\left(1 + \frac{J_2}{f_2}S\right)}{\frac{N f_1 S}{K_A K_B K_T}\left\{\frac{J_1 J_2}{f_1 f_2}S^2 + \frac{J_1 f_2 + (f_1 + f_2) J_2}{f_1 f_2}S + 1 + \frac{J_2 (T_{co} + T_{so})}{f_2 f_1 N^2 \theta_o} + \frac{T_{co} + T_{so}}{N^2 f_1 S \theta_o}\right\} + 1 + \frac{J_2}{f_2}S}$$

... the closed loop transfer function ------------(9)

5.1.2 Static Resolution

This parameter is defined as the maximum change in input angle that produces no motion of the output shaft, i.e., overall "dead spot" value of the input angle.

Consider the closed loop transfer function, equation (9).

For static conditions $S^3 = S^2 = S = T_{c.o} = 0$

$$\therefore \frac{\theta_o}{\theta_i} = \frac{1}{\frac{T_{s.o}}{N K_A K_B K_T \theta_o} + 1}$$

$$\text{or } \theta_i - \theta_o = \theta_R = \frac{T_{s.o}}{N K_A K_B K_T} \quad \text{---------------------(10)}$$

where θ_R is the static resolution.

Since the slot effect and bearing friction of the servo motor have been neglected in deriving the system transfer function, and hence in equation (10), this equation is valid only if the voltage $K_A K_B \theta_R$ exceeds the motor breakaway voltage.

5.1.3 Following Rate Error

For a given constant input angular velocity ωi, the output must necessarily lag the input by an angle $\theta_{v.e}$ in order to generate an error signal of sufficient magnitude to slew the output at rate ω_i.

Setting $S^2\,\theta_o = Ts.o = 0$, and $S\theta_o = \omega_i$ the steady state angular velocity, in equation (9) gives:

$$\theta_i - \theta_o \equiv \theta_{v.e} = \frac{Nf_1}{K_A K_B K_T}\left(1 + \frac{T_{c.o}\,J_2}{N^2 f_1 f_2 \theta_o}\right)\omega i + \frac{T_{c.o}}{NK_A K_B K_T} \quad \text{------(11)}$$

Neglecting the term $\frac{T_{c.o}\,J_2,}{N^2 f_1 f_2 \theta_o}$ the following rate error is then:

$$\theta_{v.e} = \frac{Nf_1}{K_A K_B K_T}\,\omega i + \frac{T_{c.o}}{NK_A K_B K_T} \quad \text{----(12)}$$

5.1.4 Large Signal Break Frequencies

Consider a periodic input of large amplitude; ie., sufficient to drive the motor to saturation. If the output is to remain equal in magnitude to the input as the frequency is increased, the torque required to accelerate the load must increase. Beyond a particular frequency, this torque requirement exceeds that available from the motor and the output amplitude decreases. This frequency is termed the break frequency.

The load torque required at any instant is given by:

$$\text{Load Torque} = J_1 S^2\theta_m + f_1 S\ \theta_m + f_2 S(\theta_m - \theta_d) + F \quad \text{------(13)}$$

since $\theta_d = \dfrac{\theta_m}{1+\dfrac{J_2}{f_2}S}$ (equation 4)

$\theta_m = N\theta_o$ (equation 5)

$F = \dfrac{Ts.o + T_{c.o}}{N}$ (equation 6)

then:

Load Torque = $Nf_1 \, \theta_o \, S \; \times$

$$\frac{\left\{\frac{J_1J_2}{f_1f_2}S^2 + \frac{J_1f_2+J_2(f_1+f_2)}{f_1f_2}S + 1 + \frac{T_{co}+T_{so}}{N^2f_1S\theta_o} + \frac{(T_{so}+T_{co})J_2}{N^2f_1f_2\theta_o}\right\}}{\left(1 + \frac{J_2}{f_2}S\right)} \quad \text{---(14)}$$

Neglecting $T_{s.o}$ and $T_{c.o}$ simplifies this equation to:

$$\text{Load Torque} = Nf_1\theta_o \frac{S\left\{\frac{J_1J_2}{f_1f_2}S^2 + \frac{J_1f_2+J_2(f_1+f_2)}{f_1f_2}S + 1\right\}}{\left(1 + \frac{J_2}{f_2}S\right)} \quad \text{---(15)}$$

Let the maximum available motor torque be T_{max}.

Since the magnitude only need be considered a frequency break occurs when

$$T_{max.} \Big| = Nf_1 \Big| \theta_o \, max \Big| \frac{S\left(\frac{J_1J_2}{f_1f_2}S^2 + \frac{J_1f_2+J_2(f_1+f_2)}{f_1f_2}S + 1\right)}{\left(1 + \frac{J_2}{f_2}S\right)} \Big| \quad \text{---(16)}$$

or rearranging, frequency break occurs when:

$$\left| \frac{\left(1 + \frac{J_2}{f_2}S\right)}{S\left(\frac{J_1J_2}{f_1f_2}S^2 + \frac{J_1f_2+J_2(f_1+f_2)}{f_1f_2}S + 1\right)} \right| = \frac{Nf_1 \left|\theta_o\right| max.}{T_{max.}} \quad \text{---(17)}$$

For sinusoidal inputs the magnitude plot of the left hand term, where $S = j\omega$, is sufficient to determine the numerical value of this break frequency.

5.1.5. Repeater Load and System Constants

These physical constants related to the performance of the servo-loops of the D-DG6000B-1 repeater are listed in the following. No significant variation from these figures exists for the D-DG6000A-1 configuration, however, the gear train and gear ratio values do not apply for the D-DG6000G-1 repeater.

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5.1.5.1 Output Devices

OUTPUT DEVICE	HONEYWELL AERO NO.	INERTIA J, gm cm^2	FRICTION @ 25°C F, gm cm	FRICTION @ -55°C F, gm cm
Synchro	DD-480584	3.6	3	6
	480590	3.3	3	6
	480650	3.6	3	6
	480645	3.3	3	6
	480591	3.3	3	6
	480588	3.3	3	6
	480589	3.3	3	6
	480585	3.6	3	6
	480587	3.6	3	6
Potent-iometer	DD-480651	<1	<4.7	4.7
	480780	<1	<4.7	4.7
	480661	<1	<4.7	4.7
Sector Switch	DD-480592	<1	< 72	72
	480829	<1	< 72	72
	481071	<1	< 14	14.4

5.1.5.2 Gears

GEAR	HONEYWELL AERO NO.	INERTIA J, gm cm^2	INERTIA REF-ERRED TO OUT PUT C.T. SHAFT, gm cm^2
Compound Assembly	DD-480609	33.4	89.2
80T Anti-backlash	480606	7.3	7.3
72T Anti-backlash	480607	4.9	1.2
Compound Centre	480617	214.5	214.5
80T Stainless steel	480618	27.1	27.1
Gearhead	481117	0.02 at input	60.5

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The total gear ratio of control transformer shaft to motor shaft, N, is 55:1.

5.1.5.3 Total Module Loads

Using the figures listed in the foregoing sections, the total inertia and frictional torque for each module of the D-DG6000B-1 repeater are as follows:

AXIS	TOTAL LOAD INERTIA AT MOTOR SHAFT J_o, gm cm^2	FRICTIONAL TORQUE AT MOTOR SHAFT @ +25°C F_o dyne-cm	FRICTIONAL TORQUE AT MOTOR SHAFT @ -55°C. F_o, dyne-cm
Azimuth D-DG6001B-2	0.16	587 max.	1174 max.
Elevation D-DG6001B-3	0.16	1235 "	1662 ".
Roll D-DG 6001B-1	0.16	1355 "	1725 ".

The output velocity dependent damping f_o is assumed to be zero with respect to the motor damping f_1.

5.1.5.4 Control Device Constants

a) Control Transformer DD480584:
Sensitivity K_B = 21.8 volts/radian

b) Servo Motor DD480792:
Two such units, Beckman 151M460-3 numbers PT-13 and PT-0 are to be considered. The constants common to both are:

Torque constant K_T = 2650 dyne-cm/volt
Rotor inertia J_r = 2.0 gm cm2
Damper mass inertia J_2 = 45 gm cm2

Minimum control phase breakaway voltage, E min = 1.0 volts (slot effect)

Those constants peculiar to each motor are:

Motor damping constant f_1 = 120 dyne-cm/rad/sec for PT-13.

= 129 dyne-cm/rad/sec for PT-0.

Damper mass coupling constant f_2

= 411 dyne-cm/rad/sec for PT-13

= 643 dyne-cm/rad/sec for PT-0.

5.1.6 Numerical Results

The predicted primary performance parameters have been evaluated below as functions of the amplifier system gain constant KA. Where applicable, both servo motors have been considered, to show the effect of the different damping constants.

5.1.6.1 Static Resolutions

Taking the servo motor slot effect and bearing friction into account, equation (10) can be written as:

$$\theta_R = \frac{T_{s.o}}{NK_AK_BK_T} \qquad K_AK_B\theta_R > E_{min}$$

$$= \frac{E_{min}}{K_AK_B} \qquad K_AK_B\theta_R < E_{min} \quad \text{---- (18)}$$

Where E_{min} is the breakaway voltage on the motor control phase required to overcome the slot effect and bearing friction.

From equation (18) above, it can be seen that the resolution is motor governed (as opposed to load governed)as long as:

$$\frac{T_{s.o}}{N} = F_o < E_{min}K_T \quad \text{---------------- (19)}$$

Using the values listed in section 5.1.5.4., the term $E_{min}K_T$ is 2650 dyne-cm. Comparing this with the table in 5.1.5.3., shows that the load frictional torque F_o is less than 2650 dyne-cm for all axes at low temperatures.

The resolution obtainable from the servo loops is thus dependent solely on the motor characteristics for any given gain. For motors PT-13 and PT-0 these values are:

GAIN, K_A, $\frac{\text{Volts}}{\text{Volts}}$	RESOLUTION MINUTES OF ARC
60	2.6
100	1.6
140	1.1

The specified resolution of 3 minutes is thus met for these gains.

5.1.6.2. Following Rate Error

From equation (12):

$$\theta_{v.e} = \frac{Nf_1}{K_A K_B K_T}\,\omega_i + \frac{T_{c.o}}{N\,K_A K_B K_T} = \frac{1}{K_A K_B K_T}\left\{ Nf_1\,\omega_i + F_o \right\}$$

The F_o term is generally small with respect to $Nf_1\omega_1$, hence the following rate is essentially equal for all three axes. Also, f_1 is very nearly the same for both motors under consideration, hence the following results apply for either unit.

The maximum following rate and the corresponding minimum following rate error can be obtained from the self-evident equations below:

$$\omega_o \max = \frac{\omega_m \max}{N} \quad \text{------------------------------} (20)$$

where ω_m max is the rated motor velocity of 6000 revolutions per minute

$$\theta_{v.e} \min \text{ at } \omega_o \max = \frac{E \text{ control phase max}}{K_A K_B} \quad \text{------} (21)$$

The rated control phase voltage is 40 volts. Thus, for both the D-DG6000B-1 and D-DG6000A-1 repeaters, the calculated following rates are:

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GAIN K_A = 60 $\frac{\text{Volts}}{\text{Volt}}$		GAIN K_A = 100 $\frac{\text{Volts}}{\text{Volt}}$		GAIN K_A = 140 $\frac{\text{Volts}}{\text{Volt}}$	
ω_i $\frac{\text{Degs.}}{\text{Sec.}}$	$\theta_{v.e}$ Degs.	ω_i $\frac{\text{Degs.}}{\text{Sec.}}$	$\theta_{v.e}$ Degs.	ω_i $\frac{\text{Degs.}}{\text{Sec.}}$	$\theta_{v.e}$ Degs.
100	0.23	100	0.14	100	0.10
300	0.64	300	0.39	300	0.28
500	1.05	500	0.63	500	0.45
655= ω_o max.	1.75	655= ω_o max.	1.05	655= ω_o max.	0.75

It is apparent that the specified maximum error of 3 degrees for an input rate of 400 degrees per second presents no problem.

5.1.6.3 Open Loop Frequency Response; Motor PT-13

The open loop transfer function, equation (8) was given as:

$$\left.\frac{\theta_o}{\theta_i}\right|_{O.L} = \frac{K_A K_B K_T}{N f_1} \frac{\left(1 + \frac{J_2}{f_2} S\right)}{S\left\{\frac{J_1 J_2}{f_1 f_2} S^2 + \frac{J_1 f_2 + (f_1 + f_2) J_2}{f_1 f_2} S + 1\right\}}$$

Substituting for the constants gives:

$$\left.\frac{\theta_o}{\theta_i}\right|_{O.L} = 7.57 K_A \frac{(1 + 0.109\ S)}{(S)(1.972 \times 10^{-3}\ S^2 + 0.502\ S + 1)} \quad \text{--(22)}$$

Factoring the denominator quadratic gives:

$$\left.\frac{\theta_o}{\theta_i}\right|_{O.L} = 7.57 K_A \frac{(1 + 0.109\ S)}{(S)(1 + 0.498\ S)(1 + 3.96 \times 10^{-3}\ S)} \quad \text{----(23)}$$

Graph #1 shows a plot of the magnitude and phase of the complex factors, assuming a sinusoidal input.

It is generally considered that the phase margin should exceed 30 degrees and preferably more than 45° for satisfactory operation. Critical damping is normally obtained with a phase margin of about 60 degrees.

Phase margin versus amplifier system gain, K_A, data are readily obtained by adding $7.51 K_A$ in decibels to the magnitude plot of graph #1. The phase margin at unity gain (0 Db) is then read from the phase plot. These values are tabulated below.

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AMPLIFIER GAIN K_A	PHASE MARGIN
60 volts/volt	65 degrees
100 " "	57 "
140 " "	52 "

5.1.6.4 Closed Loop Frequency Response; Motor PT-13

Using a Nichol's chart, the preceding open-loop response was converted into a closed-loop plot for three values of amplifier gain K_A.

Graphs #2, 3, and 4 show these predicted response curves for gains of 50, 100 and 140 volts per volt respectively.

The significant parameters taken from these curves are tabulated below:

THEORETICAL CLOSED LOOP FREQUENCY RESPONSE, MOTOR PT-13			
PARAMETER	K_A = 50 $\frac{\text{Volts}}{\text{volt}}$	K_A = 100 $\frac{\text{volts}}{\text{volt}}$	K_A = 140 $\frac{\text{volts}}{\text{volt}}$
Peak Magnitude Db.	+0.6	+0.8	+1.5
Freq. of Peak Mag. $\frac{\text{cys}}{\text{sec}}$.	4.0	16.0	23.9
Bandwidth $\frac{\text{cys}}{\text{sec}}$ (-3Db)	19.5	37.2	48.3
-90° phase lag $\frac{\text{cys}}{\text{sec}}$	23.0	32.0	38.5
Equiv. 2nd. Order System damping ratio, ζ, at resonance.	0.58	0.55	0.48

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The equivalent second orde[illegible] ratio for the value of K_A is be[illegible] of 0.6.

5.1.6.5 Large Signal Break Frequencies; Motor PT-13

Applying equation (17)

$$\left| \frac{\left(1 + \frac{J_2}{f_2} S\right)}{S\left(\frac{J_1 J_2}{f_1 f_2} S^2 + \frac{J_1 f_2 + J_2 (f_1 + f_2)}{f_1 f_2} S + 1\right)} \right| = \frac{N f_1 \left|\theta_o\right|_{max}}{T_{max}}.$$

to motor PT-13, gives large signal break frequencies at:

$$\text{Open loop magnitude plot} = \left\{0.0624 \left|\theta_o\right|_{max}\right\} \text{ in Db.}$$

where $\left|\theta_o\right|_{max}$ is in radians.

These are shown below:

θ_o max	Large Signal Break Frequency
5 degrees	6.6 cycles/sec
15 "	2.5 " "
45 "	1.2 " "

5.1.6.6 Open Loop Frequency Response; Motor PT-0

As will be shown later, significant differences in performance occurred when comparing servo-motors PT-13 (f_2 =411 dyne-cm-sec) and PT-0 (f_2 =643 dyne-cm-sec.)

In view of these, a theoretical analysis based on this new value of f_2 has been made.

Substitution in the open loop transfer function, equation (8), gives:

$$\left.\frac{\theta_o}{\theta_i}\right|_{O.L} = 8.17K_A \frac{(1+ 0.070\ S)}{(S)(1+0.432\ S)(1+3.90\ 10^{-3}S)} \quad \text{---(24)}$$

Graph #5 shows the magnitude-phase plot of this function. Comparison with that of PT-13 (Graph #1) indicates little difference except

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for the phase curve in the region of 2 to 125 radians/sec. Here the phase lag for motor PT-0 exceeds that of PT-13, but by never more than 10 degrees.

The calculated phase margins for this motor are:

AMPLIFIER GAIN K_A	PHASE MARGIN
60 volts/volt	64 degrees.
100 " "	59 "
140 " "	54 "

5.1.6.7 Closed Loop Frequency Response; Motor PT-0

As previously, the open loop plot was converted to a closed loop response for three values of amplifier gain. Graphs #6, 7 and 8 show these plots. The main data are tabulated below:

THEORETICAL CLOSED LOOP FREQUENCY RESPONSE, MOTOR PT-0.			
PARAMETER	K_A= 50 volts	K_A = 100 Volts/volt	K_A = 140 volts/volt
Peak Magnitude Db	+1.0	+0.8	+1.1
Freq. of peak mag. cys/sec	4.0	8.0	19.2
Bandwidth (-3Db) cys/sec	15.9	30.8	41.1
-90° phase lag cys/sec	19.7	28.6	34.8
Equiv. 2nd order system Damping ratio, ζ, at resonance.	0.52	0.54	0.52

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5.1.6.8 Large Signal Break Frequencies; Motor PT-0

Applying equation (17) to motor #PT-0 shows that large signal break frequencies occur at:

Open loop magnitude plot = $\left\{0.067\left|\theta_o\right|_{max}\right\}$ in Db where the plot is now graph #5.

These frequencies are listed below:

$\theta_{o\ max.}$	LARGE SIGNAL BREAK FREQUENCY
5 degrees	4.9 cycles/sec
15 "	2.2 " "
45 "	1.1 " "

5.1.7 Servo System with Rate Feedback

It is informative to compare the foregoing results with those derived for the more usual form of an A.C. servo-system; namely one employing tachometric feedback. In this discussion the use of a Beckman 15MG460/460 motor-tachometer is assumed. Such a motor is equivalent to the 15M460 except for the method of compensation.

5.1.7.1 Theoretical Analysis

5.1.7.1.1 Transfer Functions - Consider a system as shown in Figure 5.1.7.1.1.

θ_i, θ_m, θ_o = input, motor shaft and output angles, in radians.

S = the Laplace operator
β = fraction of inner loop output, feedback
$\mathcal{E}_i$ = amplifier input signal, volts
KA = amplifier gain, volts/volt;
K_B = control transformer sensitivity, volts/radian
KT = motor torque constant, dyne-cm/volt
K_g = generator sensitivity, volts/radian/sec.
aK_g = effective generator sensitivity, volts/rad/sec
N = gear ratio, control transformer to motor shaft
J_1 = effective inertia at motor shaft, gm cm^2
J_r = rotor inertia, gm cm^2
J_o = output load inertia, gm cm^2
f_1 = effective damping at motor shaft, dyne-cm/rad/
f_r = motor damping constant, dyne-cm/rad/sec. sec.
f_o = output damping, dyne-cm/rad/sec.
F = effective frictional torques at motor shaft
$T_{c.o}$ = output coulomb friction, dyne-cm. dyne-cm.
$T_{s.o}$ = output starting friction, dyne-cm.

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As before: $J_1 = J_r + \frac{J_o}{N^2}$ ---------------(1)

$f_1 = f_r + \frac{f_o}{N^2}$ ---------------(2)

$F = \frac{T_{s.o} + T_{c.o}}{N}$ ------------(6)

For the inner, open loop we have:
Motor torque: $= K_A K_T \mathcal{E}_i$

Load torque $= J_1 S^2 \theta_m + f_1 S \theta_m + F$

$\therefore K_A K_T \mathcal{E}_i = J_1 S^2 \theta_m + f_1 S \theta_m + F$ --------(25)

This can be written as:

$$\left.\frac{\theta_m}{\mathcal{E}_i}\right|_{O.L} = \frac{K_A K_T}{J_1 S^2 + f_1 S + F/\theta_m} \quad \text{--------(26)}$$

Closing the loop we obtain:

$$\left.\frac{\theta_m}{\mathcal{E}_i}\right|_{C.L} = \frac{1}{\dfrac{J_1 S^2 + f_1 S + F/\theta_m}{K_A K_T} + \beta}$$

Since $\beta = \frac{a K_g S \theta_m}{\theta_m} = a K_g S$ Then:

$$\left.\frac{\theta_m}{\mathcal{E}_i}\right|_{C.L} = \frac{K_A K_B K_T}{J_1 S^2 + (f_1 + K_A K_T a K_g) S + F/\theta_m} \quad \text{---(27)}$$

To obtain the outer, open loop transfer function, substitute:

$\mathcal{E}_i = K_B \theta_i$

$\theta_m = N \theta_o$

$$\therefore \left.\frac{\theta_o}{\theta_i}\right|_{O.L} = \frac{K_A K_T K_B}{N J_1 S^2 + N(f_1 + K_A K_T a K_g) S + F/\theta_o} \quad \text{---(28)}$$

Closing this loop the resultant transfer function for the system becomes:

$$\left.\frac{\theta_o}{\theta_i}\right|_{C.L} = \frac{K_A K_B K_T}{N} \cdot \frac{1}{J_1 S^2 + (f_1 + K_A K_T a K_g) S + \dfrac{K_B K_T}{N} + \dfrac{F}{N \theta_o}} \quad \text{---(29)}$$

Neglecting the output torque term $\frac{F}{N \theta_o}$, this can be written as:

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$$\left.\frac{\theta_o}{\theta_i}\right|_{C.L} = \frac{1}{\frac{NJ_1}{K_A K_B K_T}S^2 + \frac{N(f_1 + K_A K_T a K_g)}{K_A K_B K_T}S + 1} \quad \text{------(30)}$$

5.1.7.1.2 Static Resolution

Letting $S^2 = S = T_{c.o} = 0$ in equation (29) we obtain:

$$\left.\frac{\theta_o}{\theta_i}\right| = \frac{1}{1 + \frac{T_{s.o}}{N\,\theta_o\,K_A K_B K_T}} \quad \text{or}$$

$$\theta_o - \theta_i = \theta_r = \frac{T_{s.o}}{N\,K_A K_B K_T} \quad \text{------------------(31)}$$

This is identical to the inertial damped system (equation 10), as would be expected.

5.1.7.1.3 Damping Ratio

For a second order system written as:

$$\left.\frac{\theta_o}{\theta_i}\right|_{C.L} = \frac{1}{-A^2\omega^2 + j\omega B + 1}$$

The damping ratio ζ is defined as: $\zeta = \frac{B}{2A}$
Thus, for the transfer function of equation (30) and a sinusoidal input, the damping ratio is:

$$\zeta = \frac{\frac{N(f_1 + K_A K_T a K_g)}{K_A K_B K_T}}{2\sqrt{\frac{NJ_1}{K_A K_B K_T}}}$$

$$\text{or } \zeta = \sqrt{\frac{N}{4\,K_A K_B K_T J_1}}\left\{f_1 + K_A K_T a K_g\right\} \quad \text{--------(32)}$$

5.1.7.1.4 Following Rate Error:

For a constant angular input velocity ω_i, $S^2 = 0$ and $S\theta_o = S\theta_i = \omega_i$. Thus, the closed loop transfer function (equation 29) becomes:

$$(\theta_i - \theta_o) = \theta_{v.e} = \frac{T_{c.o}}{N\,K_A K_B K_T} + \frac{N(f_1 + K_A K_T a K_g)}{K_A K_B K_T}\omega_i \quad \text{---(33)}$$

5.1.7.2 Numerical Results

The constants associated with the Beckman 15MG460/460, 6000 r.p.m., size 15, motor tachometer are:

K_T = 2560 dyne-cm/volt (vs.2550 for I.D.motor)
J_r = 1.4 gm cm2
f_r = 158 dyne-cm/rad/sec
K_g = 9.55 x 10-3 volts/rad/sec.

Load and other system constants are as listed in section 5.1.5.

Assuming the breakaway voltage to be the same as for the inertial damped motor, the amplifier system gains must be within the same general range previously considered to obtain the required resolution. Thus, values of K_A = 60, 100 and 140 volts/volt will be considered here.

5.1.7.2.1 Damping Ratio -

This parameter must be set by assigning the appropriate value to the effective generator constant aK_g. Thus, for a damping ratio of 0.6, equation (34) yields a as a function of gain as shown:

$$\underline{a} = \frac{1.96\sqrt{K_A} - 6.48}{K_A} \quad \text{-------------------(34)}$$

For K_A = 60, 100 and 140 volts/volt, the values of a are 0.145, 0.131 and 0.112 respectively.

5.1.7.2.2 Following Rate Error

Using equation (33) and the foregoing value of a at K_A = 100, we obtain -

$$\theta_{v.e} = 3.0 \times 10^{-4} + 4.70 \times 10^{-3}\, \omega_i \quad \text{------(35)}$$

For an input rate of 400 degrees per second the following rate error will be 1.88 degrees, well within the specified value of 4.0 degrees.

5.1.7.2.3 Open Loop Frequency Response

Equation (28), the open loop transfer function can be rewritten as:

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$$\left.\frac{\theta_o}{\theta_i}\right|_{O.L} = \frac{K_A K_B K_T}{N(f_1 + K_A K_{Ta} K_g)} \times \frac{1}{S\left(1 + \frac{J_1}{f_1 + K_A K_{Ta} K_g} S\right)} \quad \text{---(36)}$$

where the output torque term F has been neglected.

Substituting for the constants and considering the case for K_A = 100 volts/volt, we obtain

$$\left.\frac{\theta_o}{\theta_i}\right|_{O.L} = 213 \frac{1}{S(1 + 3.26 \times 10^{-3} S)} \quad \text{---(37)}$$

Graph #9 gives the phase magnitude plot of this, assuming a sinusoidal input. From these curves it can be seen that a phase margin of 59 degrees exists.

5.1.7.2.4 Closed Loop Frequency Response

Substituting in the closed loop transfer function (equation 30) gives:

$$\left.\frac{\theta_o}{\theta_i}\right|_{C.L} = \frac{1}{1.53 \times 10^{-5} S^2 + 4.70 \times 10^{-3} S + 1} \quad \text{---(38)}$$

for a gain constant K_A of 100 volts/volt and a damping ratio of 0.6.

Graph #10 shows this frequency response curve. The bandwidth of 47.5 cycles/second is considerably larger than that for the inertia damped motors PT-13 and PT-0. There the bandwidths were 37.2 and 30.8 cycles/second respectively.

It is apparent from these results that the dynamic and static behaviour of the servo-loop is essentially the same for both the inertia damped or the motor tachometer form of compensation. The system specifications, with the possible exception of damping ratio in the inertial damped case, can be met with either unit. As indicated earlier, this was not always the case when a following rate of 1200 degrees per second (unobtainable with a motor-tach system) was required.

The major disadvantage of the inertia damped motor however, is the inability to adjust the system damping factor.

5.2 Test Results

Unless otherwise noted, the servo-loop test results in this section were obtained from the elevation axis D-DG6001B-3 of the L-2 repeater. The two servo-motors, Beckman 151M460-3 numbers PT-13 and PT-0 were used for comparison purposes.

5.2.1 Amplifier System Tests

As previously described, the amplifier system for each module consists of a D-EG113C amplifier driving the DD480813 power amplifier. An overall negative voltage feedback loop provides gain adjustment facility.

The gain control feature of the D-EG113C amplifier by means of a resistor across terminals 1 and 3 is not used in this application. Figure 5.2.1 shows the test circuit used for the following checks, Sections 5.2.1.1 through 5.2.1.3.

5.2.1.1 Gain Curve

Graph #11 gives the overall gain curve for the elevation axis module. For input voltages in excess of about 760 millivolts (corresponding to two degrees of error signal from the control transformer) the amplifiers can be considered to be saturated. A residual voltage of 0.5 volts exists on each half of the control phase. The phase shift does not exceed ± 5 degrees throughout the entire input range of 0 to 15 volts.

In this report the gain constant K_A is always evaluated for an output voltage of 5.0 volts on each side of the motor control phase.

5.2.1.2 Gain Calibration

The series feedback resistor R_3 (here 27K ohms) has been chosen to provide gain calibration. The assembly practice is to choose the largest standard value of 5% resistance for R_3, such that the voltage gain does not exceed the desired value. This provides amplifier system gain control within minus 10% of the nominal specified value.

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Graph #12 shows the effect of this feedback resistor on amplifier system gain. Since the entire amplifier system is tuned to 400

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cycles per second, this curve applies only to the one-amplifier-motor combination and cannot be used as a geneal calibration curve.

5.2.1.3 Amplifier System Time Constants

In order to check the assumption of section 5.1 that the amplifier system contains no significant time constants, the following test was performed:

a) A suppressed carrier modulated 400 cycle/second signal was applied to the input of the motor loaded amplifier system. This signal was derived from a synchro transmitter control transformer pair with the transmitter shaft rotating at a constant rate (see Figure 5.2.5) With this, the envelope frequency could be varied from 0 to about 60 cycles per second while the peak amplitude was kept constant at 190 millivolts (1/2 degree).

b) Both the input and output envelope waveforms were monitored simultaneously with a Sanborn pen recorder, while the input frequency was increased, in steps, from 0 to 60 cycles per second.

c) The observed traces showed no detectable phase shift ($\pm$ 3°) between input and output in the frequency range used. This indicated that any first order time constants within the amplifier system had values not exceeding 10^{-4} seconds and hence could be neglected here.

5.2.2 Stability Checks

With the module connected as Figure 5.2.2. any tendency for oscillation of the servo-loop was observed on the recorder error signal trace. Violent disturbance inputs were made for various values of amplifier system gain, the latter being adjusted with R_3.

Gains in excess of 170 and 210 for motors PT-13 and PT-0 respectively were needed to produce any form of sustained or long lived oscillation.

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5.2.3 Resolution Checks

Using the experimental set-up of Figure 5.2.2. the resolution of the system vs amplifier gain was determined as follows:

With the error signal being traced on the recorder, the external transmitter shaft was rotated very slowly until the recorder pen passed through a maximum displacement. At this point the transmitter shaft was then slowly rotated in the opposite direction until the recorder pen reached an opposing maximum. This was repeated for several cycles. The peak-to-peak voltage represented by the trace indicates the resolution of the system; ie., divide this voltage by K_B for the angle in radians.

Such a procedure was carried out at 20 degree intervals over the complete 360 degree range, with the maximum angle recorded taken as the system resolution.

The results using the two motors are as tabulated below:

Amplifier Gain K_A $\frac{\text{volts}}{\text{volt}}$	RESOLUTION IN MINUTES OF ARC		
	Motor PT-13	Motor PT-0	PREDICTED
60	3.5	3.0	2.6
100	2.0	1.7	1.6
140	1.3	1.2	1.1
200	0.9	0.7	0.8

5.2.4 Following Rate Error

A 0 to 5 volt, 400 cycle per second, line phase signal source was substituted for the normal control transformer error signal (Figure 5.2.2) at the D-EG113C input. The control transformer rotor leads were then connected to the pen recorder.

With this open-loop configuration the output slews at an angular velocity dependent on the amplifier voltage input. The recorder traces the sine of this angular velocity. Thus, the output following rate is presented as a function of the input error signal or its angular equivalent.

Graph #13 shows the following rates for the three gains. These rates are considerably higher than those predicted (section 5.1.6.2) owing to the fact that the servo-motors have a maximum speed (about 7280 rpm) greater than that specified. Part of this increase is also due to the use of a line frequency of 419 cycles/second for these tests.

5.2.5 Frequency Response Tests

Closed-loop frequency response tests were made using the experimental arrangement shown in Figure 5.2.5. By means of this circuitry an amplitude modulated suppressed carrier signal is added to the normally nulled servo error signal. This causes the output of the servo loop to oscillate sinusoidally about the angular null position.

The frequency of this oscillation is controlled by the drive motor angular velocity; the maximum amplitude by the 10K potentiometer R_2. Potentiometer R_1 enables the input to be kept constant as the drive rate is increased.

Recorder voltage E_2 traces the output signal amplitude and frequency (i.e., the actual mechanical oscillation at an output device). Recorder voltage E_1 traces the reference input frequency and some constant times the input signal amplitude.

Signal phase shift between the input and output may be read directly on the recorder traces or on the dial of the phase-shifting synchro if an in-phase Lissajous figure is maintained on the oscilloscope. Thus, closed loop frequency response data were obtained.

Input signal amplitudes of 1/2 degree (= 190 millivolts) were used for small signal (i.e., non-saturation conditions) plots. Also, amplitudes corresponding to 5.0 degrees and 15 degrees were inserted to determine the large signal break frequencies.

Graphs 14, 15 and 16 give the frequency response plots using motor PT-13 (f_2= 411 dyne-cm/rad/sec) and for small signal inputs.

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Graphs 17 and 18 show the large signal responses to 5 degree and 15 degree input amplitudes.

These latter curves are shown at amplifier gains of 100, however, gains of 60 and 140 were also tried with essentially identical results.

The corresponding curves using motor PT-0 are given by graphs 19, 20 and 21.

These results along with those predicted by theory, have been summarized in the following tabulation:

SMALL SIGNAL
CLOSED LOOP FREQUENCY RESPONSE
L-2 ELEVATION AXIS (D-DG6001B-3) OF
THREE AXIS REPEATER

CONDITIONS \ PARAMETER			PEAK MAGNITUDE Db	FREQ OF PEAK MAGNITUDE cys/sec	BAND WIDTH (-3Db) cys/sec	-90° PHASE SHIFT FREQ. cys/sec.	EQUIV. 2nd ORDER DAMPING RATIO AT RESONANCE.
Motor #1 Beckman 151M460-3 PT-13 (f_2 =411)	Gain Constant K_A, volts /volt	60	+5	15.8	24.1	17.9	0.30
		100	+6.3	16.9	33.5	18.5	0.25
		140	+7.3	20.7	35.0	22.6	0.22
Theoretical Results for Motor #1	Gain Constant K_A, volts /volt	50	+0.6	4.0	19.5	23.0	0.58
		100	+0.8	16.0	37.2	32.0	0.55
		140	+1.5	23.9	48.3	38.5	0.48
Motor #2 Beckman 151M460-3 PT-0 (f_2= 643)	Gain Constant K_A, volts /volt	60	+0.1	5.9	15.3	16.1	0.64
		100	+2.6	13.4	23.5	23.5	0.40
		140	+3.0	17.6	25.8	24.9	0.37
Theoretical results for Motor #2	Gain Constant K_A, volts /volt	50	+1.0	4.0	15.9	19.7	0.52
		100	+0.8	8.0	30.8	28.6	0.54
		140	+1.1	19.2	41.1	34.8	0.52

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LARGE SIGNAL FREQUENCY RESPONSE L-2 ELEVATION AXIS (D-DG6001B-3) OF THREE AXIS REPEATER				
	5 Degrees Break Frequency cys/sec	15 Degrees Break Frequency cys/sec.	5 Degrees Bandwidth cys/sec	15 Degrees Bandwidth cys/sec
EXPERIMENTAL	5.8	2.2	7.5	2.90
THEORETICAL	6.6	2.5	---	----

5.2.6 Transient Response

Transient response characteristics can be deduced from the foregoing frequency response data, however, it was found simpler to conduct separate tests.

Input step functions were applied to the system (refer Figure 5.2.2) by switching off both the control transmitter excitation and the servo motor control phase voltage, moving the transmitter rotor through the angle desired, and then simultaneously reimpressing these voltages.

The error signal was monitored on the pen recorder. Only large signal inputs have been recorded here and for these both motors gave essentially the same results.

As a measure of the speed of the system response, the rise time of 90% (defined as the time required for the error signal to pass through 90% of the initially impressed value) was used.

The the following results were obtained:

APPLIED INPUT	RESPONSE		
	No. of overshoots	% overshoot.	Rise time to 90%
5° step function.	1	13%	0.70 secs.
15° step function	1	7.9%	0.76 secs.

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5.2.7 System with Minimum Backlash

The existence of backlash in the gear train had presented some difficulties during the repeater development. To gain some insight into the effects of backlash on the present D-model configuration, tests were conducted using an additional anti-backlash mesh in the system. Thus, a double anti-backlash gear was substituted for the single anti-backlash gear DD-480609, providing zero backlash between the gearhead pinion and this gear. With this, the total backlash referred to the motor shaft was reduced from 15 to 1.7 degrees.

Since backlash is the largest non-linearity in the system, it was expected that the additional anti-backlash gear would cause the servo-loop to behave more in accordance with that predicted by linear theory.

5.2.7.1 Resolution

The additional frictional load imposed by the anti-backlash mesh had a significant effect on resolution as shown below:

GAIN K_A $\frac{\text{volts}}{\text{volt}}$	Resolution With Normal System Motor PT-13	Resolution With Anti-Backlash Gear Added. Motor PT-13
60	3.5 mins.	5.3 mins.
100	2.0 mins.	3.2 mins.
140	1.3 mins.	1.9 mins.

5.2.7.2 Frequency Response

Graphs #22, 23 and 24 show plots of the small signal closed loop frequency response. In these tests motor PT-13 only, was used.

Graph #25 gives the large signal response.

These results along with those obtained from the regular (15° of backlash) system and those predicted from linear theory are listed on the following page:

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SMALL SIGNAL CLOSED LOOP FREQUENCY RESPONSE L-2 ELEVATION AXIS (D-DG6001B-3) OF THREE AXIS REPEATER WITH AND WITHOUT DOUBLE ANTI-BACKLASH GEAR.								
CONDITIONS \ PARAMETER			PEAK MAGNITUDE Db	FREQ. OF PEAK MAGNITUDE cys/sec.	BAND-WIDTH (-3Db) cys/sec.	-90° PHASE SHIFT FREQ. cys/sec.	EQUIV. 2nd ORDER DAMPING RATIO AT RESONANCE
Theoretical Motor PT-13 151M460-3	Gain Constant KA, volts/volt	50 100 140	+0.6 +0.8 +1.5	4.0 16.0 23.9	19.5 37.2 48.3	23.0 32.0 38.5	0.58 0.55 0.48
Experimental System with 15° backlash Motor PT-13.	Gain Constant KA, volts/volt	60 100 140	+5.0 +6.3 +7.3	15.8 16.9 20.7	24.1 33.5 35.0	17.9 18.5 22.6	0.30 0.25 0.22
Experimental System with 1.7° backlash Motor PT-13	Gain Constant KA, volts/volt	60 100 140	+1.4 +2.3 +3.6	5.6 17.2 21.0	20.1 27.7 30.7	12.9 20.4 22.6	0.48 0.42 0.35

For the 5 degree large signal response, the values compared as follows:

CONDITIONS \ PARAMETER	5° Break Frequency cycles/second	5° Bandwidth cycles/second
Theoretical	6.6	---
15° Backlash in system.	5.8	7.5
1.7° " " system.	6.7	9.0

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5.2.8 Pre-Production Design Tests

Tests were conducted on a repeater module constructed in accordance with the proposed redesign configuration; i.e., the DG6000-G series. Here the entire loop gear train is contained in one gearhead with the input control transformer shaft coupled directly to the gear head output shaft. Six output devices per face, mounted concentrically about the control transformer or motor, are geared 1:1 with anti-backlash gears to the common control transformer-gearhead shaft. Figures 5.2.8a and 5.2.8b show this arrangement. The amplifier and capacitor systems from B-DG6001B-3, L-2 provided the necessary electronics. A 60:1 gearhead rated at 10 minutes maximum backlash (i.e., 10 degrees at motor shaft) was used.

These tests were carried out using the inertial damped motor PT-0, only. It should be noted that this breadboard very closely simulated the final configuration and the experimental results obtained can be regarded as a good indication of those expected from the DG 6000-G repeaters.

Initially the breadboard was tested with the maximum number of output devices mounted thereon, as shown in Figure 5.2.8c. These consisted of 7 synchros (excluding the input C.T.) 1 potentiometer, 3 double sector switches and 1 single sector switch.

Corresponding checks were then made with all of the output devices removed. Thus, the performance of each axis lies somewhere between these results and, as will be seen, is essentially independent of loading.

5.2.8.1 Resolution Checks

The static resolution versus amplifier gain is tabulated below for both the conditions of maximum and minimum loading. As would be expected in view of the D-model theory and experiment, the effect of the loads on the resolution is small.

GAIN K_A $\frac{\text{volts}}{\text{volt}}$	RESOLUTION FOR MAXIMUM LOADING, MINUTES OF ARC	RESOLUTION FOR MINIMUM LOADING, MINUTES OF ARC
30	7.5	6.3
60	3.0	2.5
100	2.2	1.5
140	1.4	1.1
200*	1.0	0.8

*For the condition of minimum loading it was possible to get the system to hunt at this gain figure. This was an oscillation of 35 cycles/sec and 9.5 minutes of arc amplitude. Values of K_A less than 180 volts/volt allowed no such hunting to occur.

5.2.8.2 Following Rate Error

Graph #26 shows the following rate as a function of angular output lag and amplifier system gain. These curves were obtained from the unloaded module. They are, however, nearly coincident with those taken under the conditions of maximum loading. Differences when compared to those plotted for the D model (Graph #13) are due to the changed gear ratio (60:1 vs. 55:1).

5.2.8.3 Transient Response

Large signal transient response traces were, within the limits of experimental accuracy, equivalent to those obtained in section 5.2.6. Again, the effect of loading was small.

5.2.8.4 Frequency Response

Graphs #27, 28 and 29 show the closed loop frequency response, at the gains indicated, for the conditions of maximum loading. The corresponding curves for minimum loading are given by graphs 30, 31 and 32.

A comparison of the salient points involved, along with those obtained from the D model configuration is tabulated on the following page.

It is apparent that the loaded DG6000-G configuration has a frequency response very nearly matching that of the DG6001B-3 module.

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SMALL SIGNAL CLOSED LOOP FREQUENCY RESPONSE DG-6000-G BREADBOARD, 3-AXIS REPEATER MOTOR: BECKMAN 151M460-3 #PT-0								
PARAMETER / CONDITIONS			Peak Magni-Tude Db	Freq. of Peak Magni-tude cys/sec.	Band Width (-3Db) cys/sec	-90° Phase Shift Freq. cys/sec.	Equiv. Second Order Damping Ratio at Resonance
Maximum Loading on DG6000G Bread-board.	Gain Constant K_A, volts/volt	60 100 140	+0.8 +2.7 +3.2	3.8 15.0 16.0	14.8 26.8 27.8	16.0 25.1 23.1	0.54 0.40 0.37
Minimum Loading on DG6000G Breadboard	Gain Constant K_A, volts/volt	60 100 140	+1.3 +2.1 +3.6	4.5 15.3 15.8	15.9 27.1 28.2	17.5 23.3 25.7	0.50 0.44 0.35
L-2 D-DG6001B-3 Elevation Axis Exper-imental Results	Gain Constant K_A, volts/volt	60 100 140	+0.1 +2.6 +3.0	5.9 13.4 17.6	15.3 23.5 25.8	16.1 23.5 24.9	0.64 0.40 0.37

5.2.9 Environmental Testing

No three axis repeater has undergone the full Astra environmental testing requirements as laid down in Astra I Environmental Specification, Rev. A.

Two D Models, the D-DG6000A-1 #L-2 and the D-DG6000B-1, #L-1 had been tested in accordance with the "Minimum Pre-shipment Tests" excerpted from the M-H memo, C.A. Swenson to Arrow Project Engineers entitled "Arrow Electronic System R & D Environmental Specifications."

The results of the testing as applied to model L-2 of the D-DG6000B-1 repeater series are summarized in the following:

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5.2.9.1 High Temperature

With the repeater in thermal equilibrium with an ambient temperature of 160°F, the parameters of loop stability, null voltage, static resolution and large signal transient response were checked. In every case and for each axis, the repeater performance was found to be within the specifications.

5.2.9.2 Low Temperature

With the repeater in thermal equilibrium with ambient temperature of -30°F, the parameters of 5.2.9.1 were again checked. Loop stability, null voltage and transient response were within specifications for all axes. The azimuth and roll axes however, failed to conform to the specified minimum static resolution of 3 minutes of arc. For these, the resolutions were 7.3 and 5.6 minutes of arc respectively.

5.2.9.3 Altitude

The repeater was placed under atmospheric pressure equivalent to that at 70,000 feet, but at room temperature, and allowed to remain there for one hour.

The servo loop checks of section 5.2.9.1 were made, with all axes meeting the specifications.

5.2.9.4 Vibration

The repeater was subjected to a resonant frequency scan over the range 5 to 500 c.p.s. with a double amplitude of 0.018 inches or a maximum acceleration of 2 g's (whichever was smaller), in each of the three mutually perpendicular coordinate axes.

Figure 5.2.9.4 below shows the choice of reference letters for the three axes:

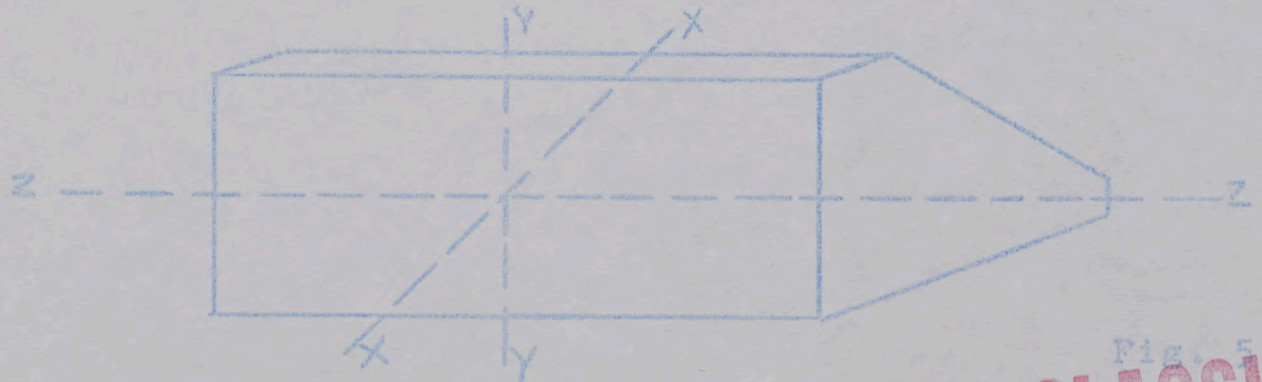

Fig. 5.2.9.4

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5.2.9.4.1 X Axis Vibration

For vibration along the X axis the worst case conditions were at 95 c.p.s.. Here, motion of the servo motors with respect to the module castings was apparent. Small oscillations (less than 11 minutes of arc) prevented the elevation and roll axes from meeting the specifications.

5.2.9.4.2 Y Axis Vibration

Again relative motor-casting motion occurred at 30 to 50 c.p.s. Electrical resonances in the range 103 to 115 cps resulted in oscillations of the elevation and roll axes (less than 10 minutes of arc amplitude) which prevented the repeater from meeting specifications

5.2.9.4.3 Z Axis Vibration

An electrical resonance at 85 cps resulted in small (12 minutes of arc) oscillations of the elevation and azimuth axes.

5.2.10 Test Results Conclusions

From all of the foregoing test results it is apparent that the three axis repeater whether of the D model or the pre-production design configuration failed only on two counts to meet the specifications:

1. The small signal damping factor was generally below the required value of 0.60 minimum.

2. Small oscillations in the servo loop occurred during the vibration testing.

Attempts to overcome these difficulties had been initiated with the following results or proposals.

1. Inertia damped servo-motors with higher values of the coupling constant f2 than those used, would amost certainly end the oscillations arising under vibration testing. The tests conducted with one such motor (PT-0) eliminated any tendency for the repeater module to hunt and permitted a significantly increased gain margin.

2. A phase-advance network (such as a Bridged

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T) inserted in the amplifier system could be expected to improve the damping factor. Also, the motor manufacturer can provide units with a still higher value of f_2, should this be thought necessary.

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6 FUTURE PLANS

6.1 General

Experience gained in manufacture, assembly and testing the Developmental Repeaters indicated room for improvements, although ultimately the unit was made to meet the performance specification except at temperatures of minus 30° Fahrenheit and below, and under severe vibration.

A full redesign was not thought advisable if the troubles could be cured by minor action. However, after careful study it was concluded that a major mechanical redesign was necessary to arrive at a unit which would be satisfactory in quantity production and in subsequent service.

6.2 Summary of Troubles Experienced

These will be presented by assemblies and sub-assemblies.

6.2.1 D-DG6000A-1 and D-DG6000B-1

The method of mounting the modules to the rack was not positive. The modules could float by the amount of the clearance between the captive screws and the holes in the rack. In extreme cases the modules could contact the front panel or side gussets.

On a model delivered to RCA Camden, the clinch nuts became loose in the module chassis, and the captive screws could not be either tightened or removed.

6.2.2 Rack Final Assembly DD480821

Vibration tests showed severe resonance of the side gussets, and a very severe resonance at the rear centre of the rack floor, at 46 cycles per second at which frequency under an applied 2g vertical acceleration a 40:1 amplification was measured on the centre repeater module. This led to failure at the rear corners of the rack.

The PT Connectors used on the 'B' series repeaters were not specifically designed for back mounting, and in some cases the mounting screw heads fouled the mating plug.

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6.2.3 Modular Repeaters D-DG6001

Distortion of the body casting during stress relieving heat treatment resulted in each casting requiring individual machine set-up to maintain tolerances.

Further distortion subsequent to machining resulted in variation on backlash in the gear train and consequently variation in the maximum stable gain of the unit.

The aluminum synchro plates had to be spot faced around the synchro mounting holes to provide a mounting surface perpendicular to the box. This required that the standard BuOrd clamps be modified. #4-48 wire thread inserts were not available and special #4-40 captive screws had to be manufactured. Also, the differential contraction between the aluminum plate and stainless steel centre gears lead to decrease in centre distance at minus 30°F sufficient to cause a very considerable increase in resolution.

The bellows coupling proved expensive and difficult to manufacture.

Assembly to the synchro and gear body was difficult due to lack of access space.

It was intended that the output devices would be zeroed by the following procedure. Coarse zeroing would be achieved by rotating the body prior to clamping. Fine zeroing would be achieved in turning the shaft while the gear was held stationary.

The procedure had to be abandoned, since tightening the gear clamp set screws disturbed the zero setting.

Zeroing was, therefore, achieved by rotating the body of the output devices. The use of double clamps made this more difficult, since the adjacent device could easily be disturbed.

It was undesirable to have lead wire soldering operations carried out on the switches and potentiometers after mechanical assembly.

The central gear on the control transformer shaft had considerable inertia, which, combined with the backlash in the gear train imposed severe limitations on maximum stable gain.

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The required accuracy of the switch sectors was not obtained by the switch manufacturer. Although the angular tolerances as specified were not unduly severe, the choice of half speed rotation and double sector pattern resulted in only half the specified tolerances being acceptable on each sector.

The method of assembly, and sub-assembly drawings required revision, so that the chassis could be completely assembled, wired and tested as a separate sub-assembly.

The fiberglas cover rings and end covers were not considered satisfactory for production (The method of manufacture was excellent for the developmental models since modifications were easily incorporated.)

Insufficient space was available for the leadwires between the plastic end covers and the output devices, consequently the leadwires and terminals were under continuous mechanical load when the cover was installed. This was offset somewhat by the flexible nature of the plastic cover, but was considered an unsatisfactory situation.

6.2.4 Power Amplifier DD480813

In general the design was too cramped. Satisfactory units were built by skilled technicians, but considerable care was required to avoid grounding.

The evacuation tube on the glass header was not satisfactory for repair purposes, and in several units a seal was effected by the use of epoxy resin.

Insufficient space was available for wiring. The heat sinks, which were not at ground potential, increased the probability of grounding due to solder flow.

The bias resistors were considered to be too highly stressed thermally.

A TJ40A silicon diode was originally specified but was later replaced since the TJ series were proscribed by RCA from the standpoint of reliability.

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6.3 Preproduction 3 Axis Repeater DG6000G-1

Consideration of the shortcomings of the Developmental models indicated the need for mechanical redesign action to give a more produceable and reliable device in pre-production quantities.

A summary of the design follows:

6.3.1 3 Axis Repeater Assembly DG6000G-1

The basic design concept of three modular repeaters mounted on a rack was preserved, but the method of retaining the modules was considerably improved. Two holes in the base of the module engaging with pins on the base of the rack, provided location in the plane of the rack floor. A quick disconnect band clamp with screw fastening secured the module to the rack. This clamp also served to dress the cables into slots on the module body. Bendix Pygmy PT06P plugs formed the termination to the module cables.

The procedure for removal of a module was thus simplified. Once the clamp screw was loosened, the clamp could be unlatched, and the two plugs disconnected by one half turn.

The rack did not have to be inverted during the operation.

6.3.2 Rack Final Assembly

The rack was redesigned to achieve maximum stiffness andease of servicing. An end view is shown in Figure 6.3.2.

An epoxy bonded aluminum honeycomb sandwich formed the base of the rack. The bottom sheet of the sandwich folded up to form the front panel and over towards the rear to form a platform to which a separate junction box assembly was bolted. Two triangular gussets connected the top flange to the front panel between the modules. Triangular end gussets formed by folding up the bottom sheet were riveted to the front panel, the upper sandwich sheet and the junction box platform.

The junction box was of folded sheet aluminum having a hinge along the centre of its top face. The front of the box hinged up and back to allow access for insertion and servicing of the wiring.

The Bendix Pygmy PT00P wall mount receptacles were fitted with nylon potting boots and the entire

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wiring harness complete with connectors and terminal boards was prefabricated as a subassembly.

By designing the box to open at the front, the modules did not have to be removed to gain access to the junction box. This enabled continuity checks to be performed on a complete assembly prior to potting if so desired.

The wiring was re-arranged to bring the necessary first line maintenance test points all to pins on Connector J7, which was increased in size for the purpose.

6.3.3 Repeater Servo Modular DG6001G

The basic principle was unchanged, though the mechanical design was extensively altered to employ a simple casting, which gave support for the electronic chassis components and provided support and enclosure for the mechanism. Figure 6.3.3a shows a typical cross section of module. By eliminating the sheet metal chassis and the rack centre gussets, sufficient additional width was obtained for each module to allow the output devices to be more widely spaced. This in turn allowed the use of three single BuOrd clamps per device, with the motor and gearhead mounted centrally on the front plate. This eliminated the large gear and cluster gear with considerable reduction in inertia. The ratio of the gearhead was increased to 60:1 with maximum backlash of 10 minutes of arc measured at the output shaft.

The two plates were connected by six pillars. The mechanism was completely assembled prior to insertion in the housing. This gave free access to each gear and output device, and allowed removal and replacement of all but the centre devices without destroying the zero adjustments of the remainder.

The front cover, which also formed the chassis for the electronic components was of deep drawn aluminum and was located on a turned diameter of the body casting. Three screws secured the chassis to hexagonal extensions on three of the mechanism mounting screws. Figure 6.3.3b shows a front view of module.

The motor windings were redesigned to allow the use of standard values of tuning and phasing capacitors which were mounted under the chassis. The two amplifiers and a terminal block were

were mounted on the front of the chassis. This allowed access to the screw terminals without inverting the assembly, thus facilitating servicing and testing of the module.

A similar, but plain cover enclosed the rear end of the module.

The mechanism was held in the body by three screws passing through the casting and front plate and engaging with tapped holes in three of the pillars. The front plate located in a turned register in the casting. No extreme precision bores or dimensions were required on the casting, other than the two locating holes in the base. The small annular clearance between the rear plate and the casting was closed by a silicone rubber ring held in place by a stainless steel ring.

The front and rear plates were made of Type 321 stainless steel. This permitted the use of #4-48 clamp screws engaging directly in tapped holes in the plate, and also eliminated the need for spot facing. Unmodified BuOrd mounting screws and clamps were used throughout. The change in plate material also resulted in an increase in gear centre distance at low temperature, offsetting the binding tendency. The tightest mesh occurred at high temperature when the viscous resistance due to the lubricant was least.

The bellows coupling was replaced by a stainless steel flexible disc-and-spider coupling. Sufficient axial alignment was obtained by the use of a gauging plug prior to dowelling the plates to the supporting pillars.

The use of large (96 tooth) gears slightly increased the static accuracy of the device.

All output devices had an integral gear cut on the mounting flange. A pinion key was used to rotate the body of the device to obtain zero adjustment.

6.3.4 Power Amplifier AD481363

The power amplifier package was redesigned using the same circuit as in the developmental version DD480813 but substituting the smaller Transitron 2N547 silicon power transistors for the Texas Instruments 2N389 transistors previously used.

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Although no significant reduction in overall size resulted, more space was available for wiring, and due to the smaller bias current, the thermal stress on the bias resistors was reduced. The evacuation pinch-tube was mounted on the top of the can. The transistors were insulated from the heat sink which was at ground potential, thus minimizing the probability of ground faults due to solder flow. Figure 6.3.4 shows a typical cross section of the amplifier.

6.3.5 Summary

The above programme resulted in a cleaner, more reliable design, and effected an estimated weight saving of some 2.5 lbs.

A Breadboard model was built, and tested, and is shown in Figure 5.2.8.a., b, and c.

A wooden mock-up module was constructed to facilitate design of the cable harness and is shown in Figure 6.3.5a, and mounted in a modified developmental rack in Figure 6.3.5b.

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7 STATUS AT CUT-OFF

The original requirement was for 6 D models; 3 units of D-DG6000A-1 and 3 units of D-DG6000B-1.

7.1 Status as of September 26, 1958

a) D-DG6000A-1 serial No. L-1 was shipped as a CSX model to RCA Camden, on May 10, 1958 and completed over 200 hours of systems tests. Was to be returned to Honeywell Controls for modifications and environmental testing to qualify as a "D" model.

b) D-DG6000A-1 Serial No. L-2 was shipped to RCA as a Flightworthy "D" model, September 13, 1958.

c) D-DG6000A-1 Serial No. L-3 assembly was completed. Outputs required zeroing and then environmental testing to qualify as a Flightworthy "D" model.

d) D-DG6000B-1 Serial No. L-1 had completed environmental tests on September 25, 1958. This unit incorporated the strengthened rack and had the best performance of units tested so far, a Flightworthy "D" model.

e) D-DG6000B-1 Serial No. L-2 was completed, but required environmental testing for flightworthy certification.

f) D-DG6000B-1 Serial No. L-3 assembly was only partially completed.

7.2 Redesign D-DG6000G-1

Layouts complete. Part drawings 50% complete. One Breadboard model of gear train including the 60/1, 10 min. gearhead tested and proved to have good performance characteristics. Wooden mockup of the module constructed to study a) space requirements in rack, b) cable layout, c) module clamping.

7.3 Test Fixture

A test fixture was designed to enable a complete 3 axis repeater to be checked out through the junction box connectors. The circuit was designed and parts procured, but assembly was curtailed by contract cancellation. Figure 7.3 shows the control panel for the test fixture.

8 CONCLUSIONS

Based upon the test results obtained from the present and the projected Three Axis Repeater configurations, it appears that the following specifications can be met.

a) A static resolution of 2 minutes of arc.

b) A following rate of 600 degrees per second at an output device, with a lag not exceeding 1 deg.

c) A mean acceleration to 67% of full speed of 17.5 radians per second squared at an output device. This is equivalent to an output device rate of 400 degrees per second attained in 0.4 seconds.

d) A damping ratio in excess of 0.5.

e) A bandwidth of 25 cycles per second.

f) Using 7 minute synchros, an overall angular accuracy with a 3σ value of 12 minutes is readily obtainable.

Note that these are obtained using an elementary servo-loop and they could, if necessary, be improved by incorporating equalizing networks, harmonic and quadrature filters, additional anti-backlash measures, etc., into the system.

The preproduction design was carried out with emphasis on ease of manufacture, calibration and servicing; so that normal factory grade labour could be employed.

The external surfaces were kept as uniform as possible to minimize accretion of dust, which is becoming of more importance due to its radio-active content.

Each module could readily be equipped with receptacles in lieu of the plug and cable harness, and could be used as a separate unit with up to 12 BuOrd Size 11 output devices.

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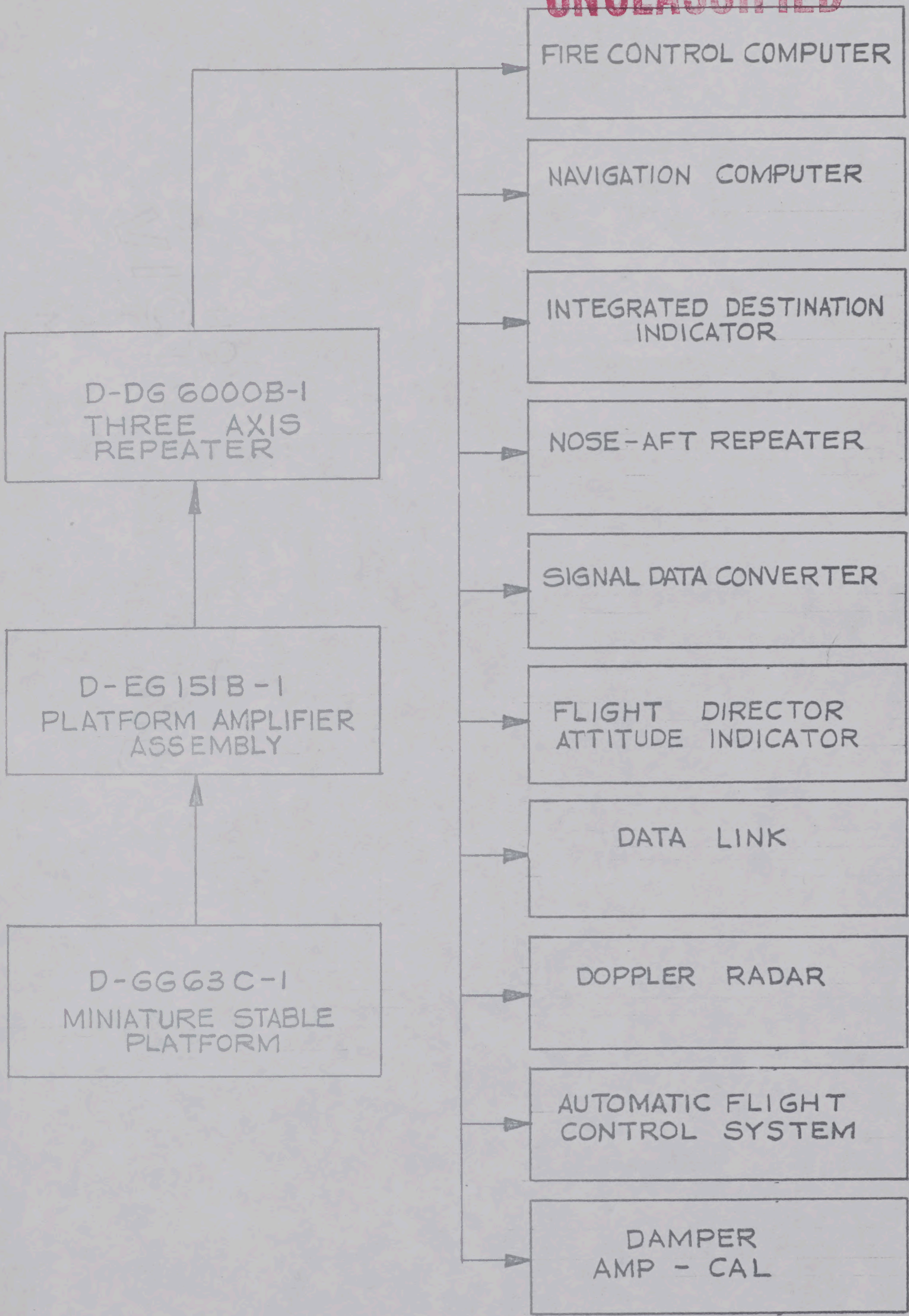

VERTICAL AND HEADING REFERENCE SYSTEM
BLOCK DIAGRAM

FIG 1·2

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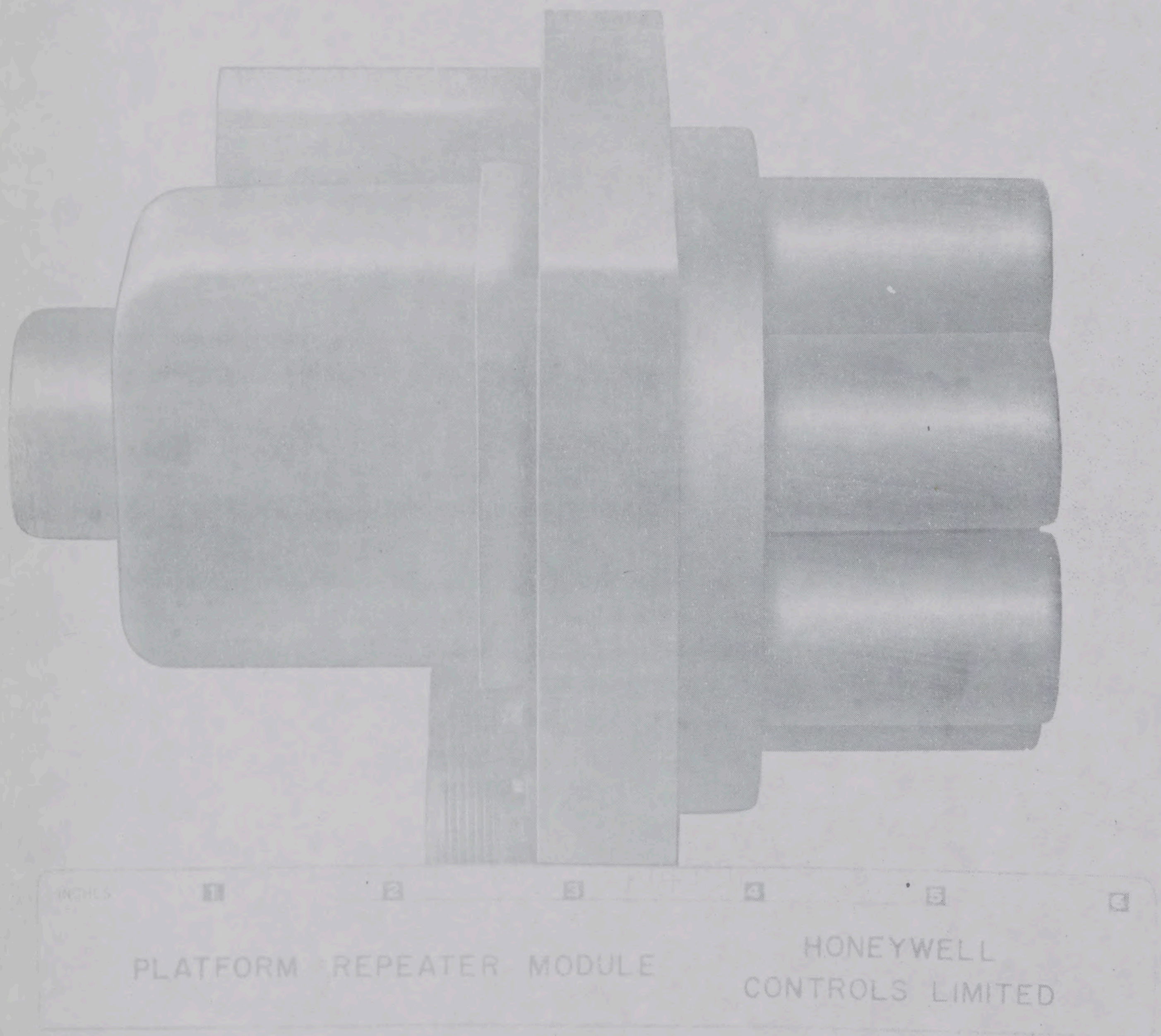

PRELIMINARY MODULE DESIGN

FIG. 1.3.6

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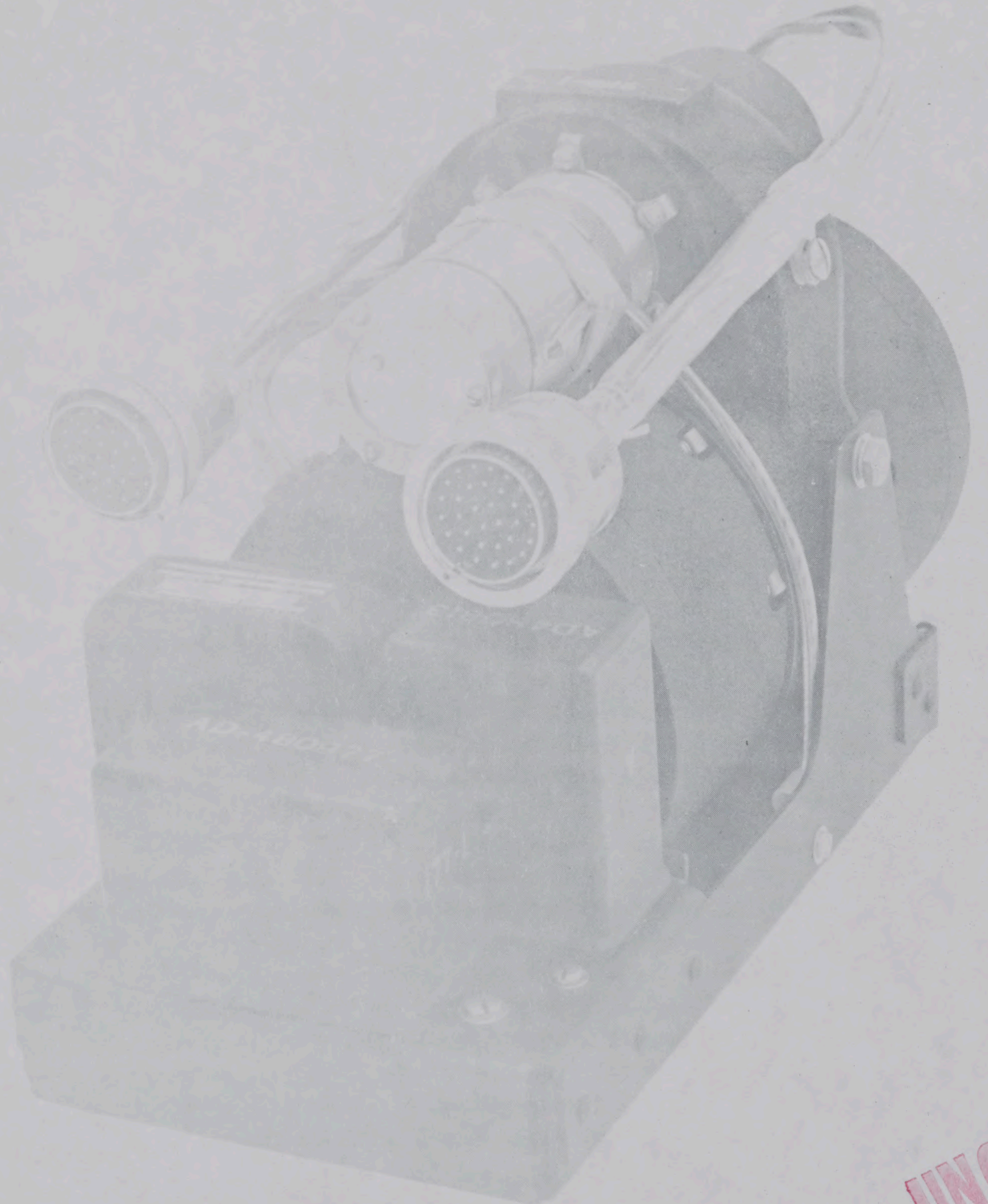

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REPEATER SERVO MODULAR
D-DG6001A-1
3-AXIS REPEATER

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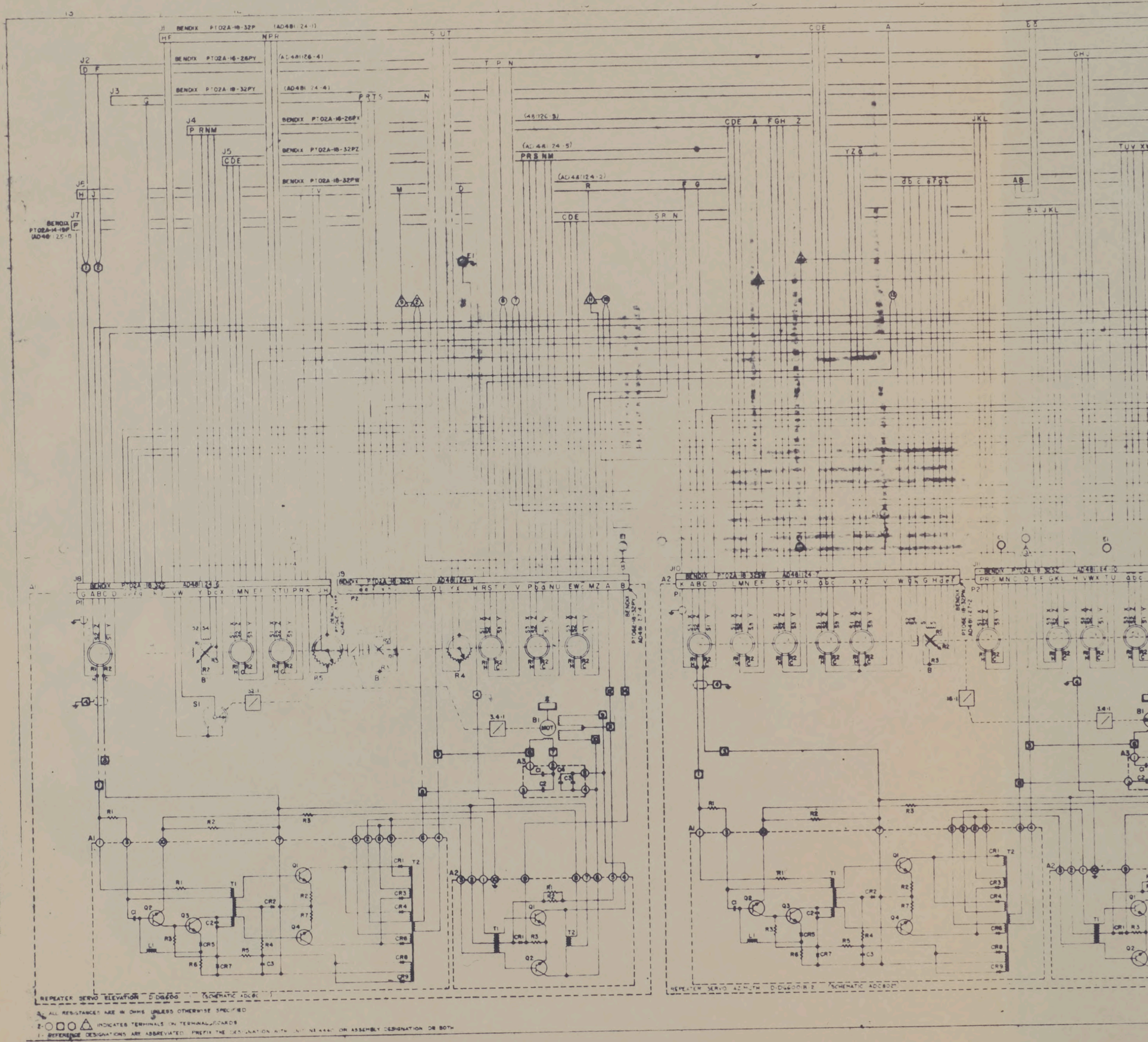
FIG 1-3

HC/MP Document CR-2D 1041



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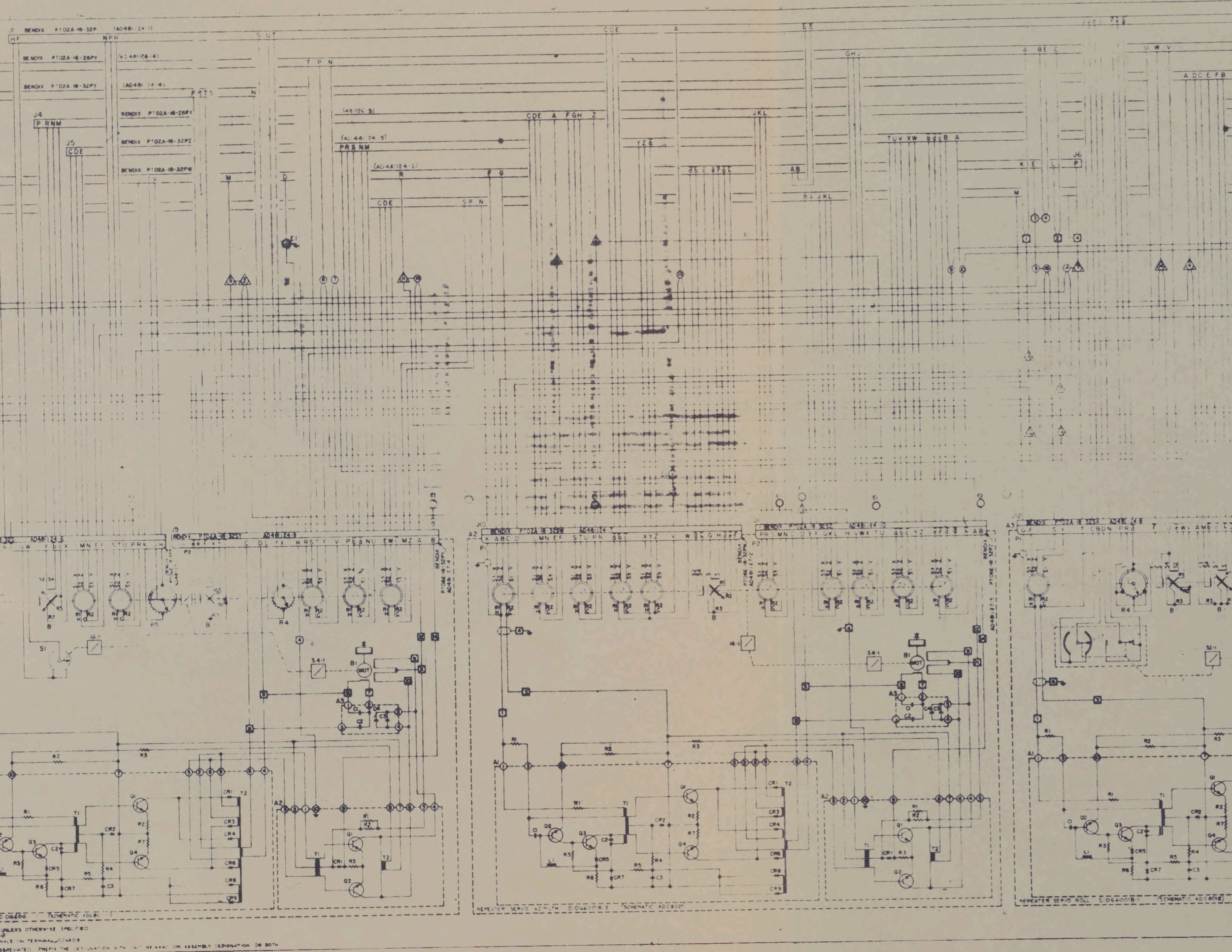
REPEATER SERVO AZIMUTH
REPEATER SERVO ROLL

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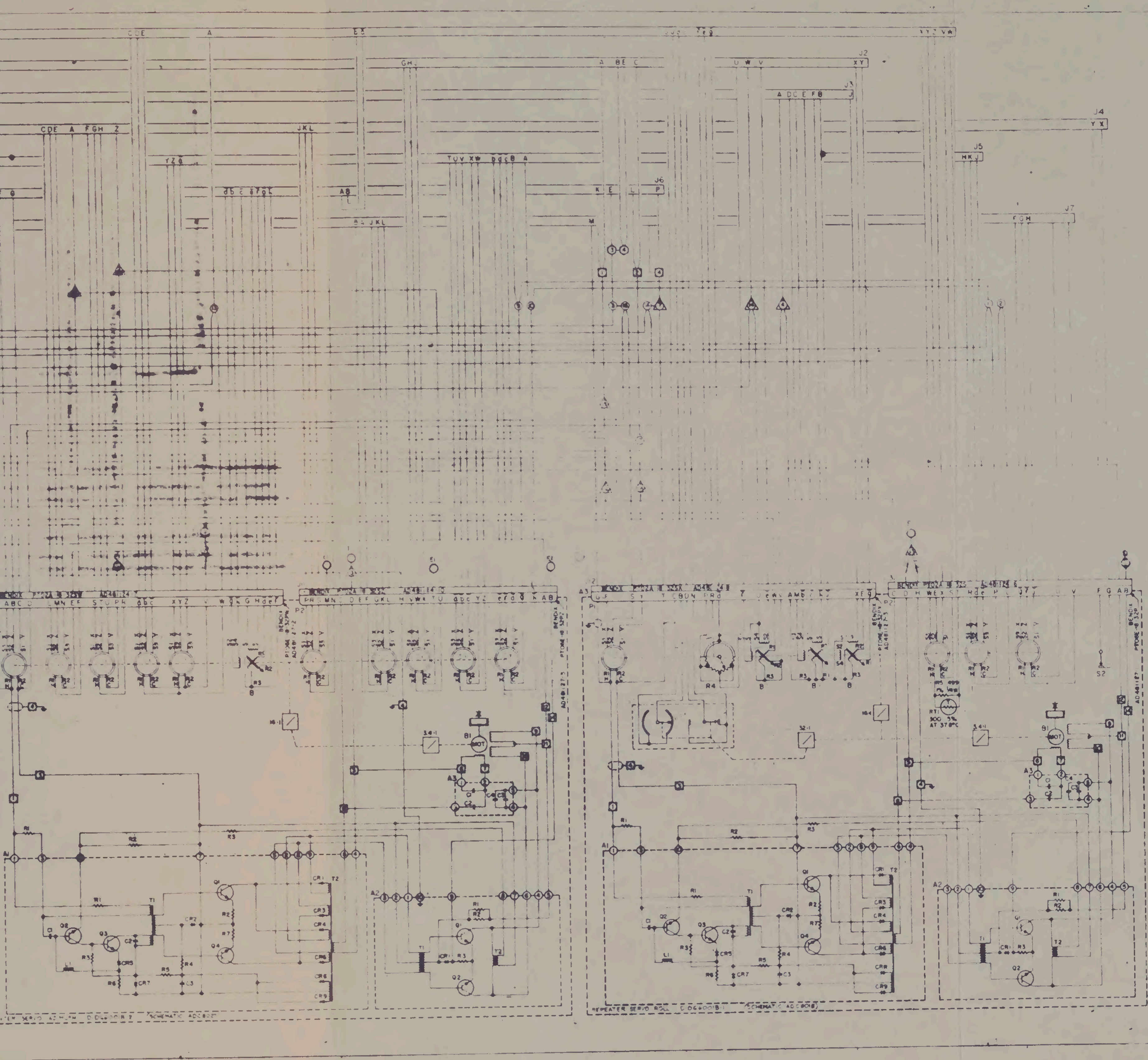

SCHEMATIC DIAG
3 AXIS REPEAT

FIGURE 3·2·

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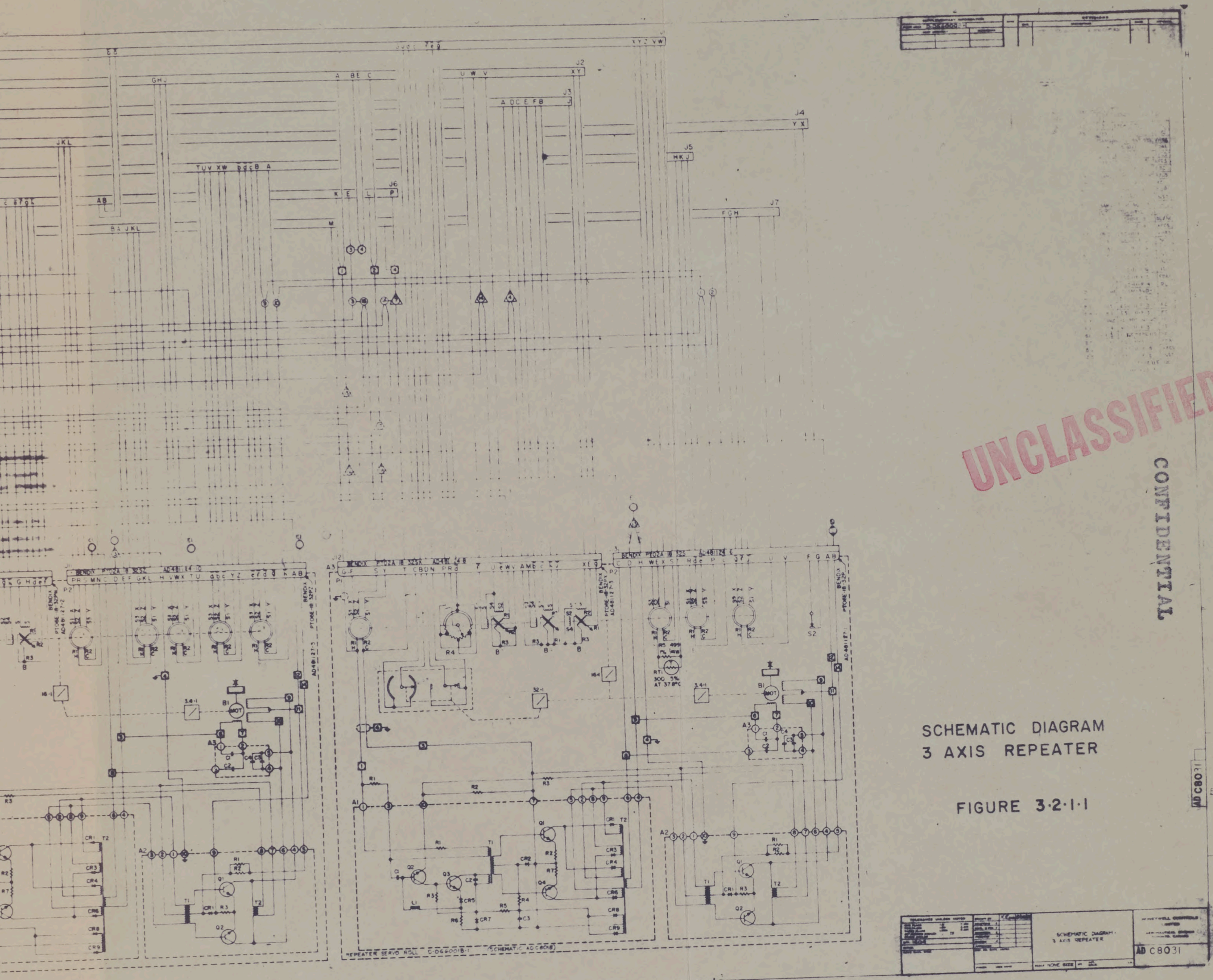

SCHEMATIC DIAGRAM
3 AXIS REPEATER

FIGURE 3·2·1·1

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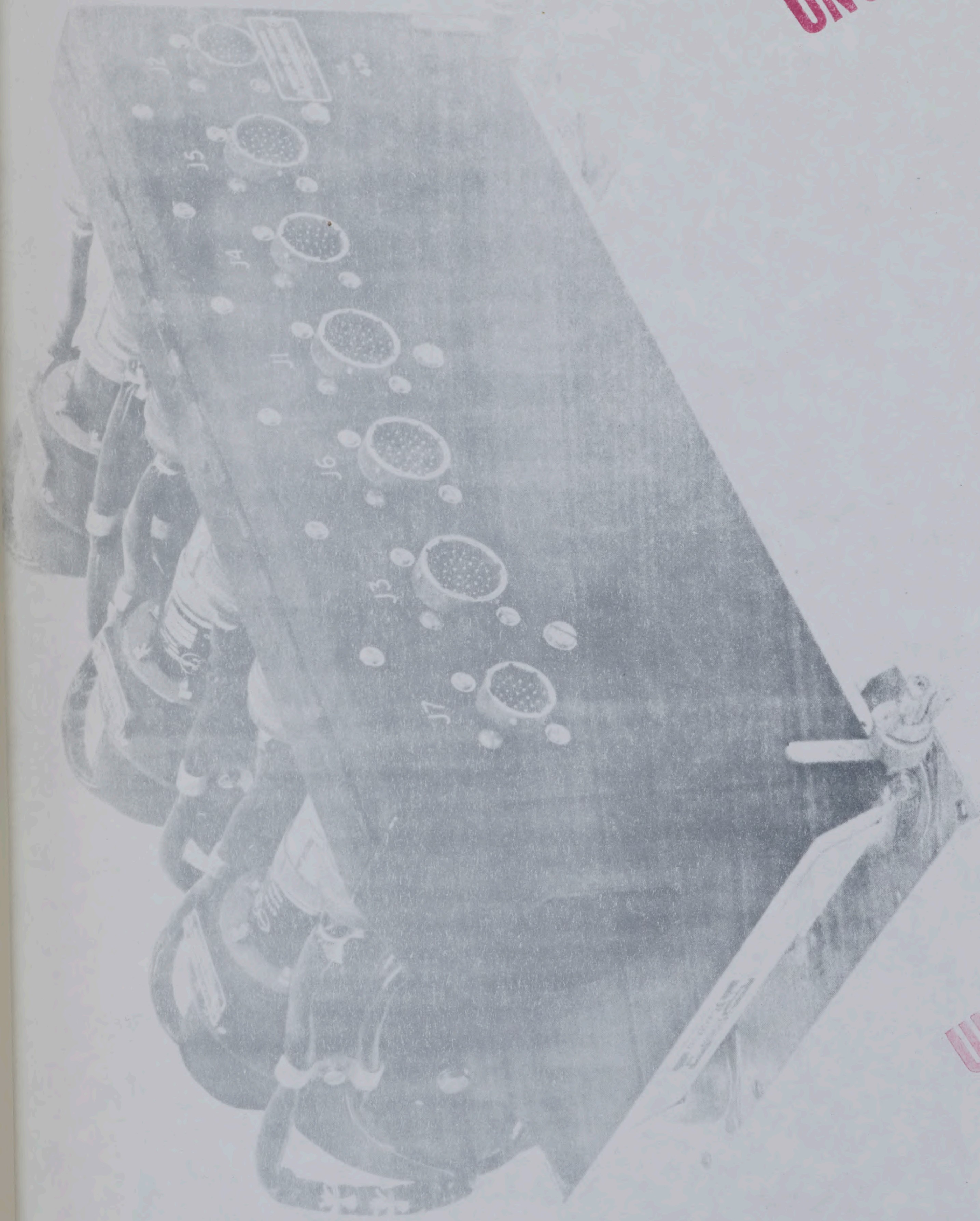

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D-DG6000A-1   3 AXIS REPEATER

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FIG. 4.1.a

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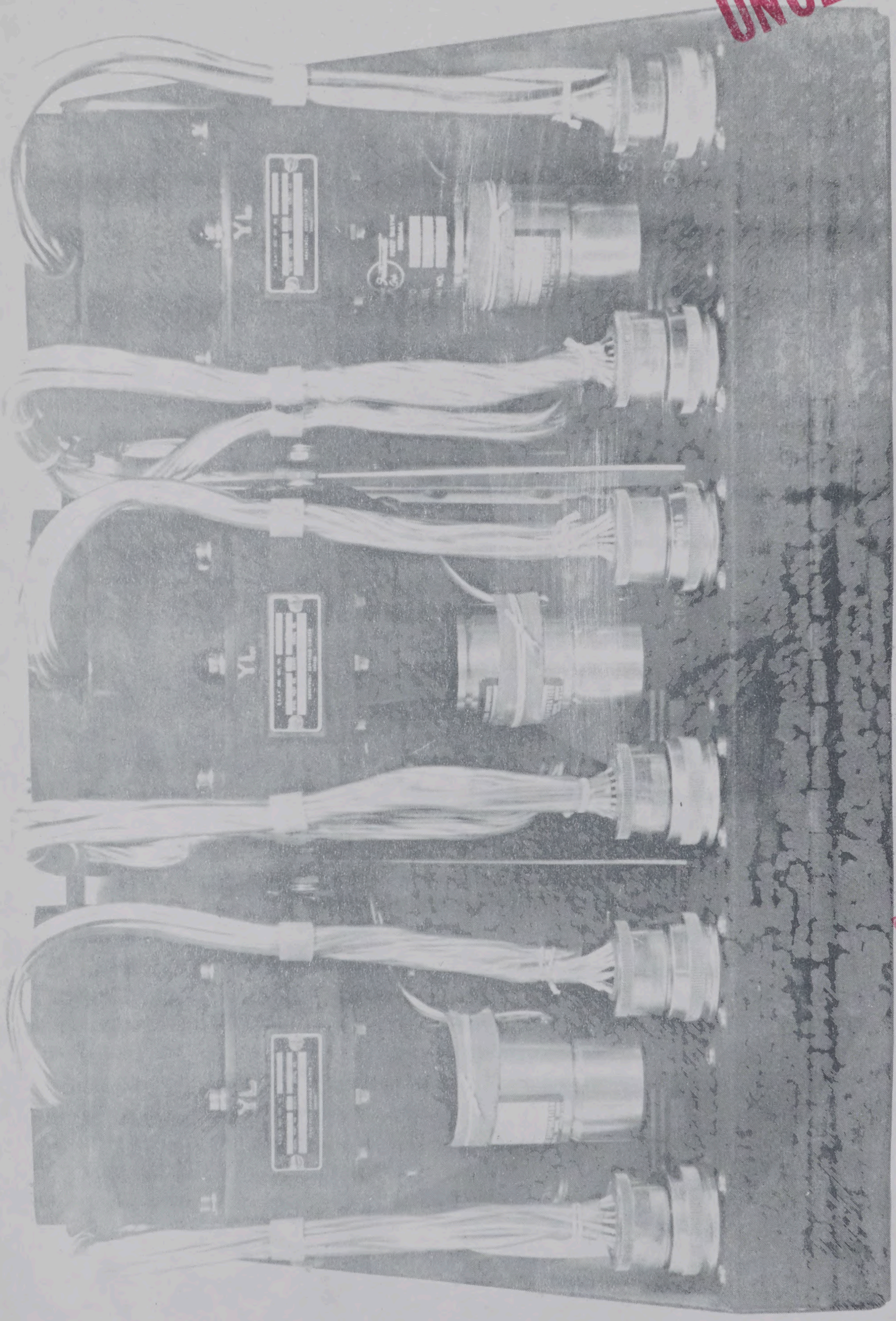

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D-DG6000A-1 3-AXIS REPEATER

FIG 4-1

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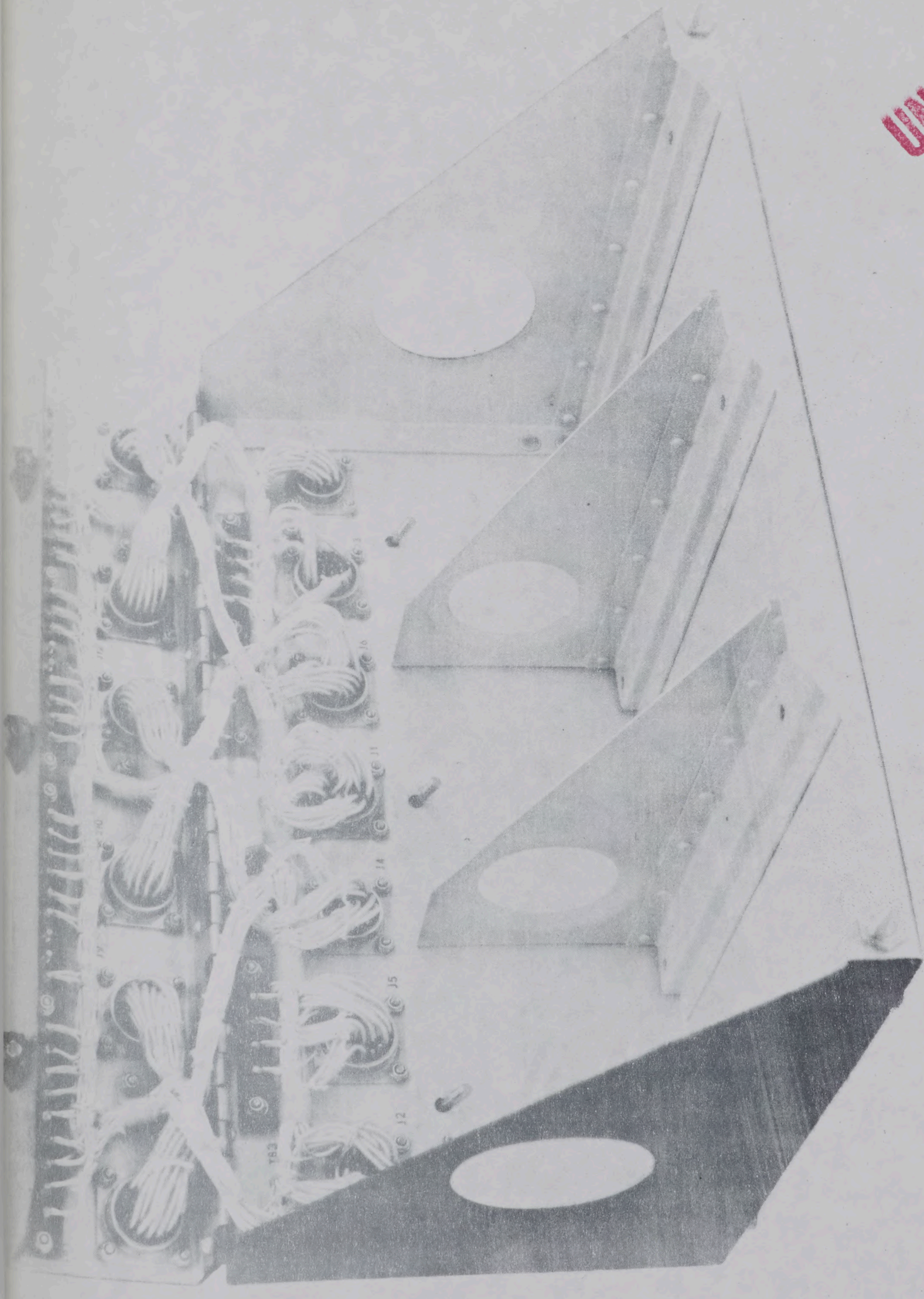

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VIEW OF RACK DD480821
WITH DISTRIBUTION BOX OPEN

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RACK, SHOCK MTG D-QG6000A-1
(3 AXIS REPEATER)

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FIG. 4·1·1·b

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THREE AXIS REPEATER

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FIG. 4-1-1-c

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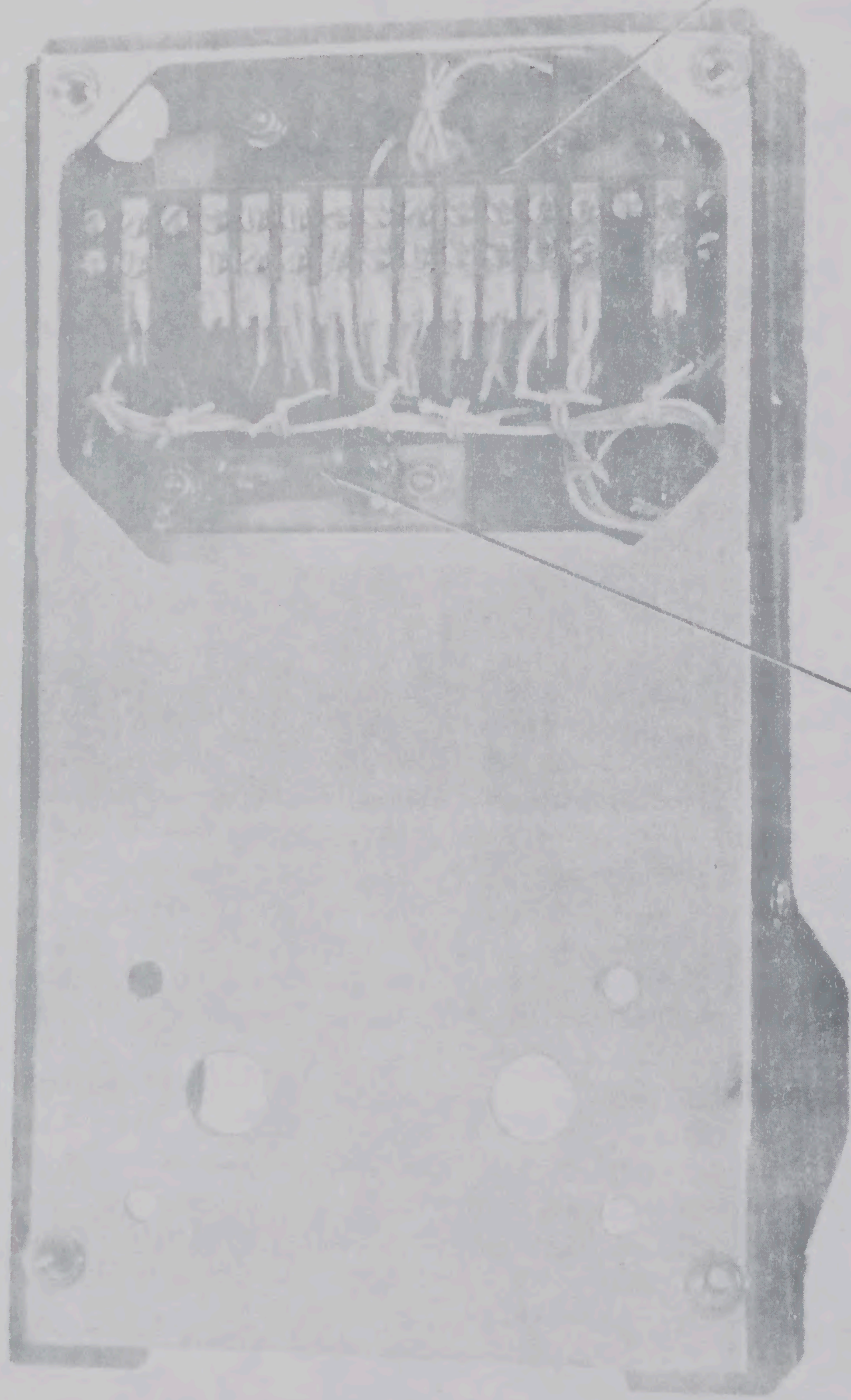

BASE VIEW OF REPEATER MODULE
D-DG6001A

FIG 4.1.2

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D-86001A REPEATER MODULE
WITH END COVER REMOVED

FIG. 4·1·3·a

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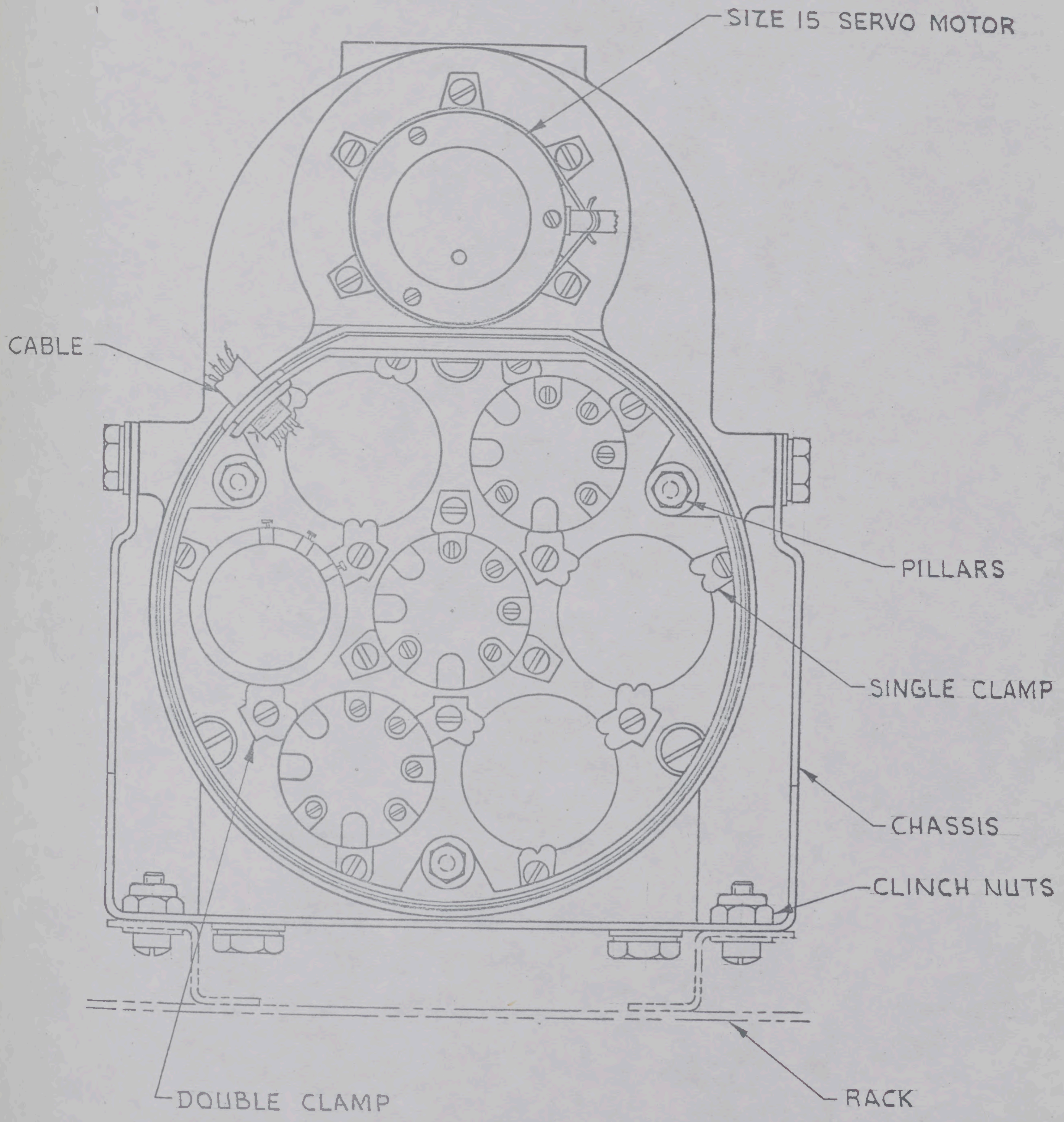

FRONT VIEW MODULE - REPEATER SERVO
3 AXIS REP. "D" MODEL DESIGN

SCALE 1-1
DATE 12-12-58

FIG 4.1.3b

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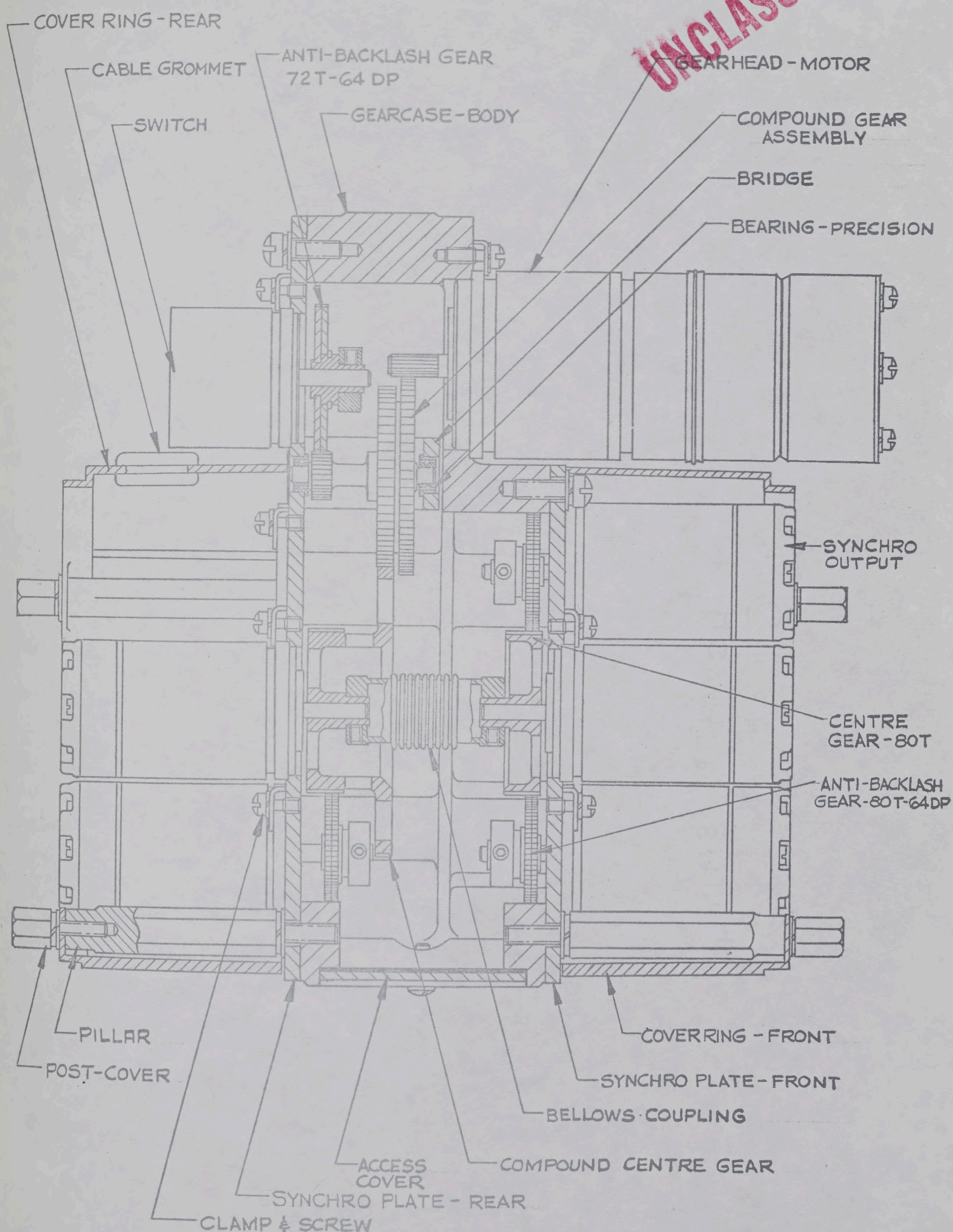

TYPICAL SECTION - MODULE SYNCHRO & GEARCASE
3 AXIS REPEATER

FIG 4.1.3.1a

SCALE 1:1
DEC 8-58

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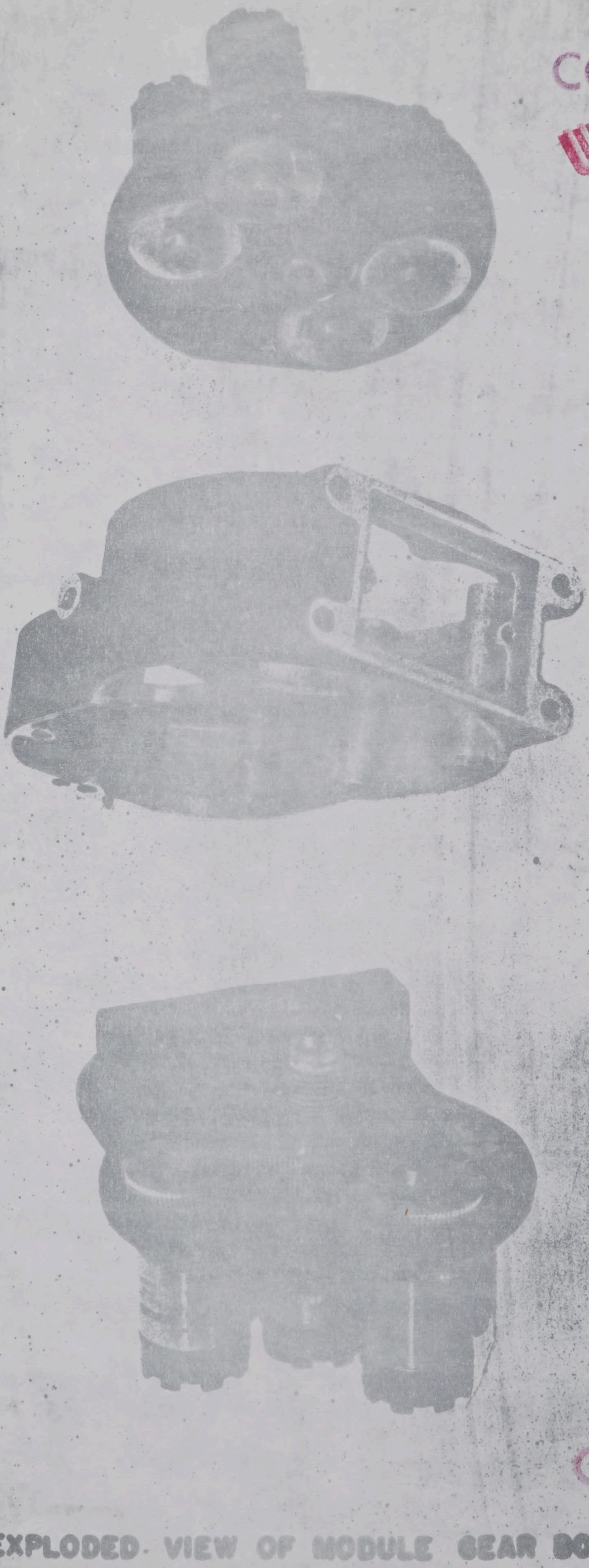

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EXPLODED VIEW OF MODULE GEAR BOX

FIG 4·1·3·1·b

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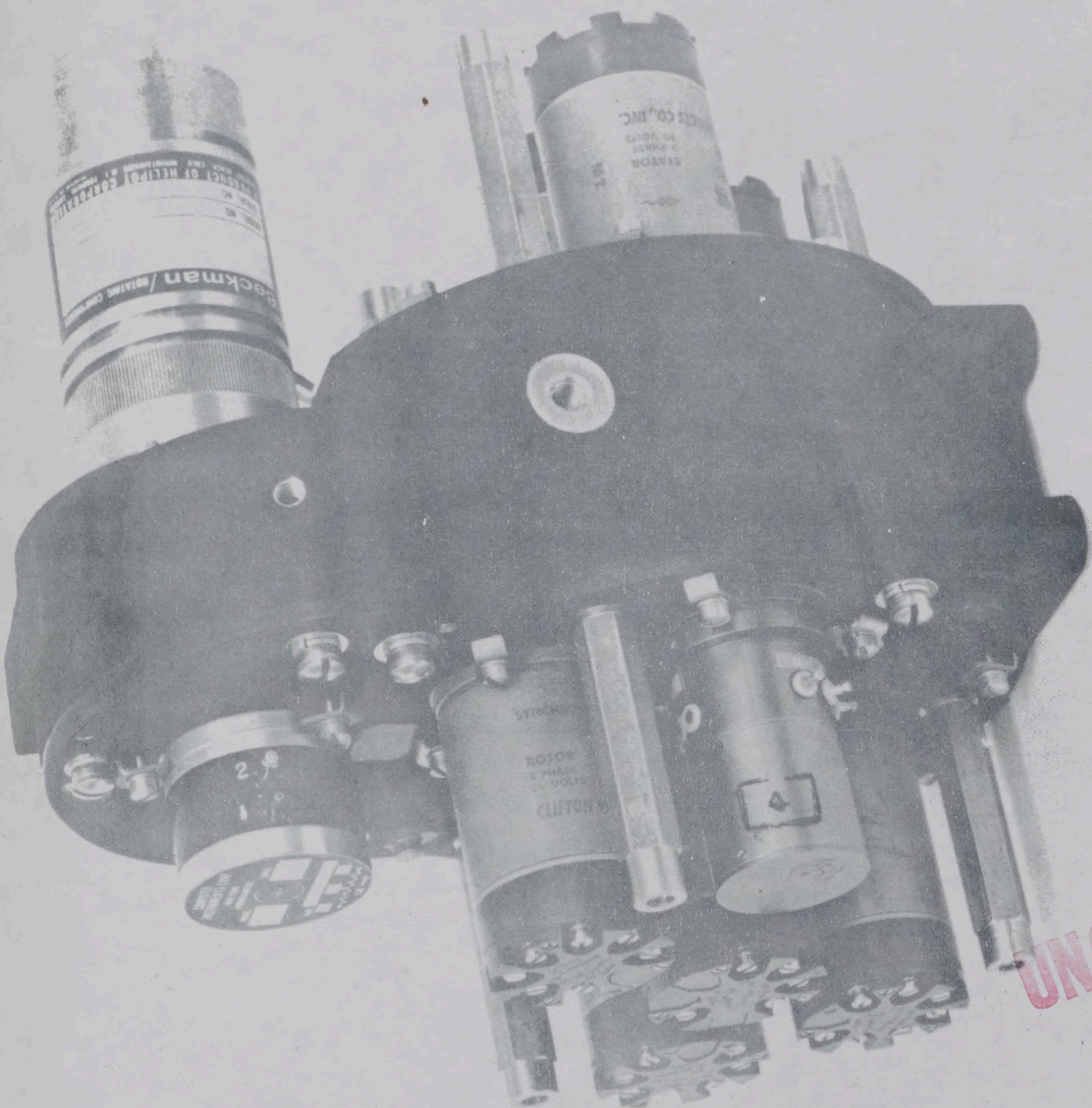

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SYNCHRO & GEAR BODY ASSEMBLY

FIG. 4·1·3·1·c

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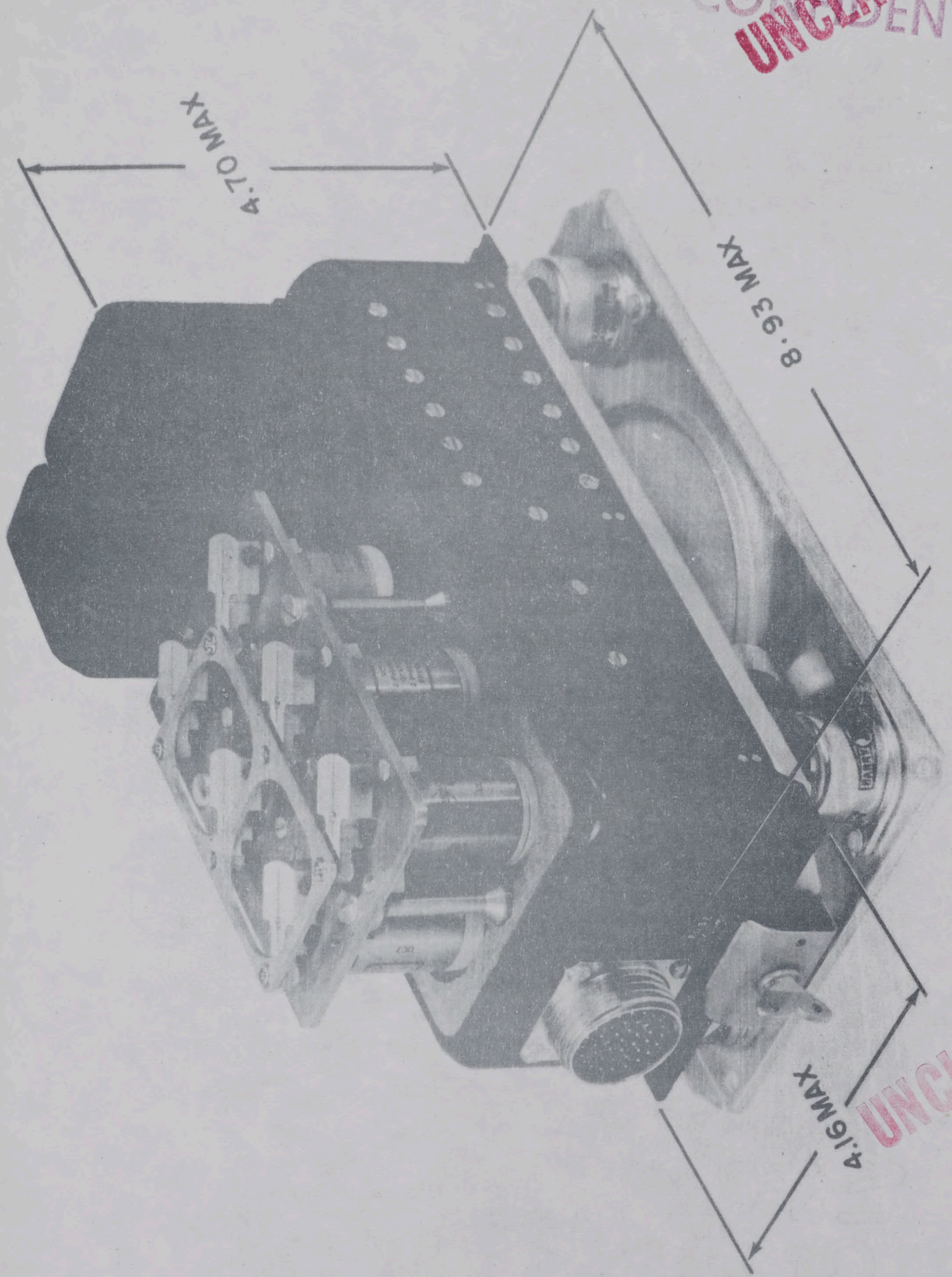

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D-AG32A SERVO REPEATER MODULE

FIG. 4-1-4

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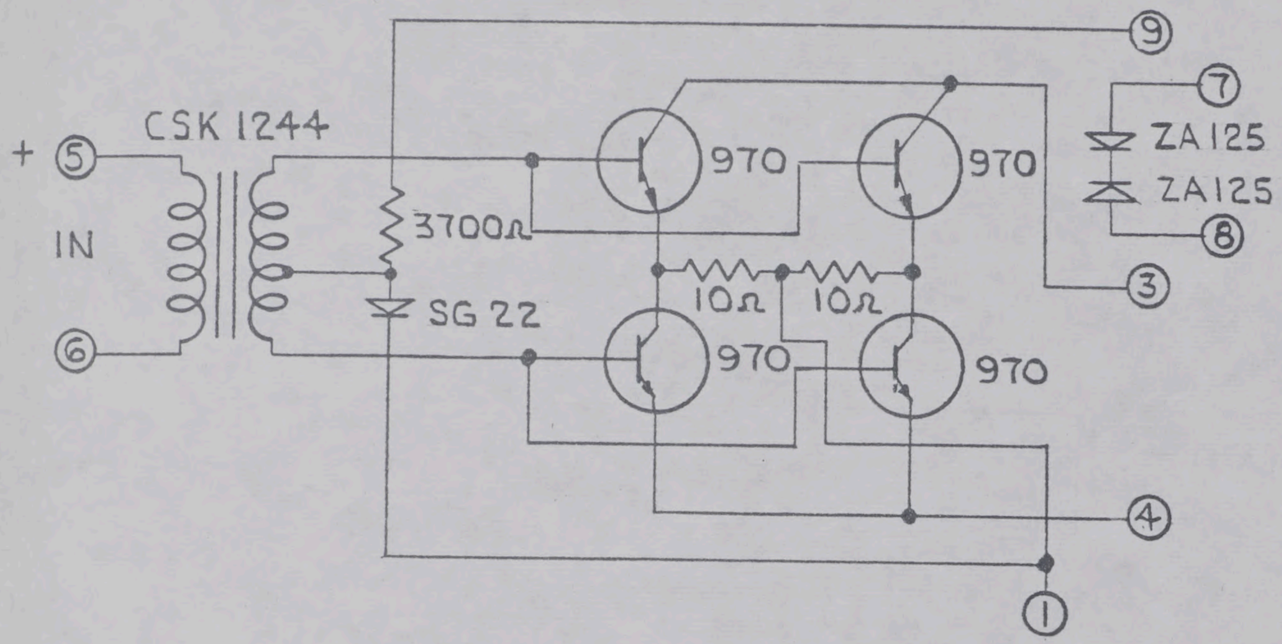
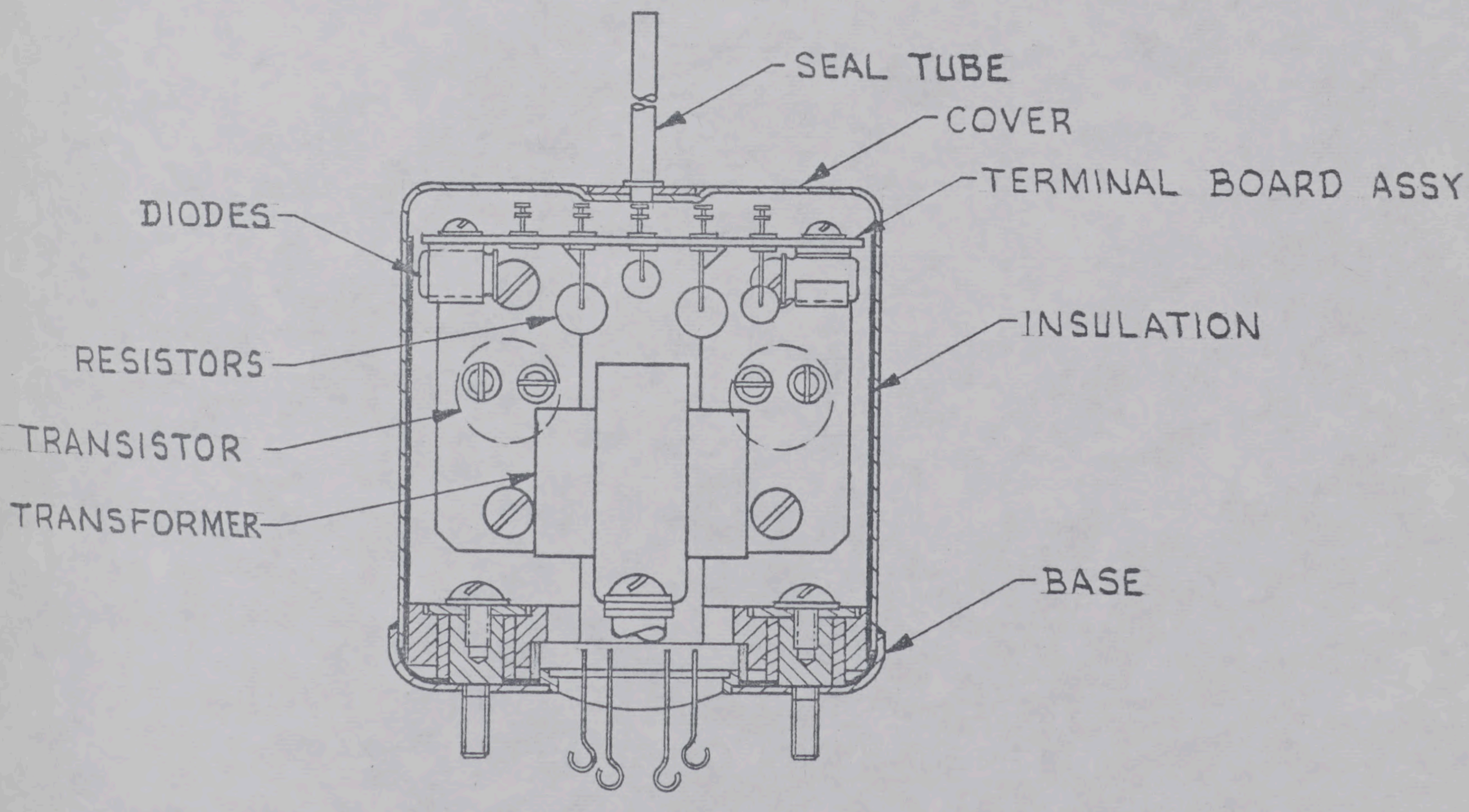


SCHEMATIC WIRING DIAGRAM



POWER AMPLIFIER

2 AXIS REPEATER

SCALE 1 : 1

DATE :- 12-16-58

FIG 4.2.2

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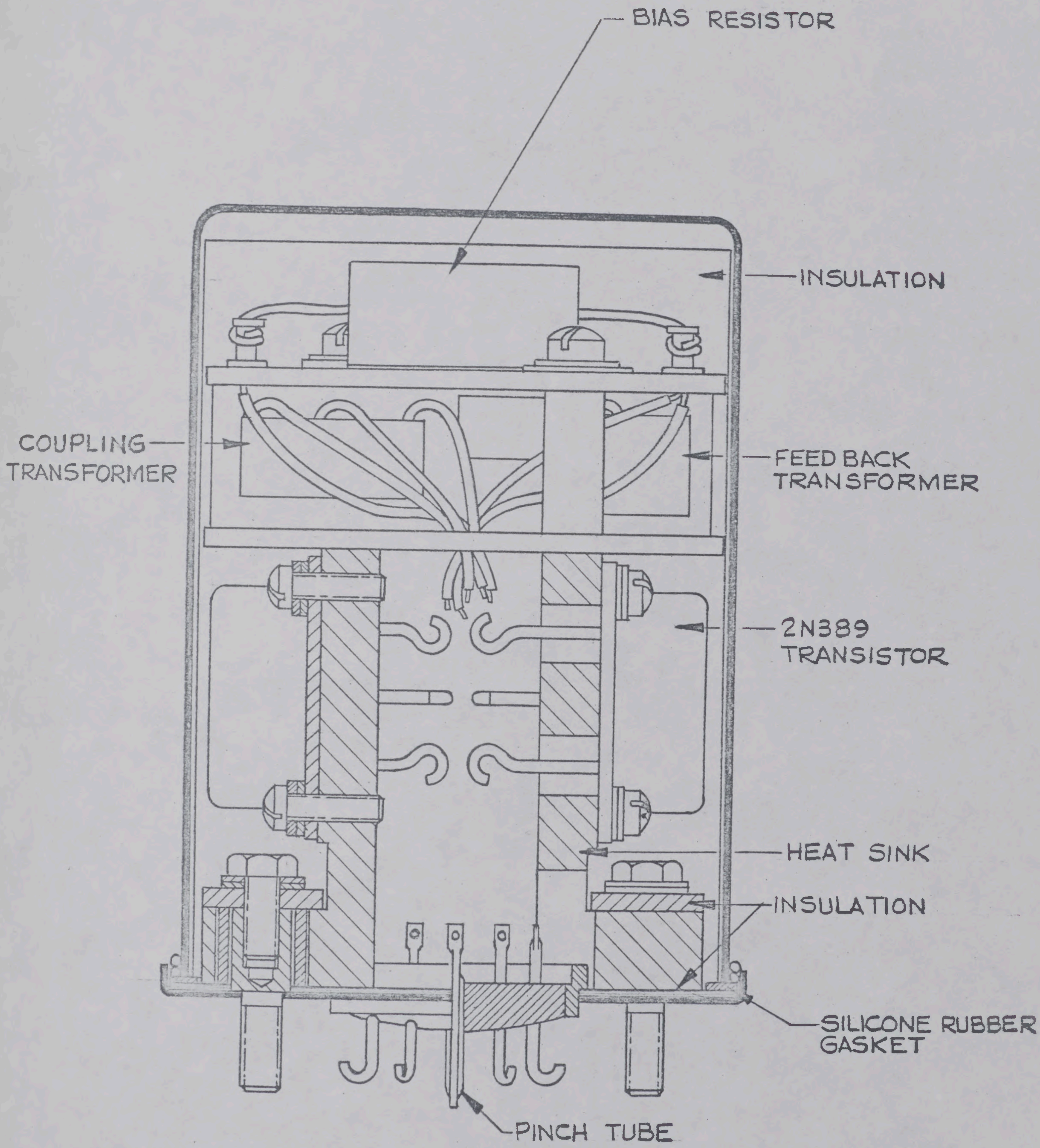

TYPICAL SECTION - AMPLIFIER-ELECTRONIC CONTROL
3 AXIS REPEATER - "D" MODEL DESIGN

HC/MP Document CR-ED 1041

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FIG 4·2·3 SCALE 2:1

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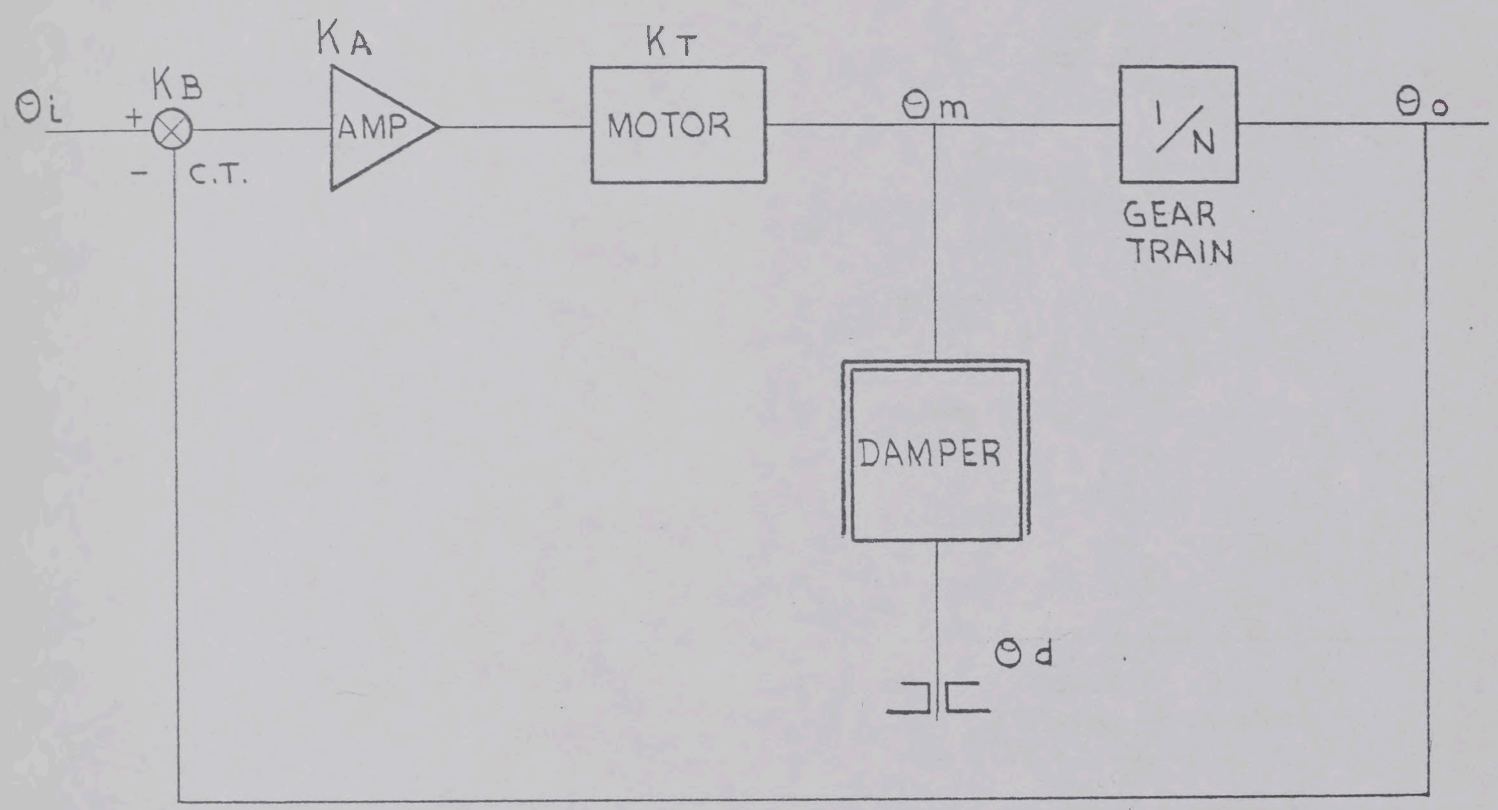

FIG. 5.1.1.

SERVO - LOOP USING INERTIAL DAMPED MOTOR

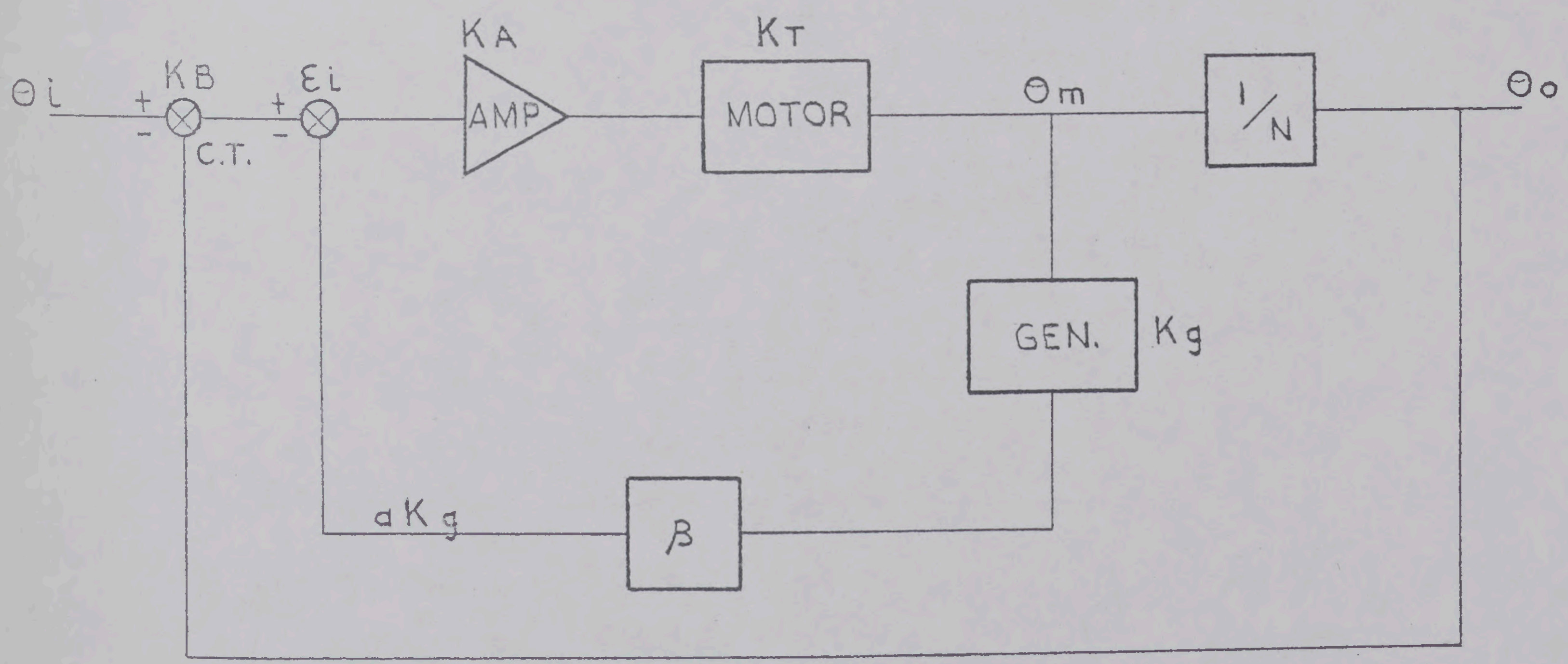

FIG. 5.1.7.1.1

SERVO - LOOP USING RATE GENERATOR FEEDBACK

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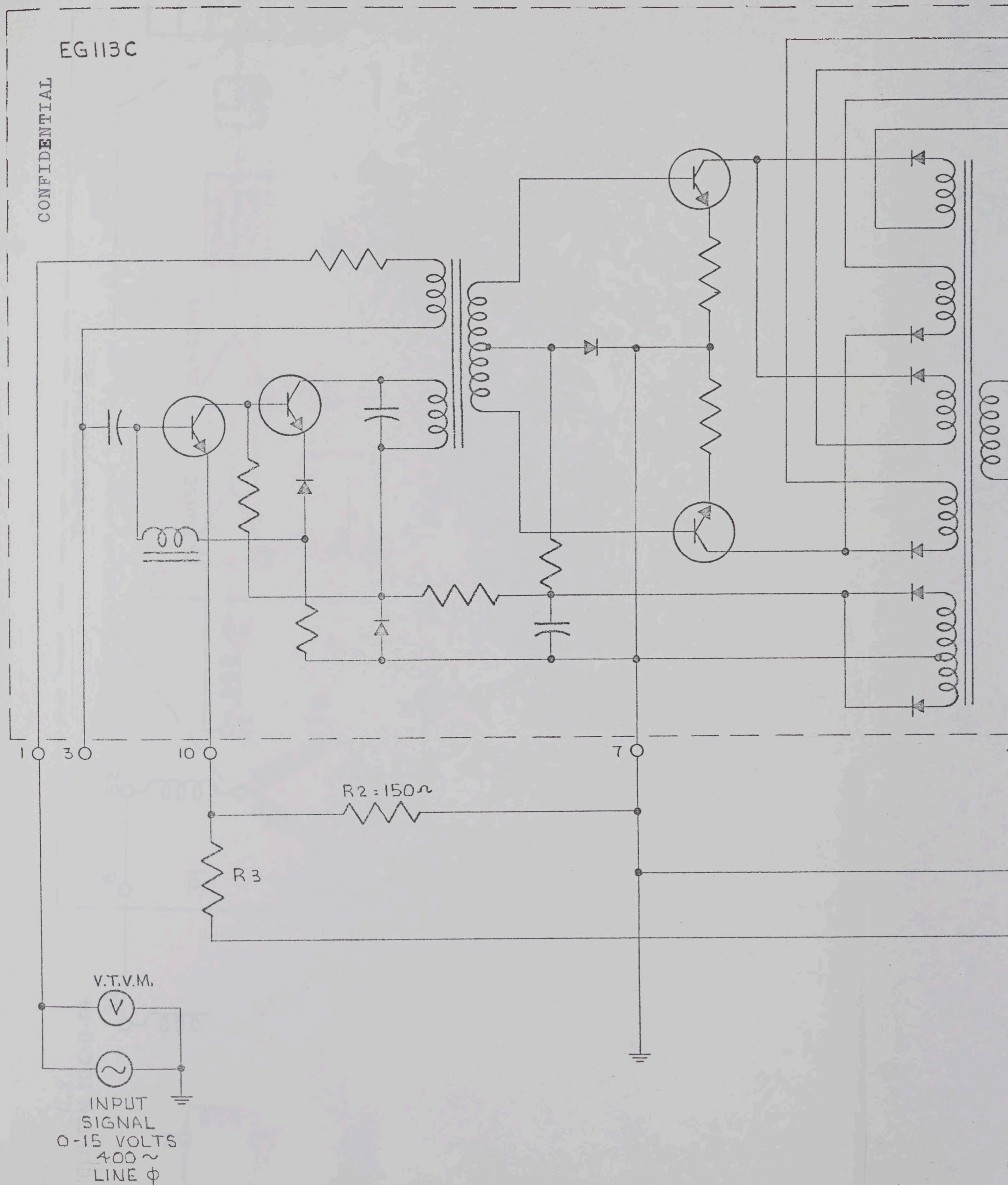

AMPLIFIER SYS

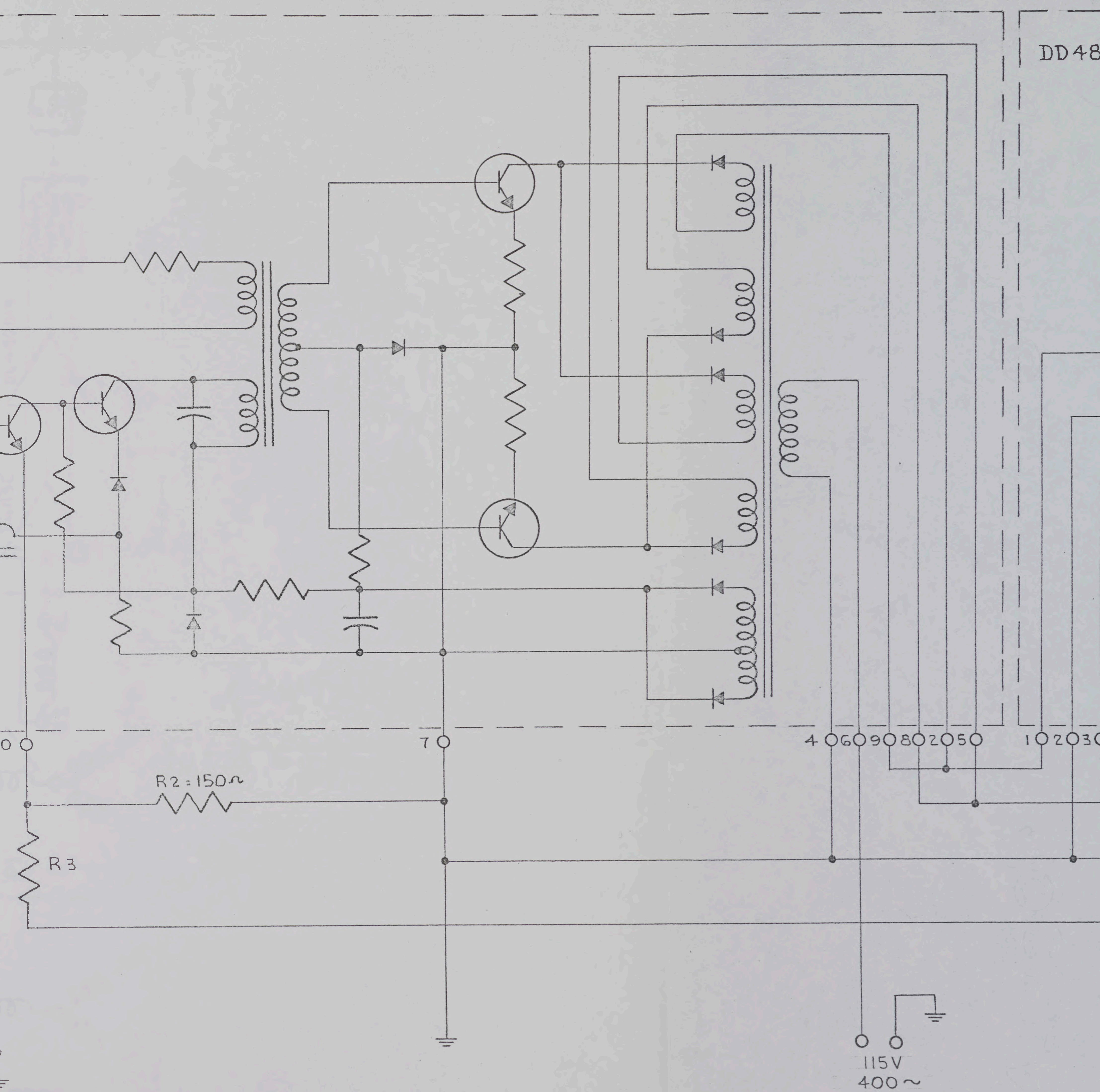

FIG 5.2.1
AMPLIFIER SYSTEM TEST CONNECTION

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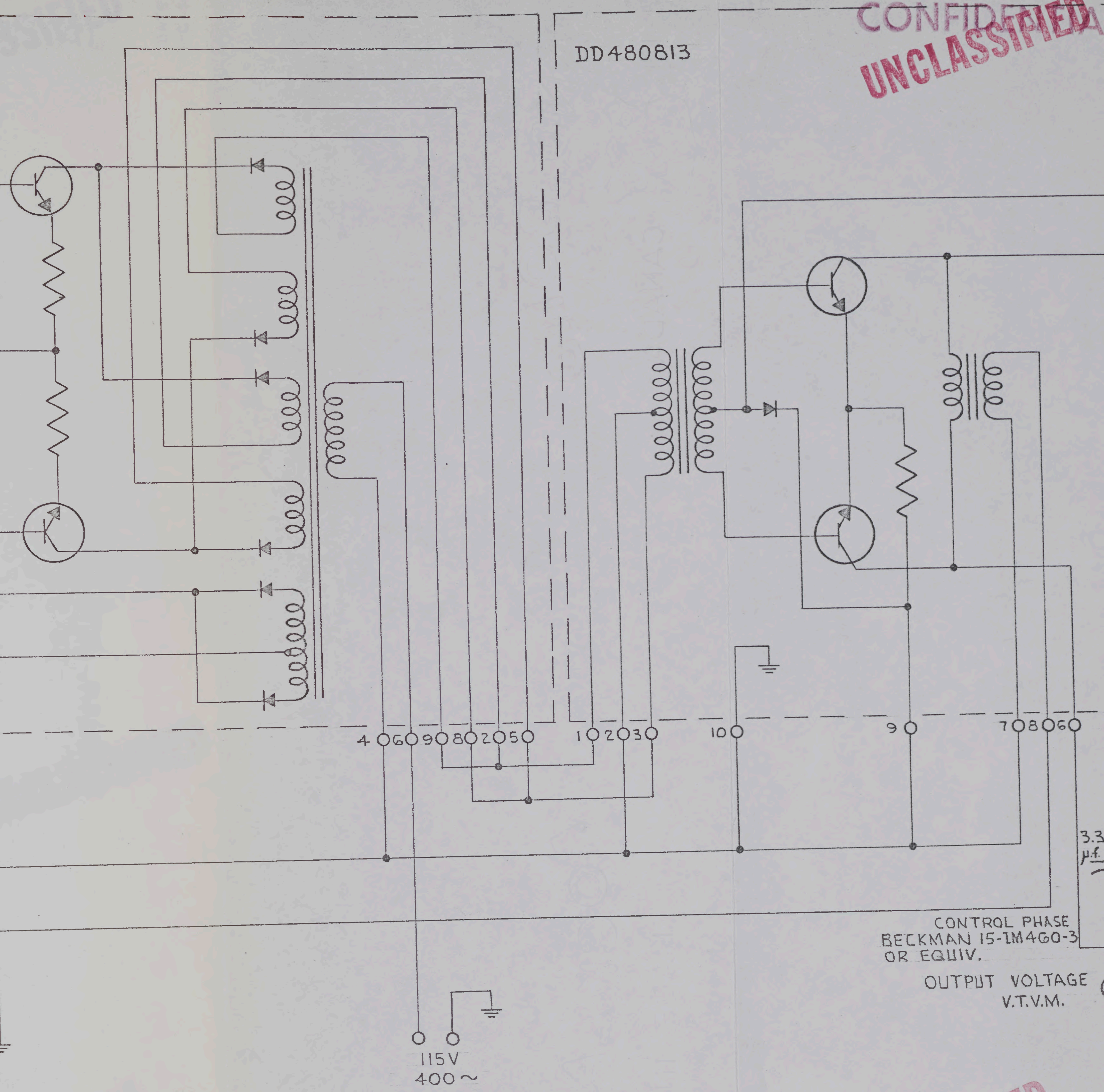

FIG 5.2.1
AMPLIFIER SYSTEM TEST CONNECTIONS

UNCLASSIFIED

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UNCLASSIFIED
CONFIDENTIAL

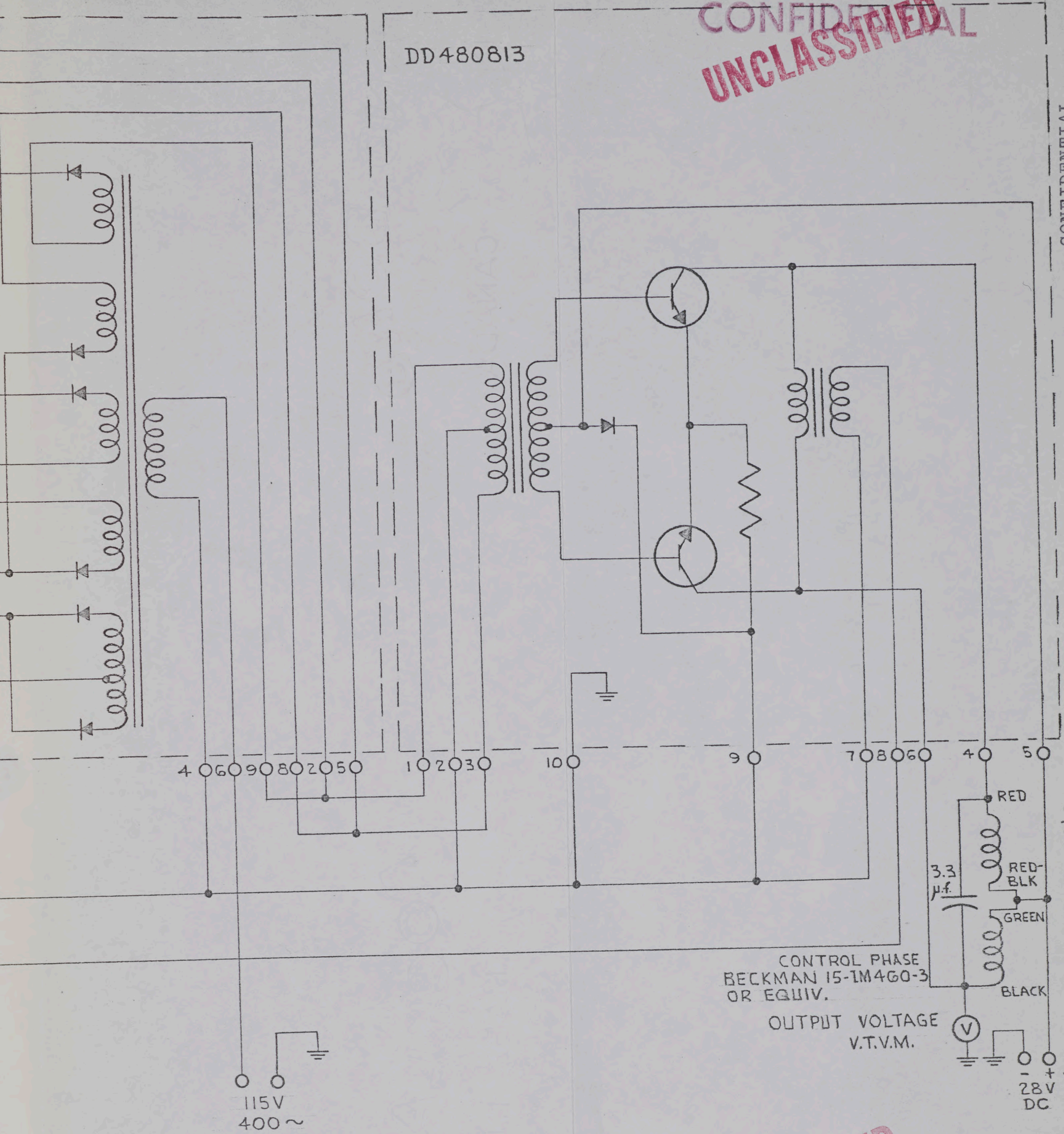

FIG 5.2.1
AMPLIFIER SYSTEM TEST CONNECTIONS

HC/MP Document CR-ED 1041
UNCLASSIFIED

DATE
1-6-59

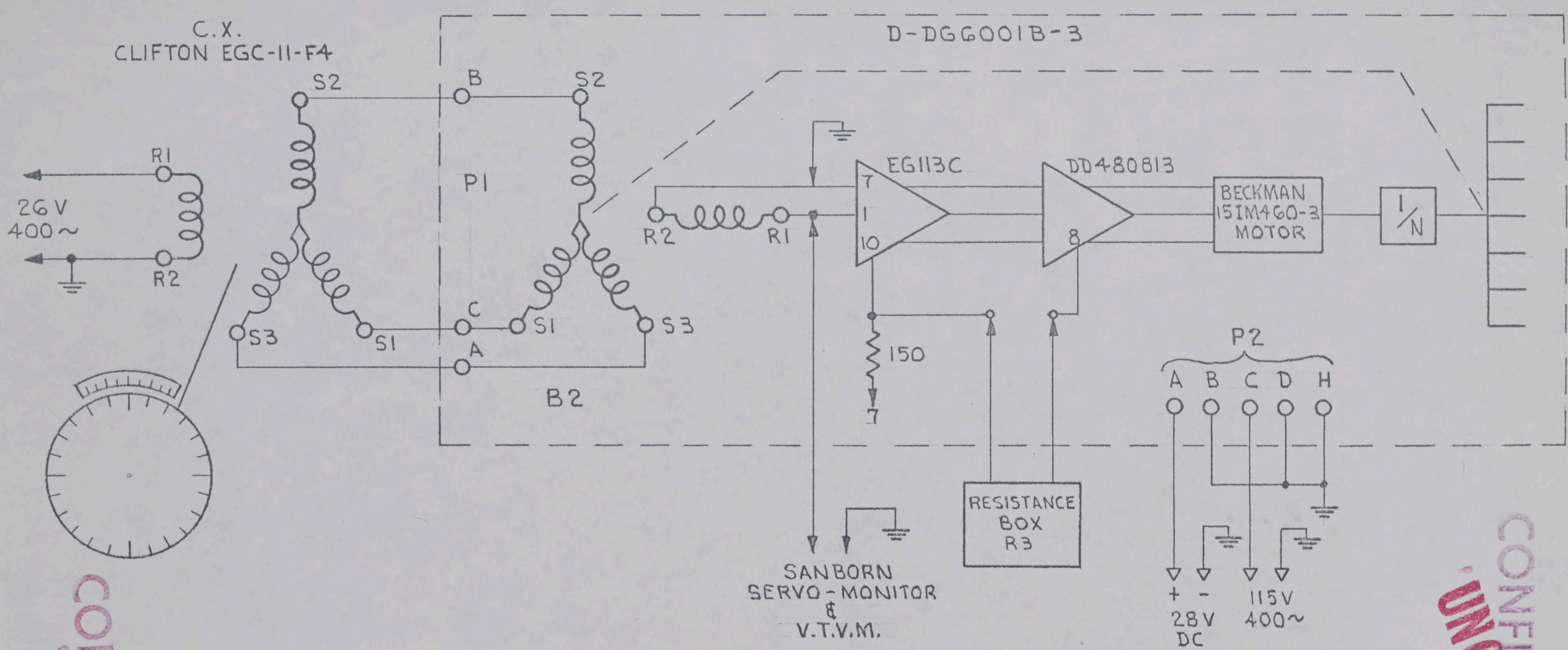

FIG 5.2.2
MODULE TEST CONNECTIONS

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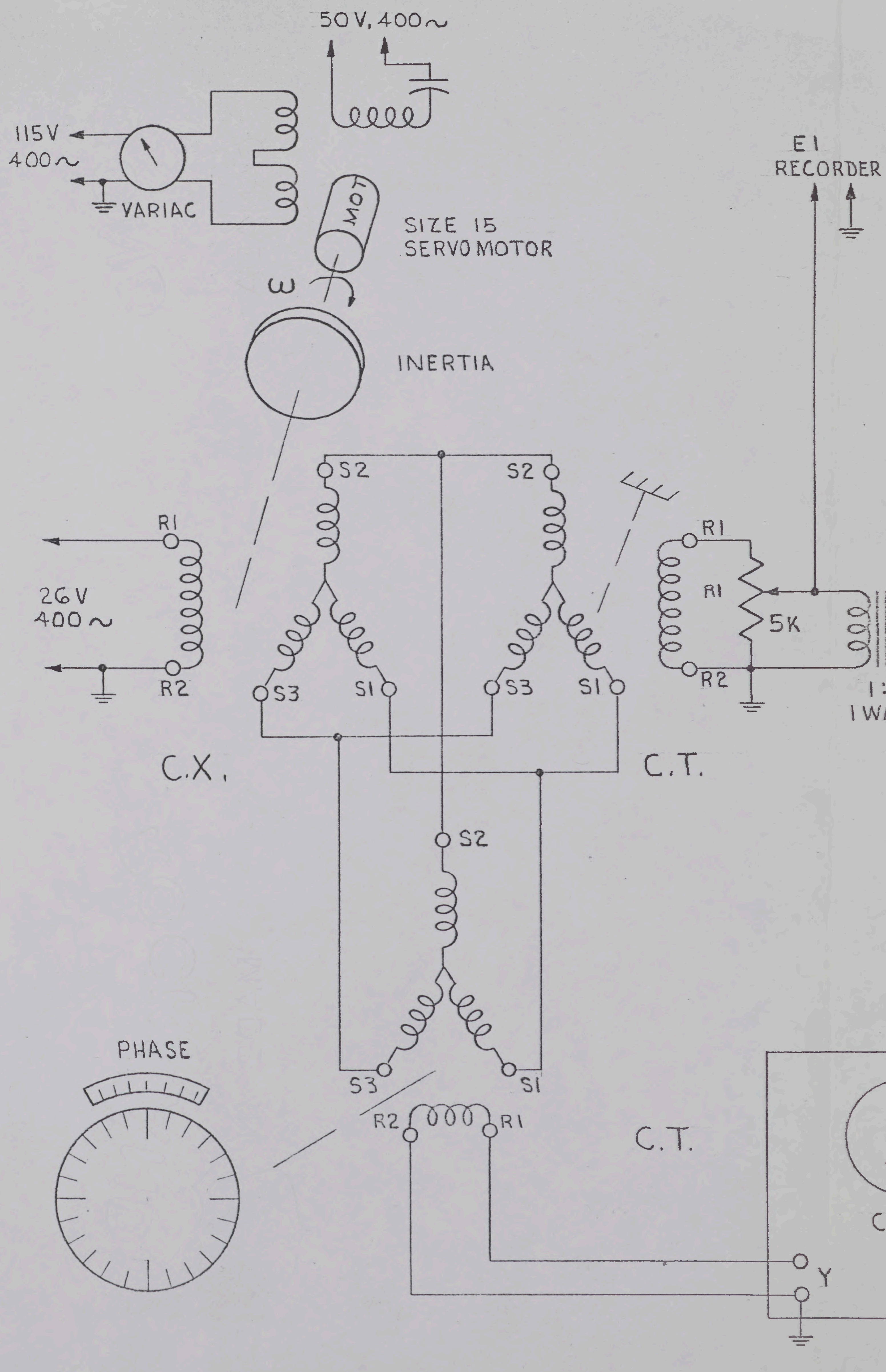
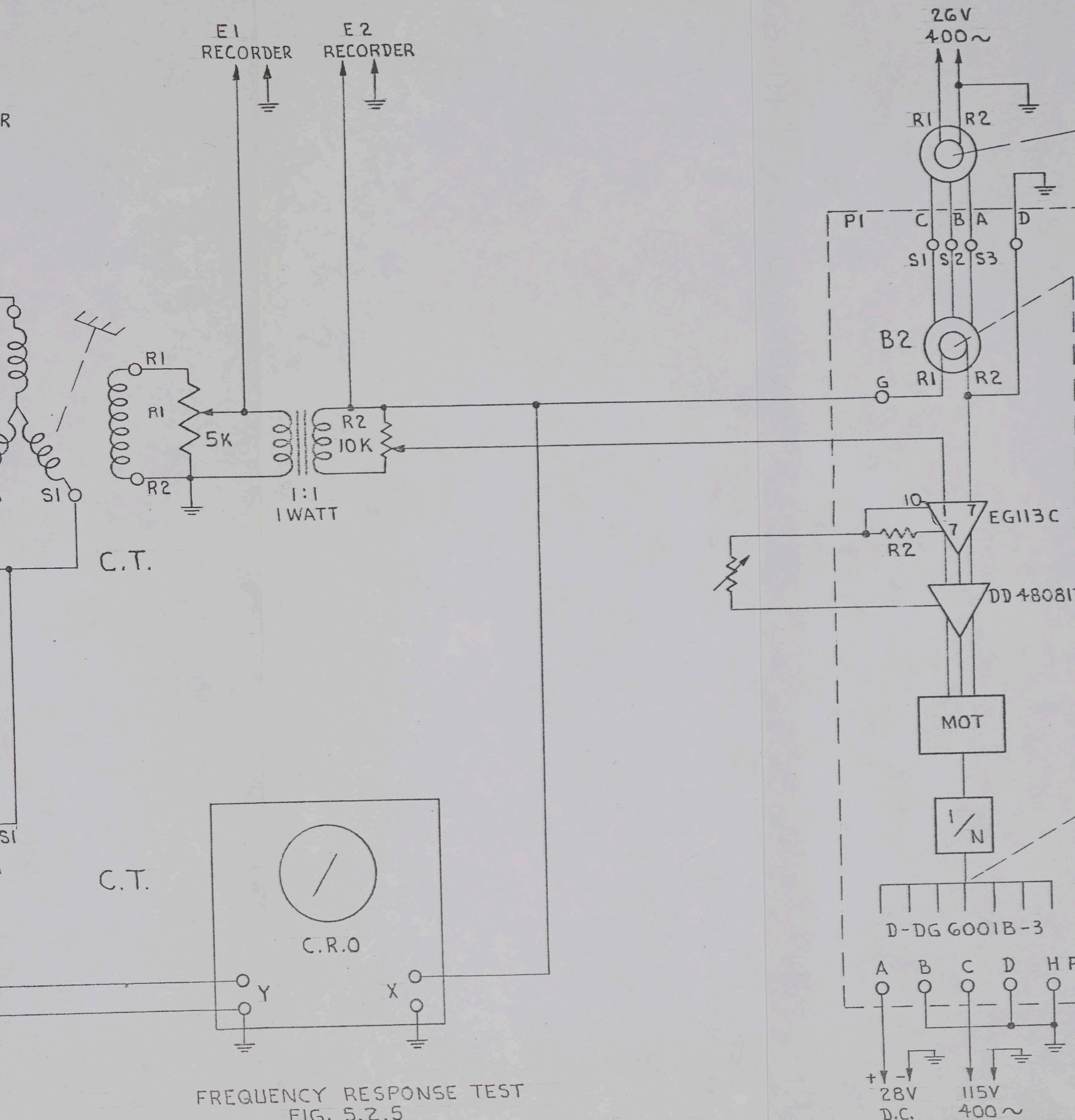
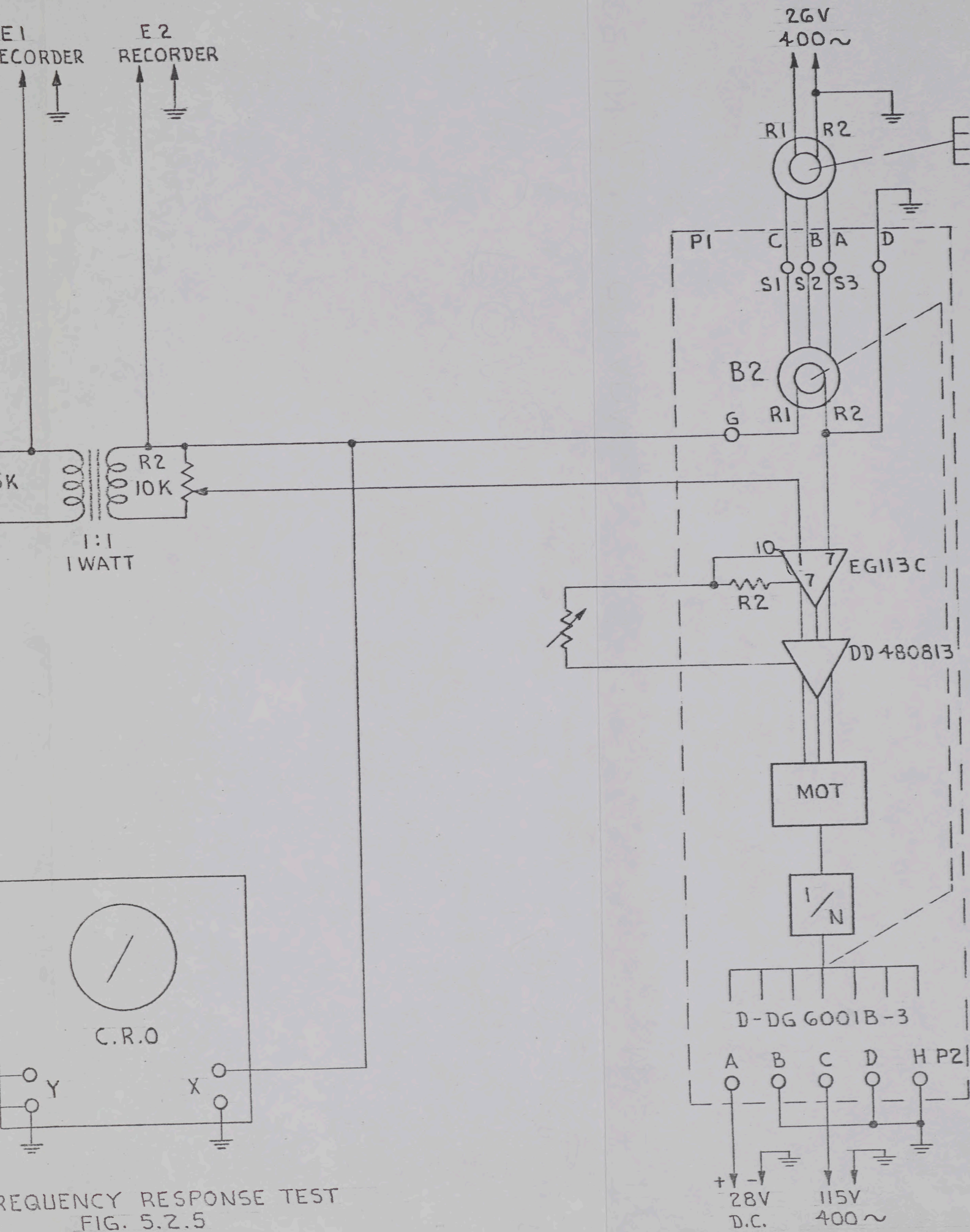
DATE
1-6-59



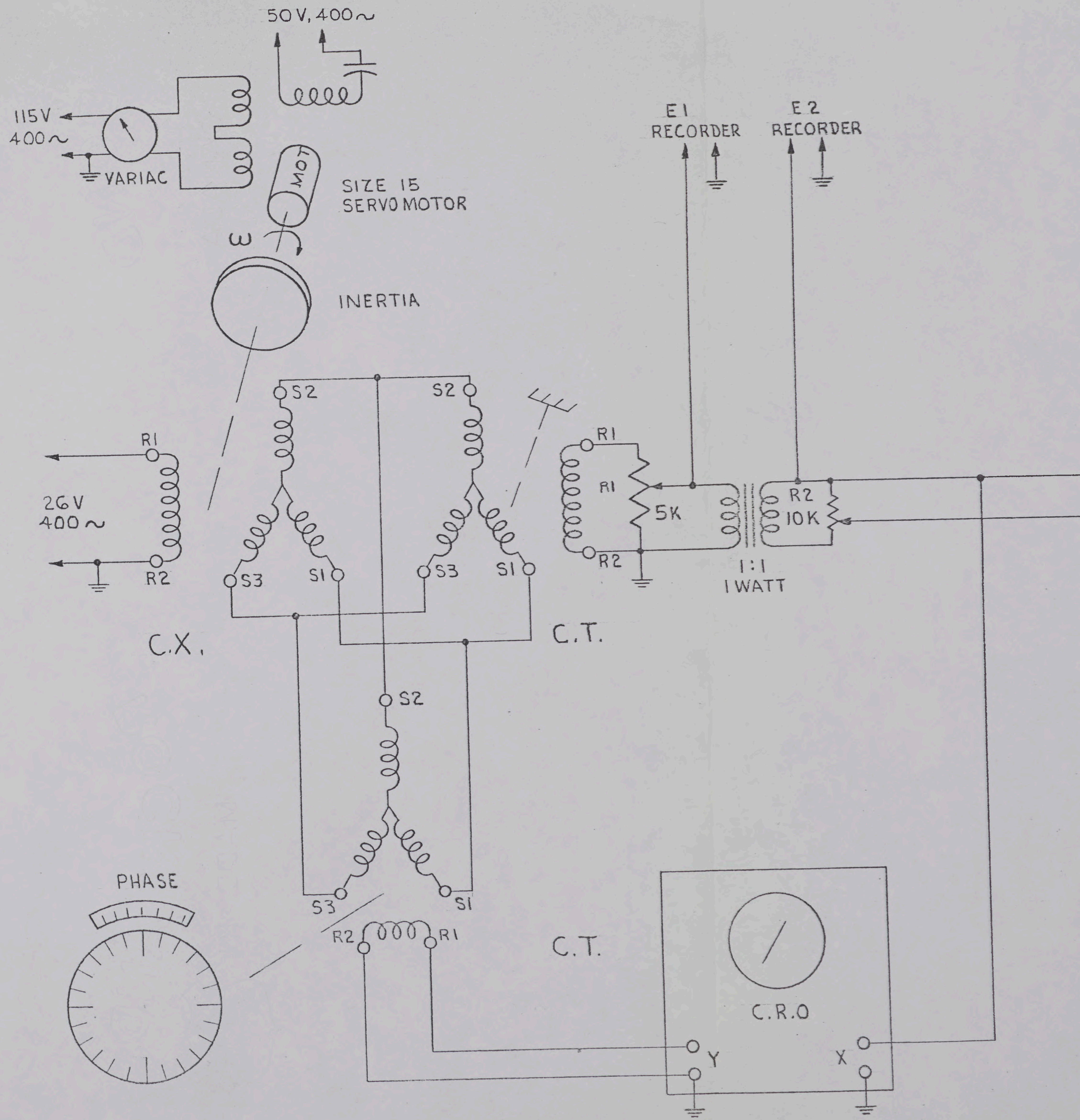
FREQUENCY
FIG



FREQUENCY RESPONSE TEST
FIG. 5.2.5



REQUENCY RESPONSE TEST
FIG. 5.2.5



FREQUENCY RESPONSE TEST
FIG. 5.2.5

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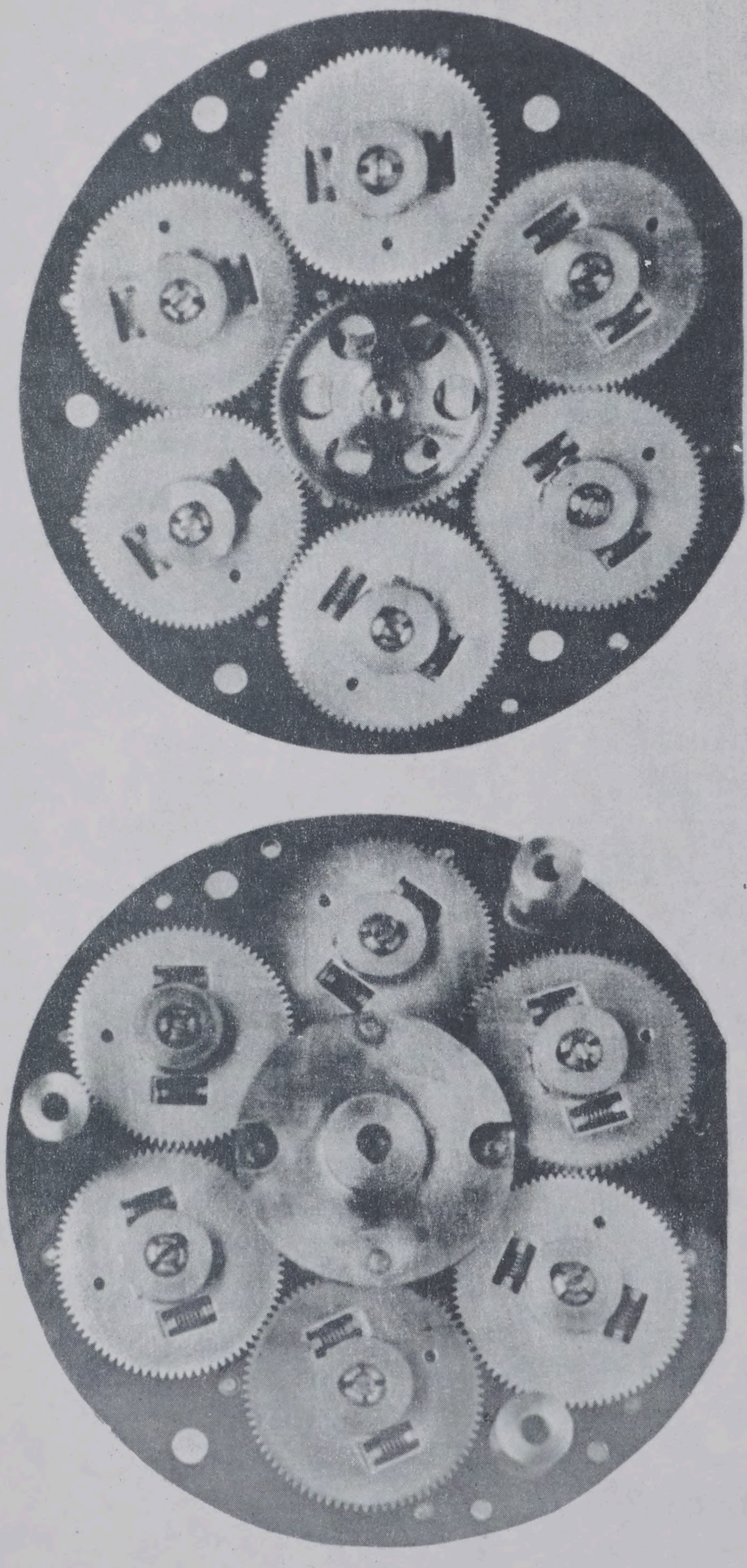

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GEAR ARRANGEMENT
DG6001 MODULE BREADBOARD

FIG. 5·2·8·a

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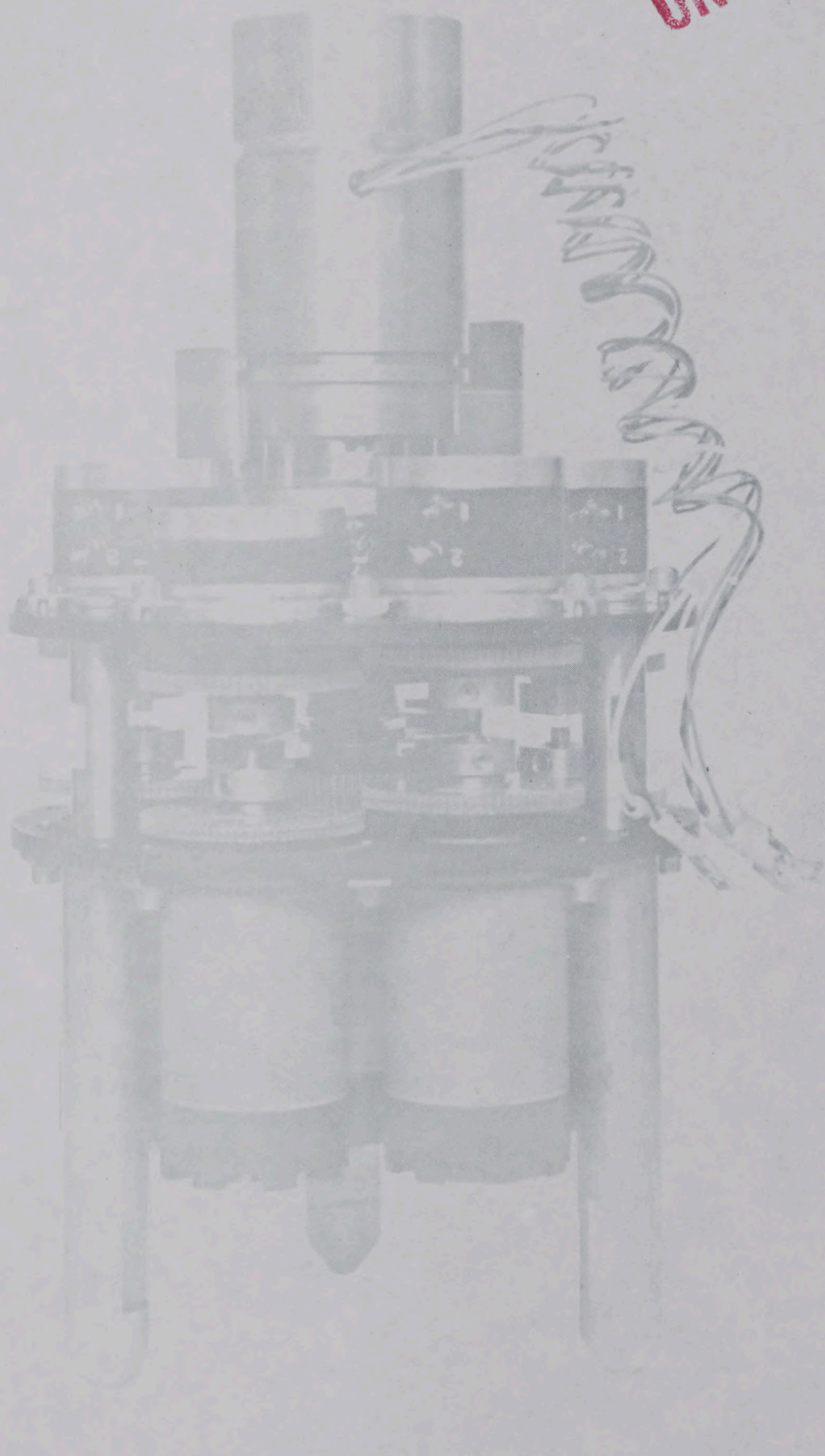

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DG6001 MODULE BREADBOARD

FIG. 5-2-8-b

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UNCLASSIFIED

UNCLASSIFIED

CONFIDENTIAL
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MOUNTING OF OUTPUTS
D-DG6001 MODULE BREADBOARDS

FIG. 5·2·8 c

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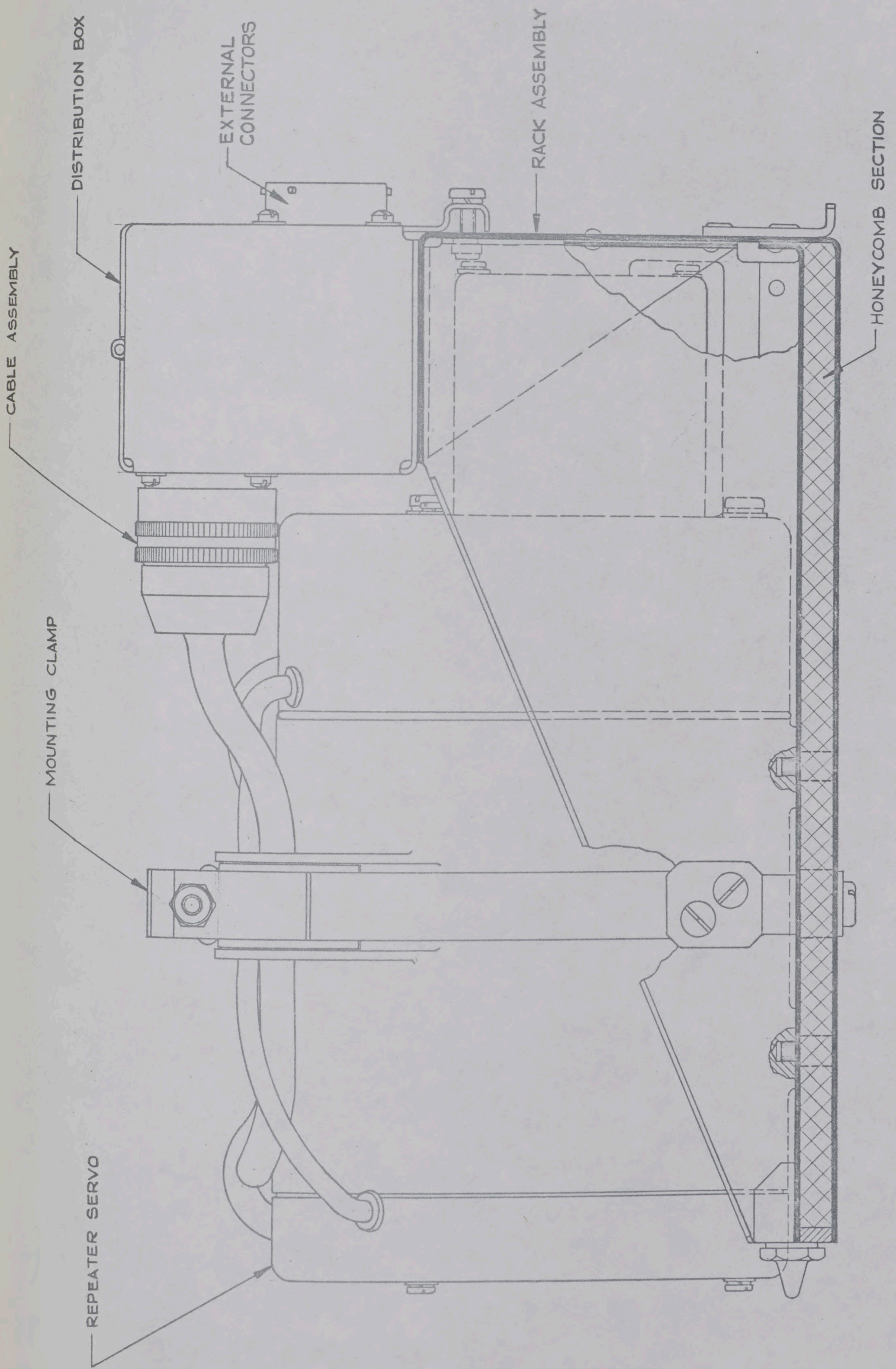

TYPICAL SECTION OF RACK - INDICATING EXPOSED HONEYCOMB, AND WITH A REPEATER SERVO MOUNTED

3 AXIS REPEATER - PRE PRODUCTION DESIGN - FIG. 6.3.2

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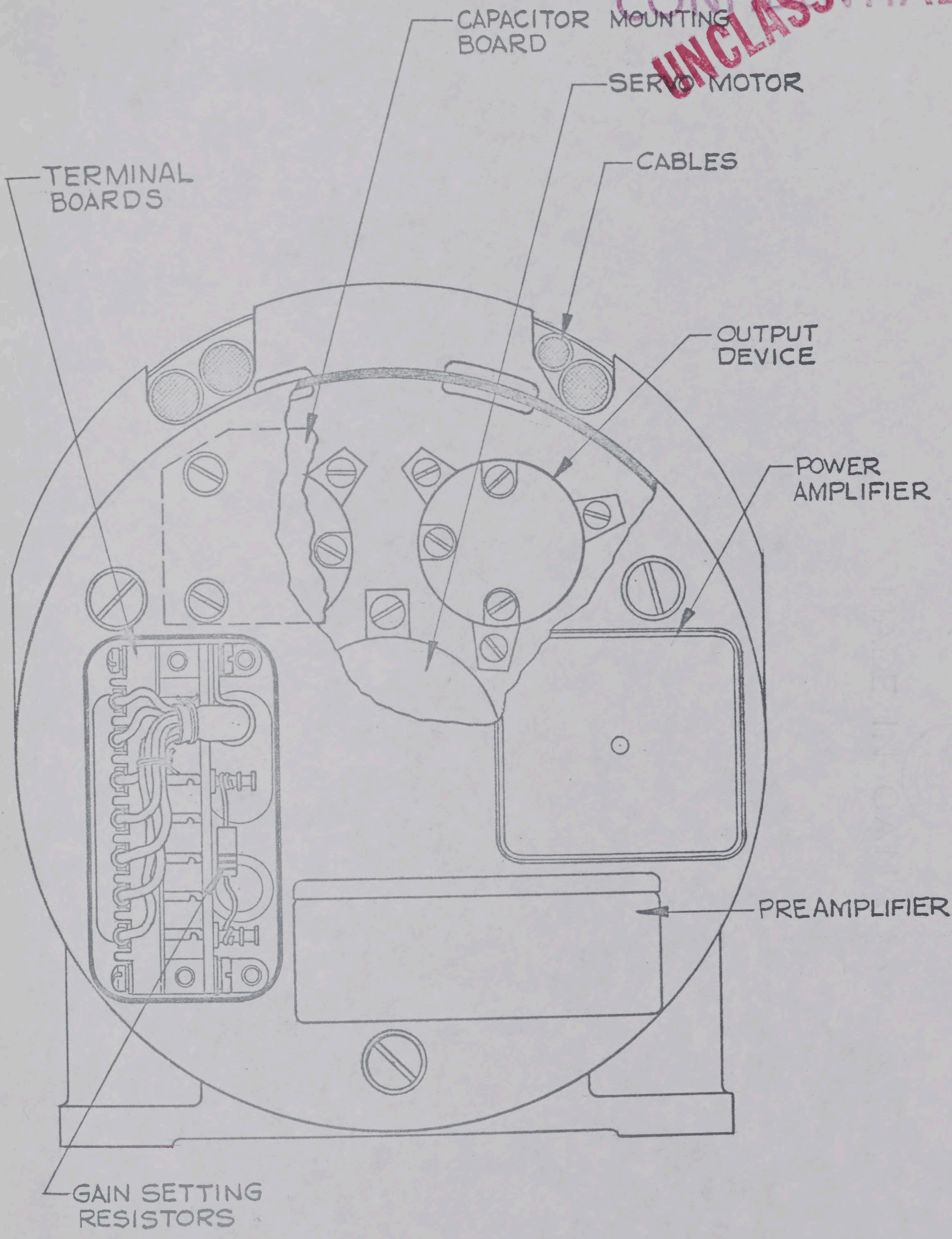

FRONT VIEW OF MODULE - REPEATER SERVO
3 AXIS REPEATER - PRE PRODUCTION DESIGN

FIG 6.3.3.b

SCALE 1:1
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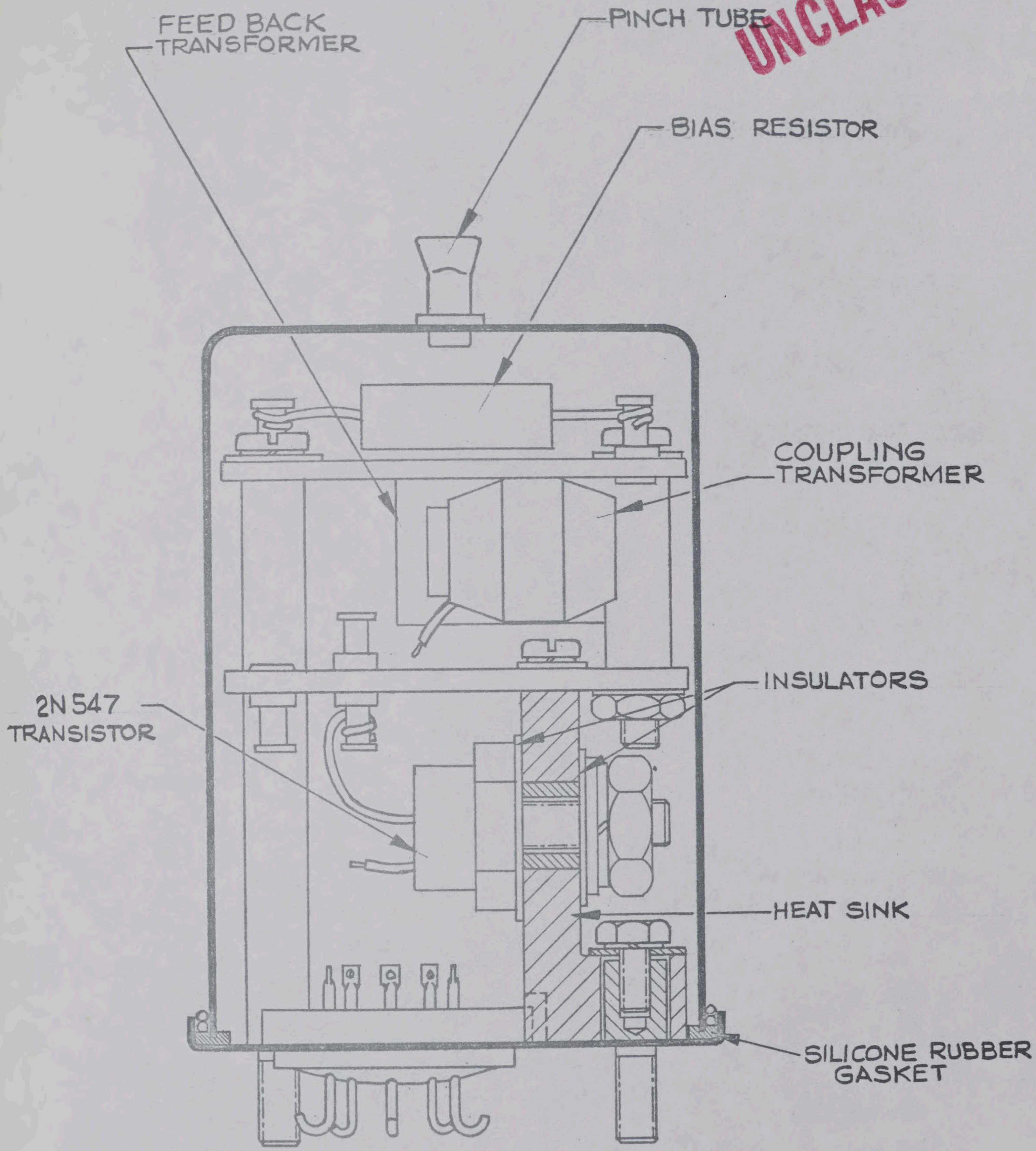

TYPICAL SECTION - AMPLIFIER - ELECTRONIC CONTROL

3 AXIS REPEATER - PRE-PRODUCTION DESIGN

FIG 6.3.4.

SCALE 2:1
DEC.-8-58

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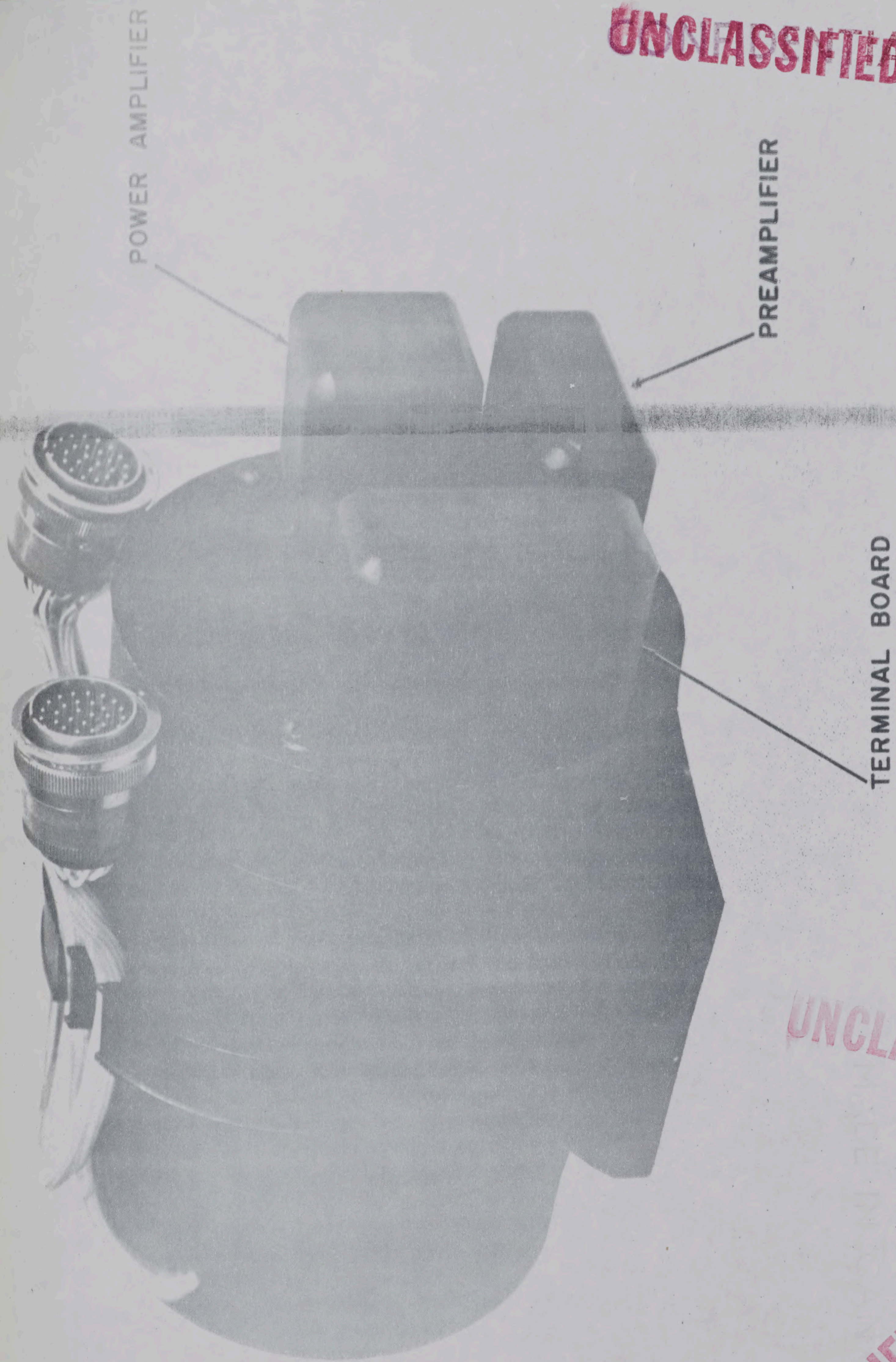

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SERVO REPEATER MODULE

FIG 6·3·5·a

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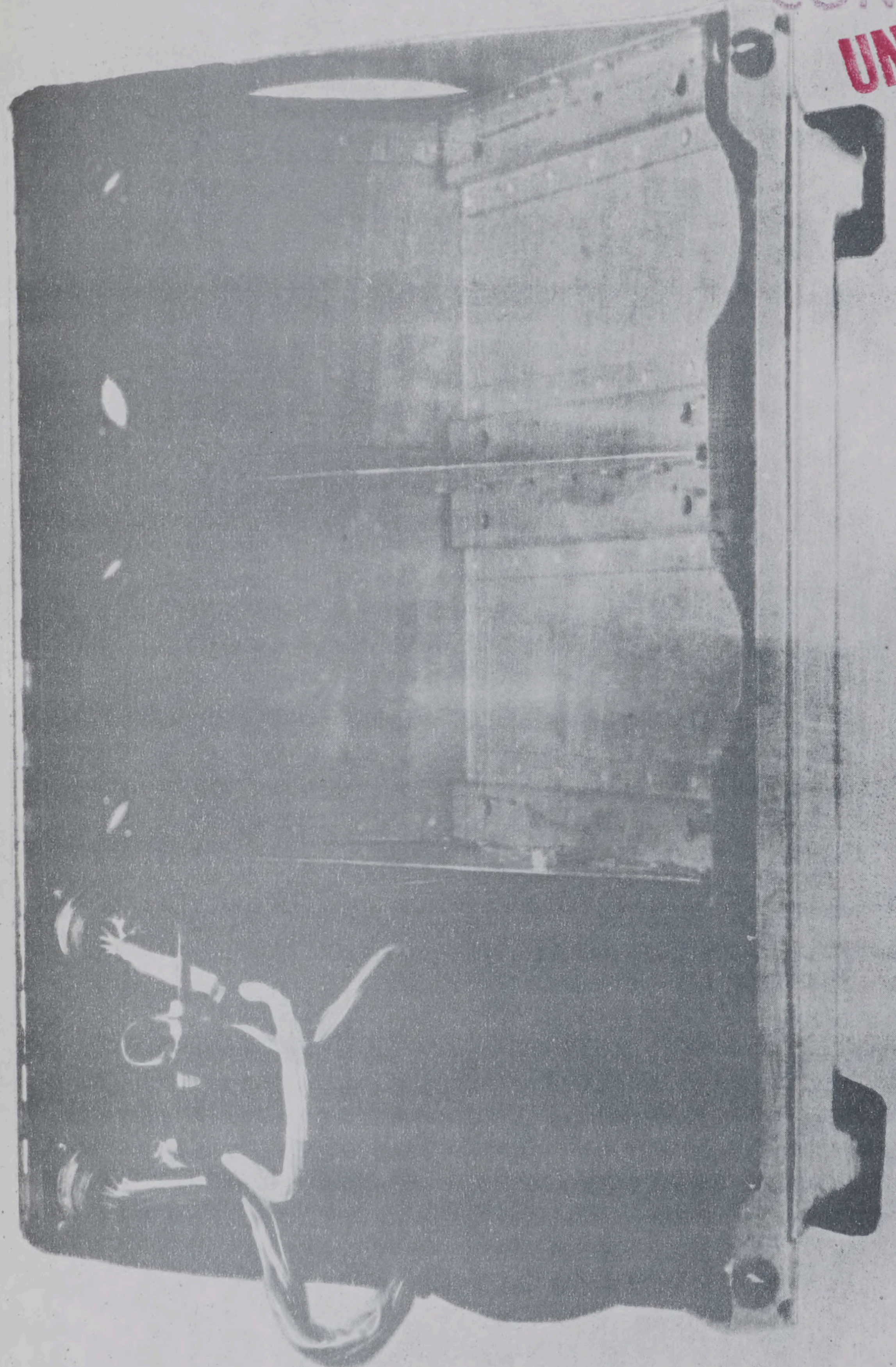

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SERVO REPEATER MODULE MOCKUP
DG6001G

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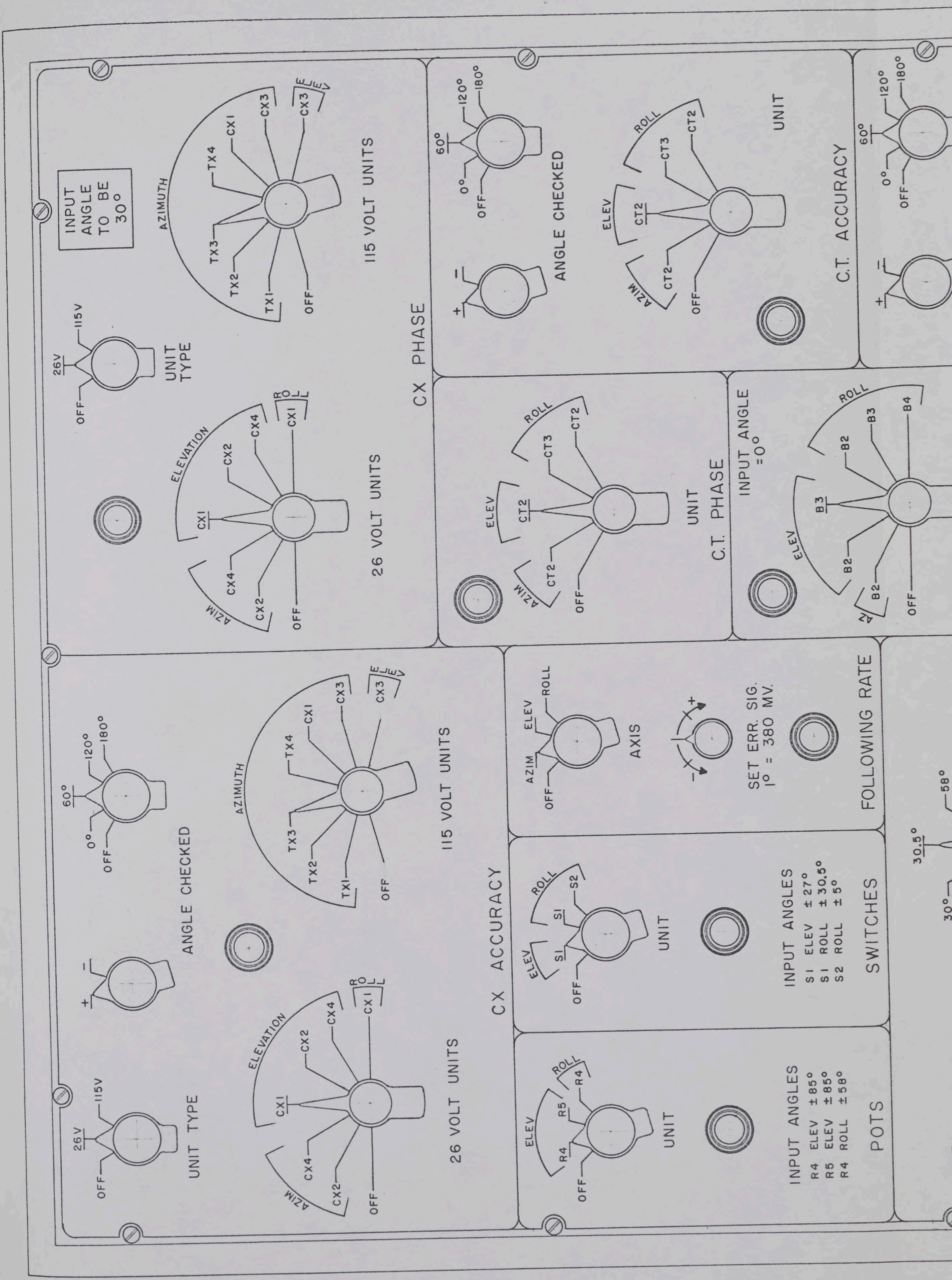
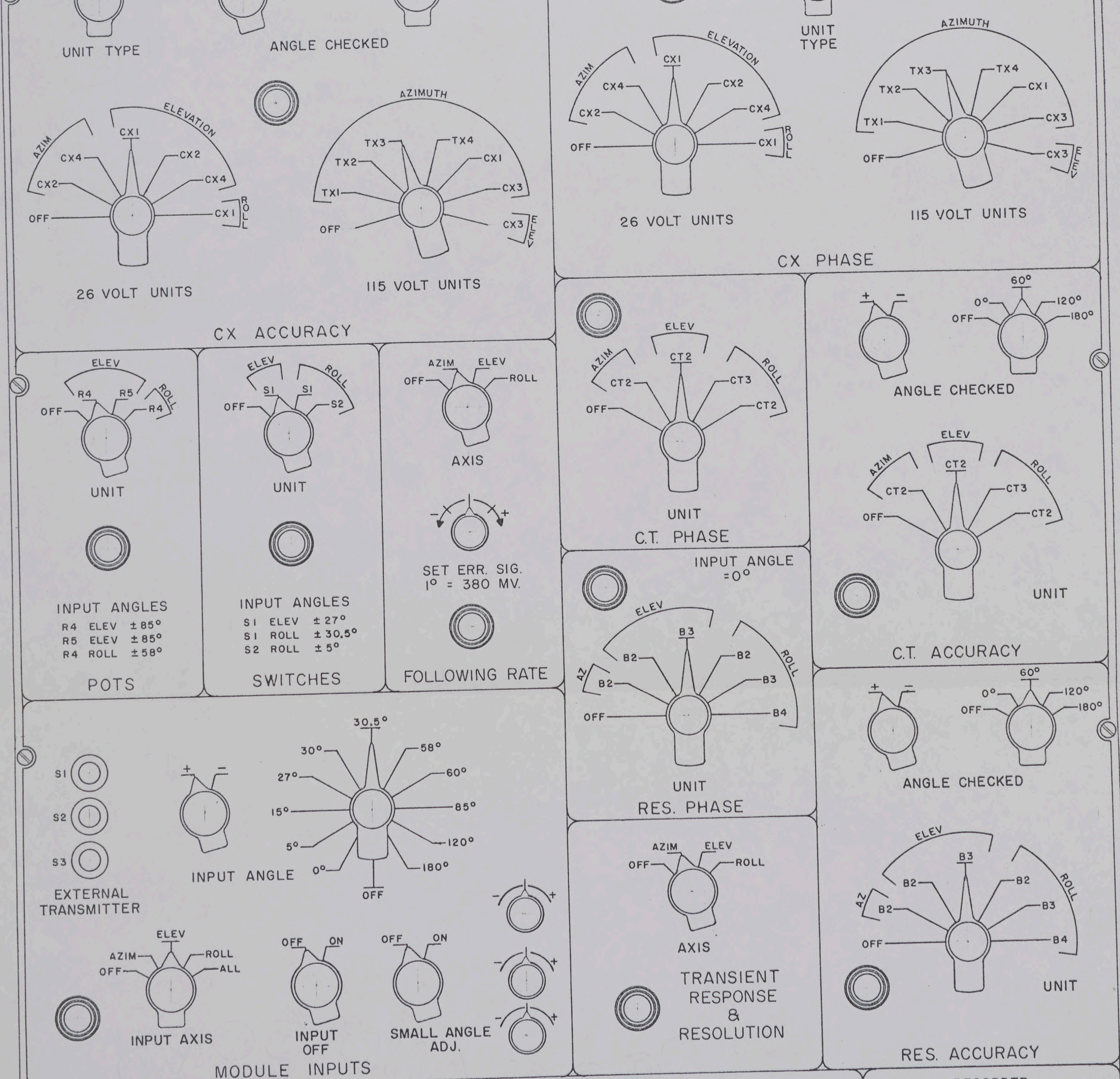
FIG. 6·3·5·b


INPUT ANGLE TO BE 30°
UNIT TYPE
26V
115V
OFF
AZIMUTH
ELEVATION
TX1 TX2 TX3 TX4
CX1 CX2 CX3 CX4
AZIM
ROLL
ELEV
115 VOLT UNITS
26 VOLT UNITS
CX PHASE
ANGLE CHECKED
0° 60° 120° 180°
C.T. ACCURACY
CT2 CT3
UNIT
C.T. PHASE
INPUT ANGLE =0°
B2 B3 B4
CX ACCURACY
AXIS
SET ERR. SIG. 1° = 380 MV.
FOLLOWING RATE
S1 S2
INPUT ANGLES
S1 ELEV ± 27°
S1 ROLL ± 30.5°
S2 ROLL ± 5°
SWITCHES
R4 R5
INPUT ANGLES
R4 ELEV ±85°
R5 ELEV ±85°
R4 ROLL ±58°
POTS
30° 30.5° 58°


UNIT TYPE
ANGLE CHECKED
AZIM
ELEVATION
CX1
CX2
CX4
ROLL
OFF
26 VOLT UNITS
AZIMUTH
TX1
TX2
TX3
TX4
CX3
ELEV
115 VOLT UNITS
CX ACCURACY
R4
R5
UNIT
INPUT ANGLES
R4 ELEV ±85°
R5 ELEV ±85°
R4 ROLL ±58°
POTS
S1
S2
INPUT ANGLES
S1 ELEV ±27°
S1 ROLL ±30.5°
S2 ROLL ±5°
SWITCHES
AXIS
SET ERR. SIG.
1° = 380 MV.
FOLLOWING RATE
S3
EXTERNAL
TRANSMITTER
INPUT ANGLE
30.5°
30°
27°
15°
5°
0°
58°
60°
85°
120°
180°
INPUT AXIS
ALL
ON
INPUT
OFF
SMALL ANGLE
ADJ.
MODULE INPUTS
CX PHASE
CT2
CT3
C.T. PHASE
0°
60°
120°
180°
C.T. ACCURACY
INPUT ANGLE
=0°
AZ
B2
B3
B4
RES. PHASE
TRANSIENT
RESPONSE
&
RESOLUTION
RES. ACCURACY

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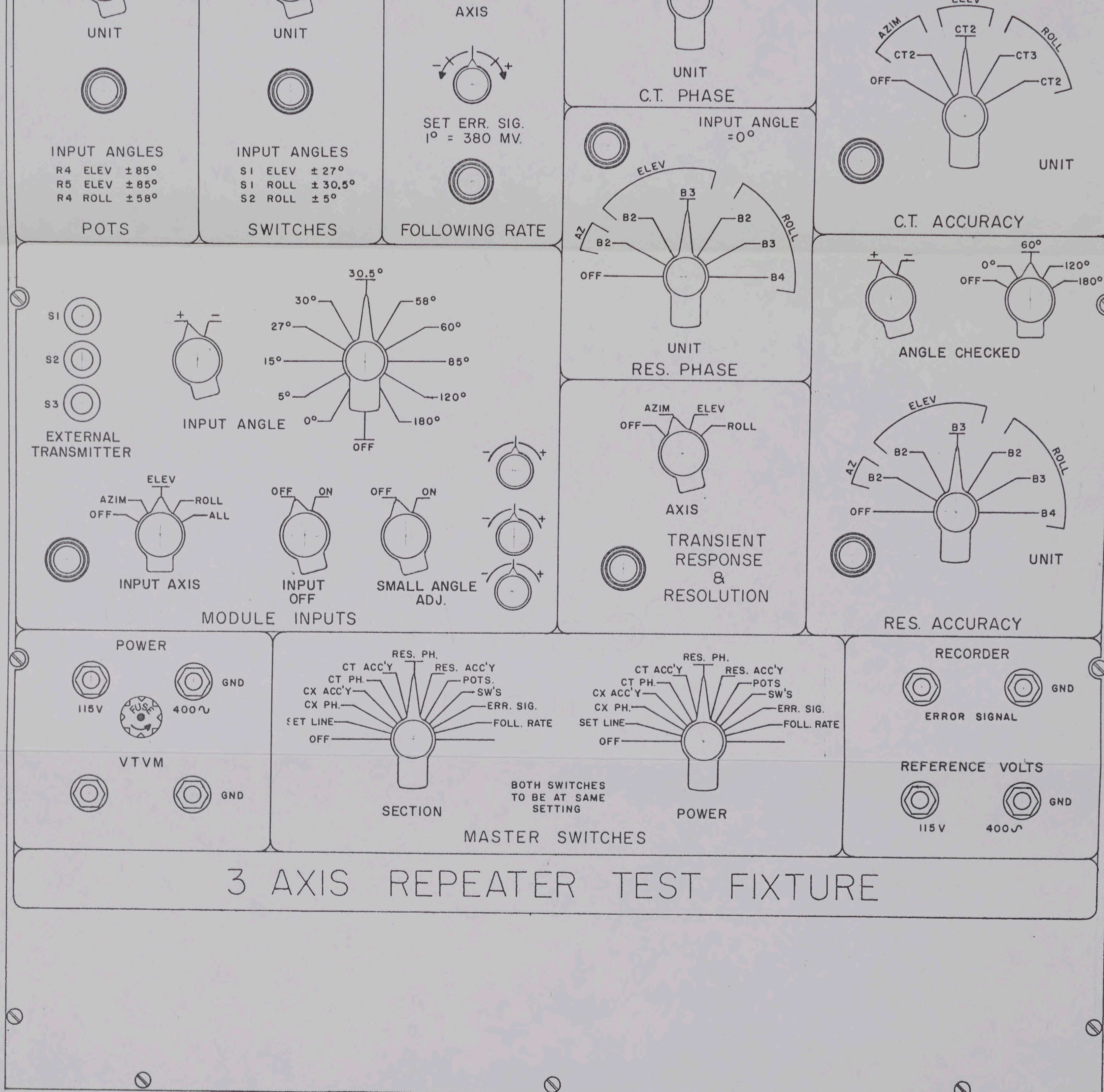

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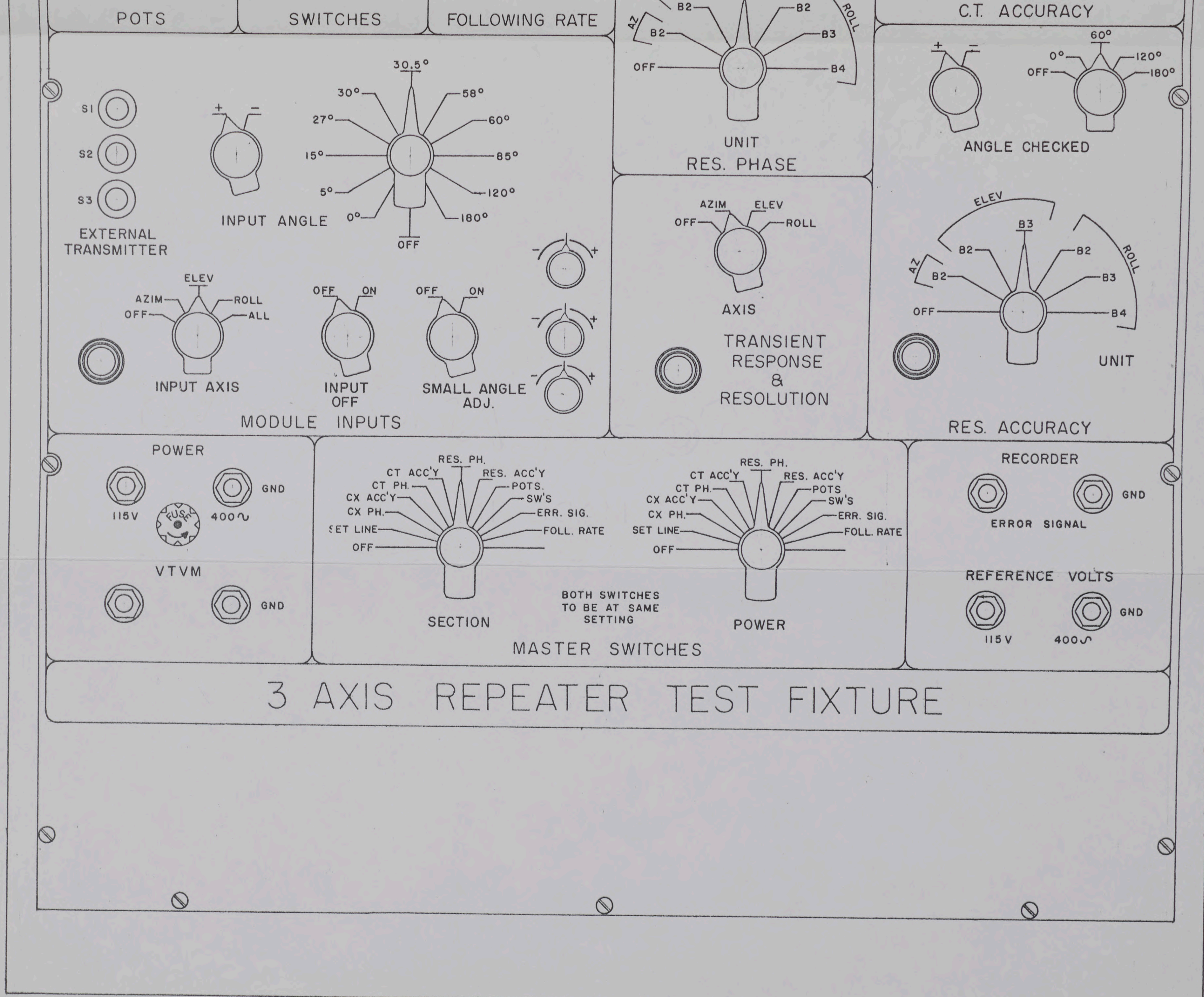

FIG. 7.3

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SCALE 1:2

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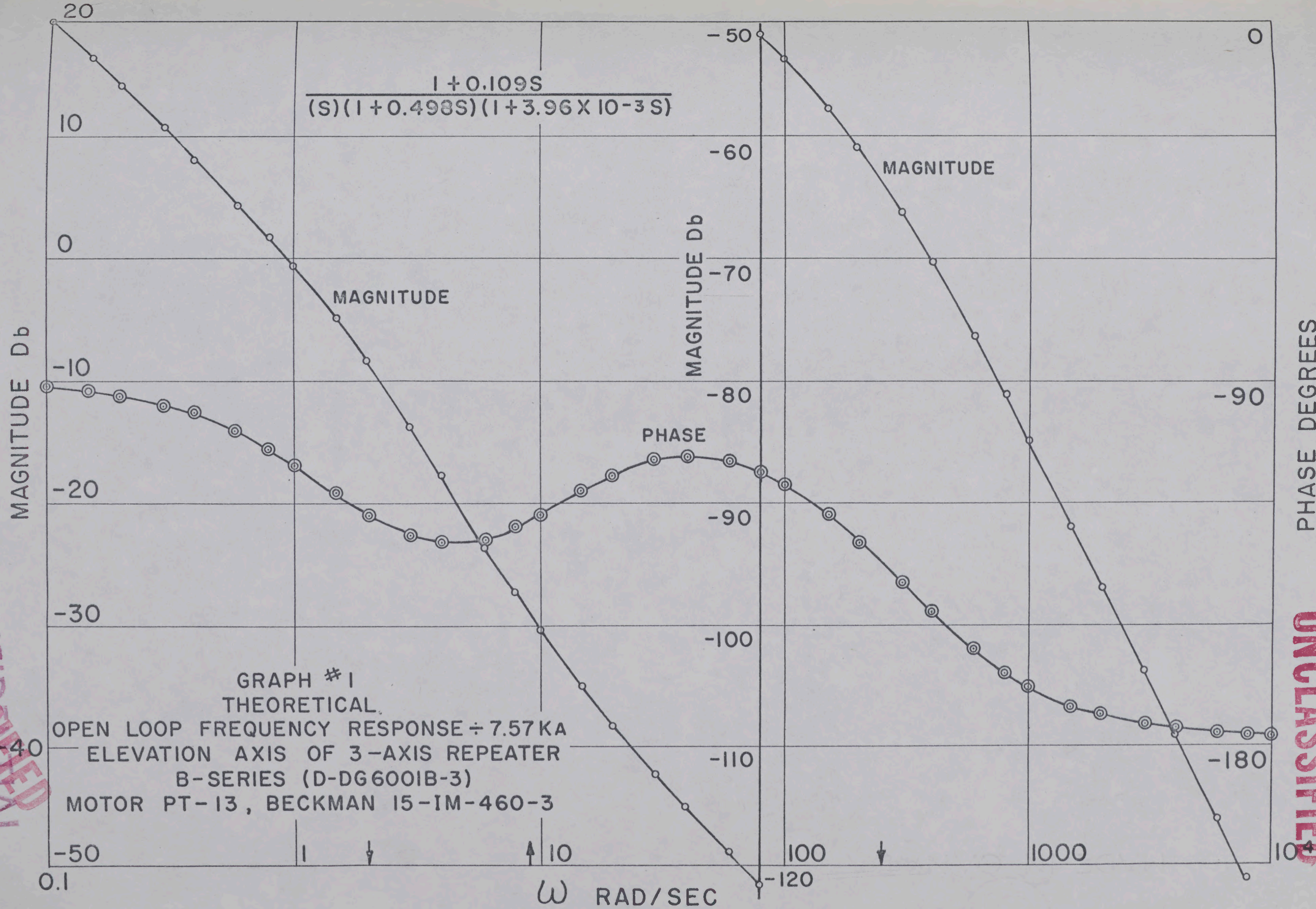

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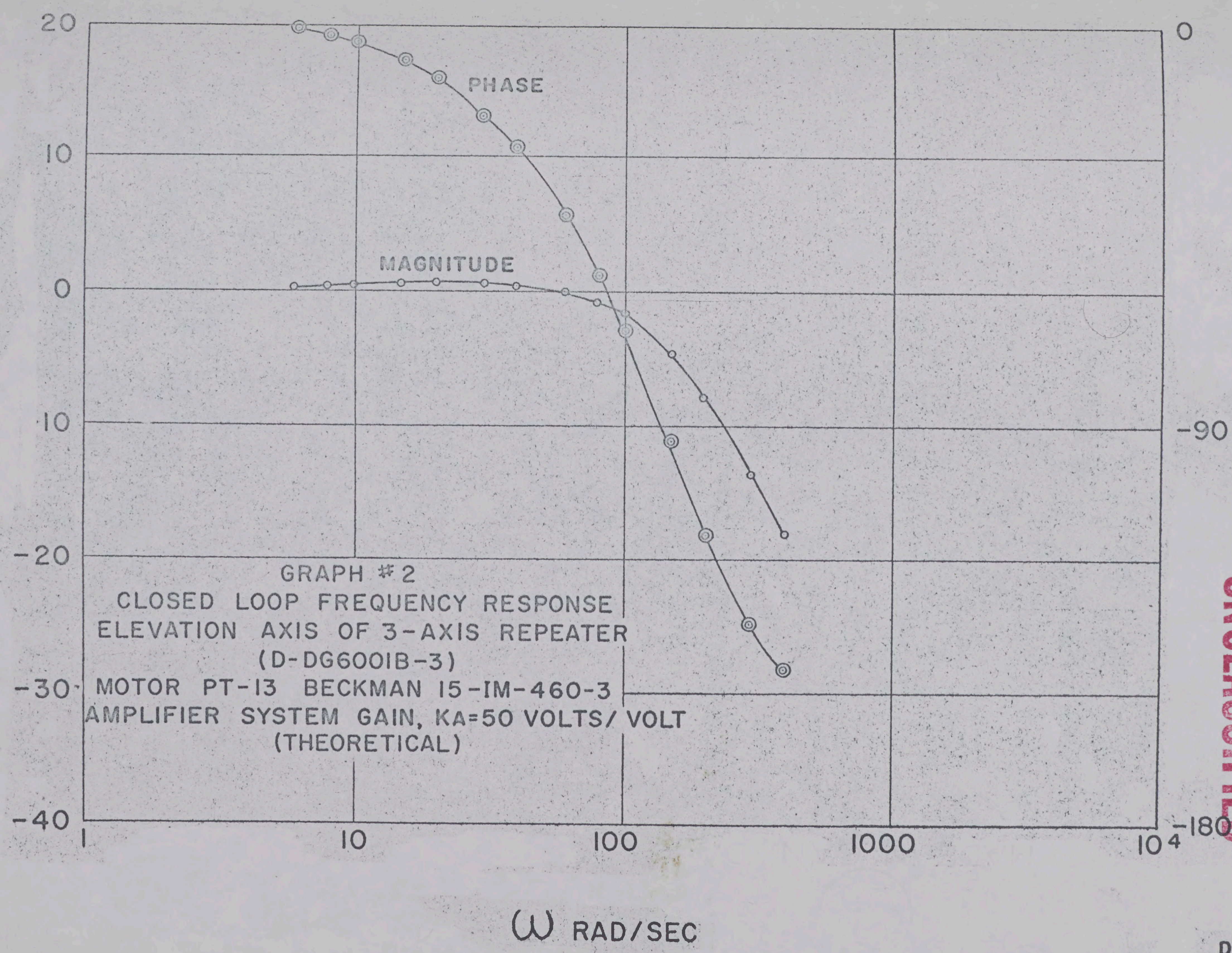

DATE
12-29-58

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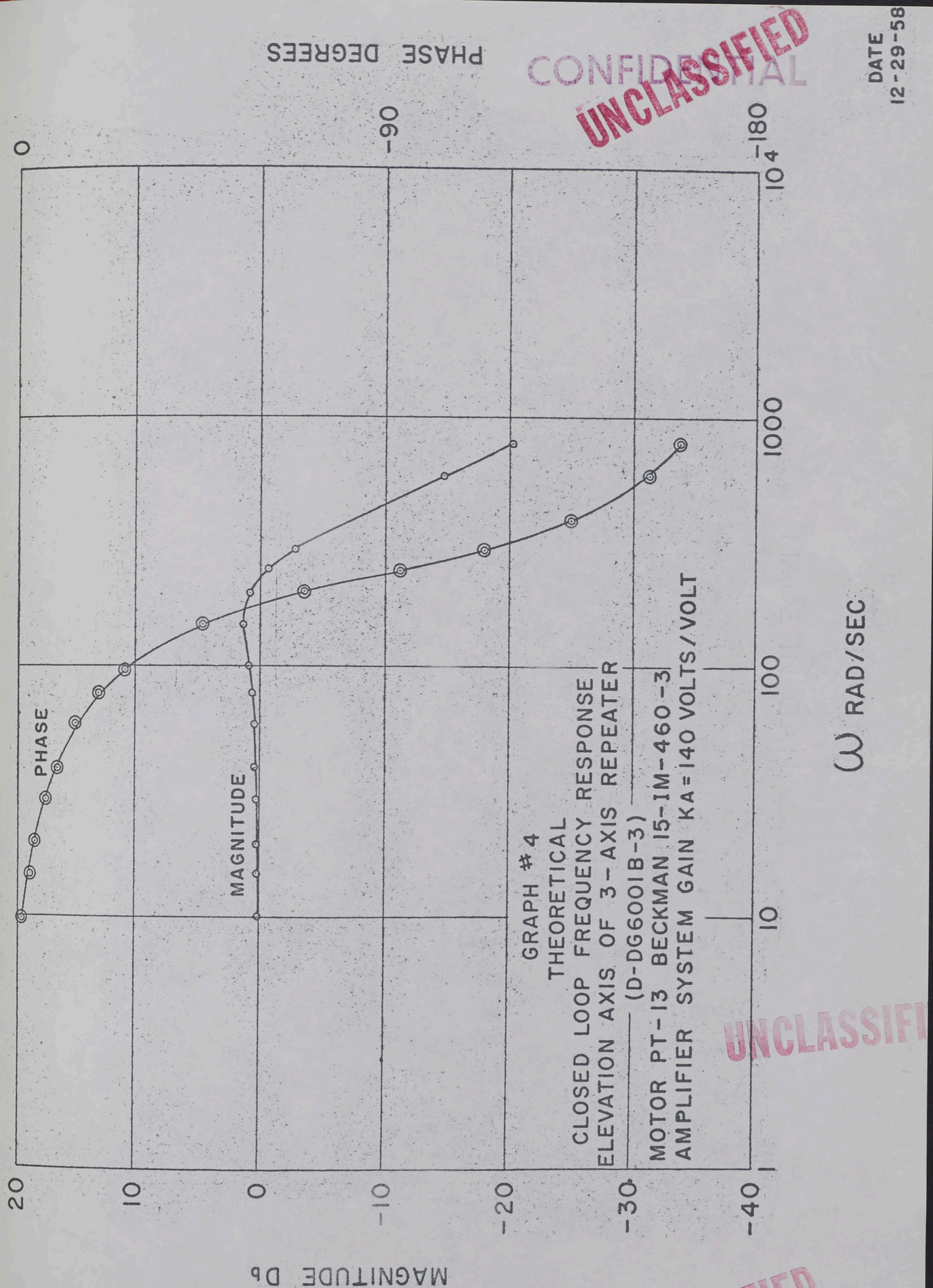

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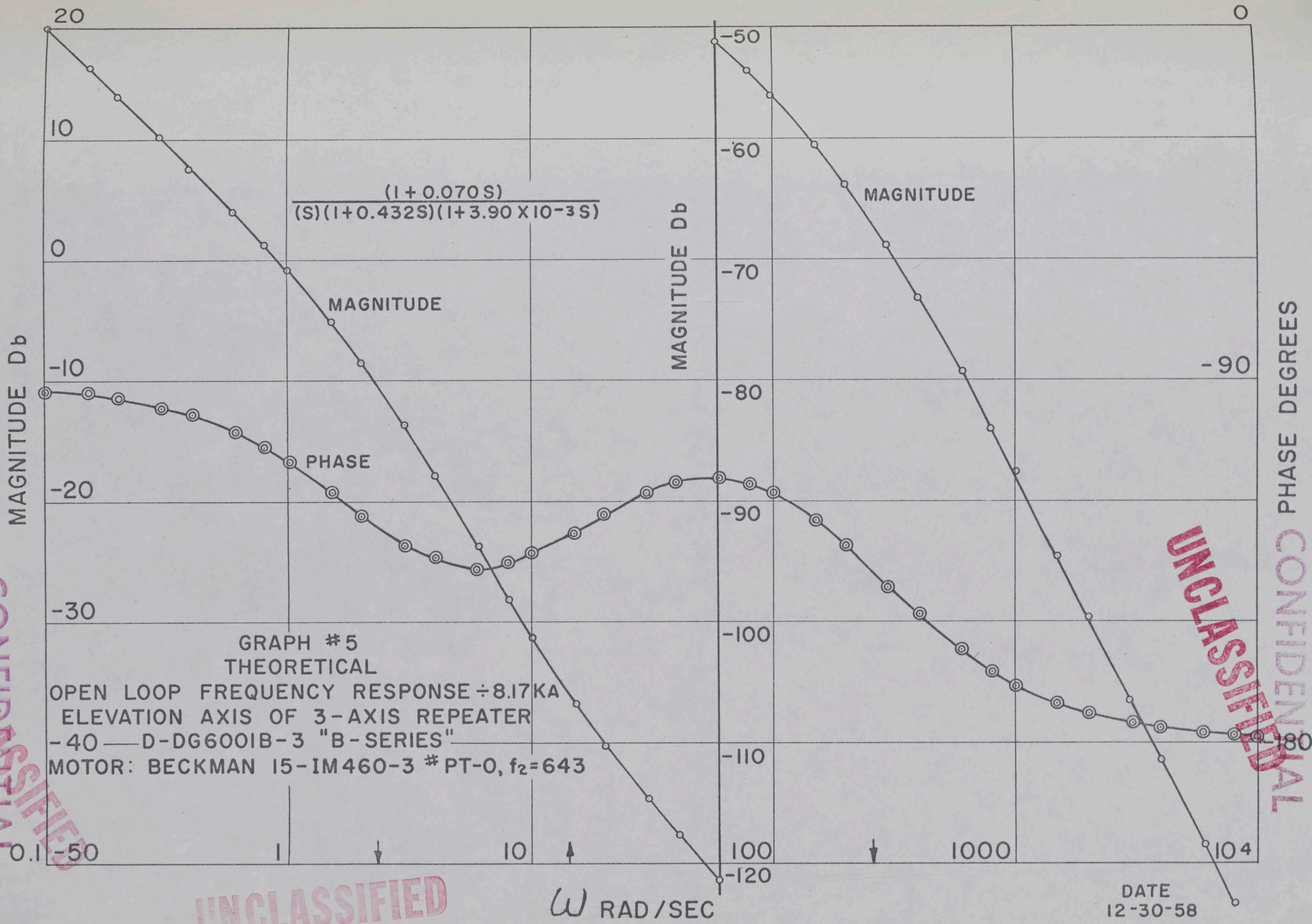

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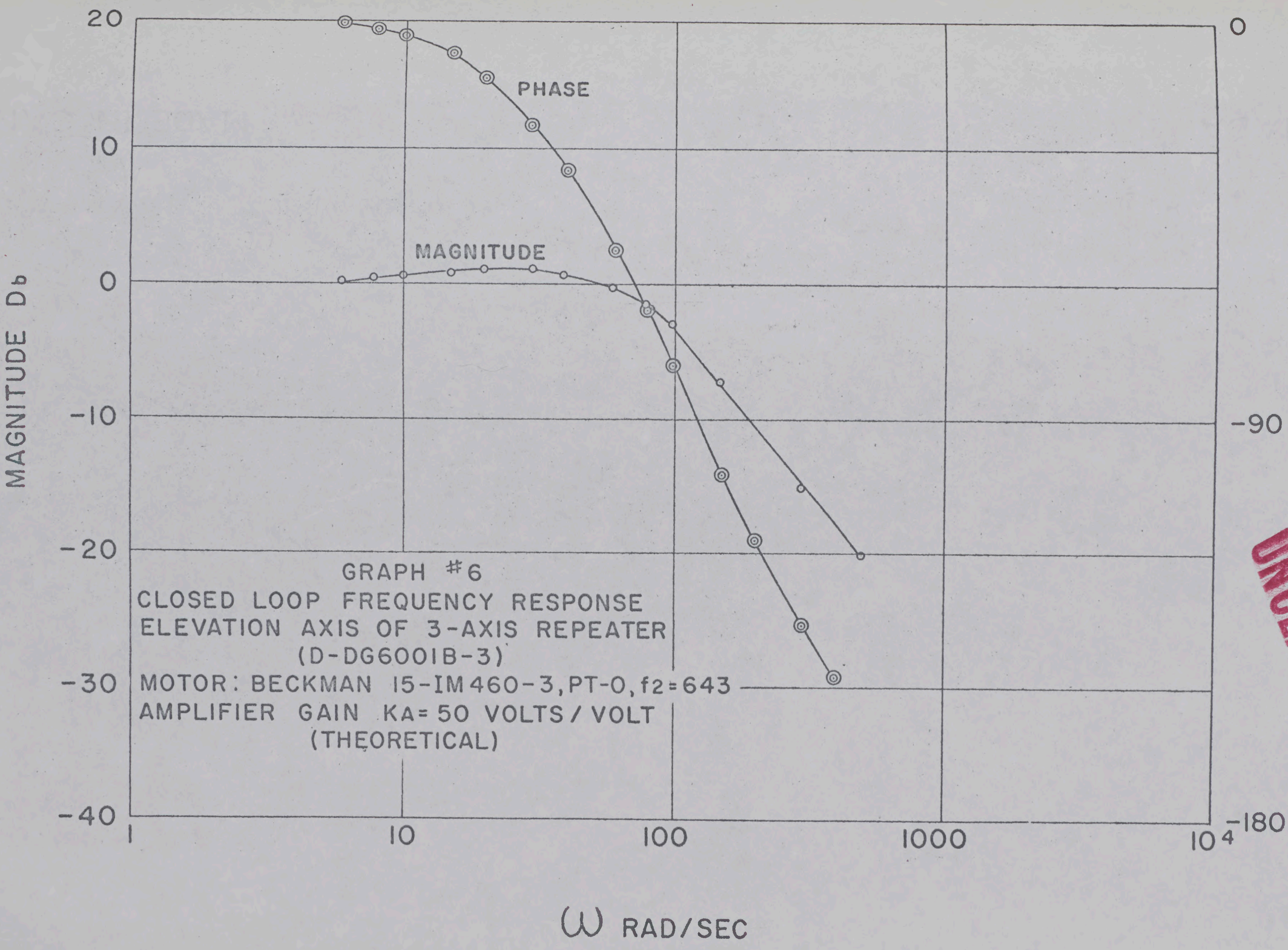

DATE 12-22-58

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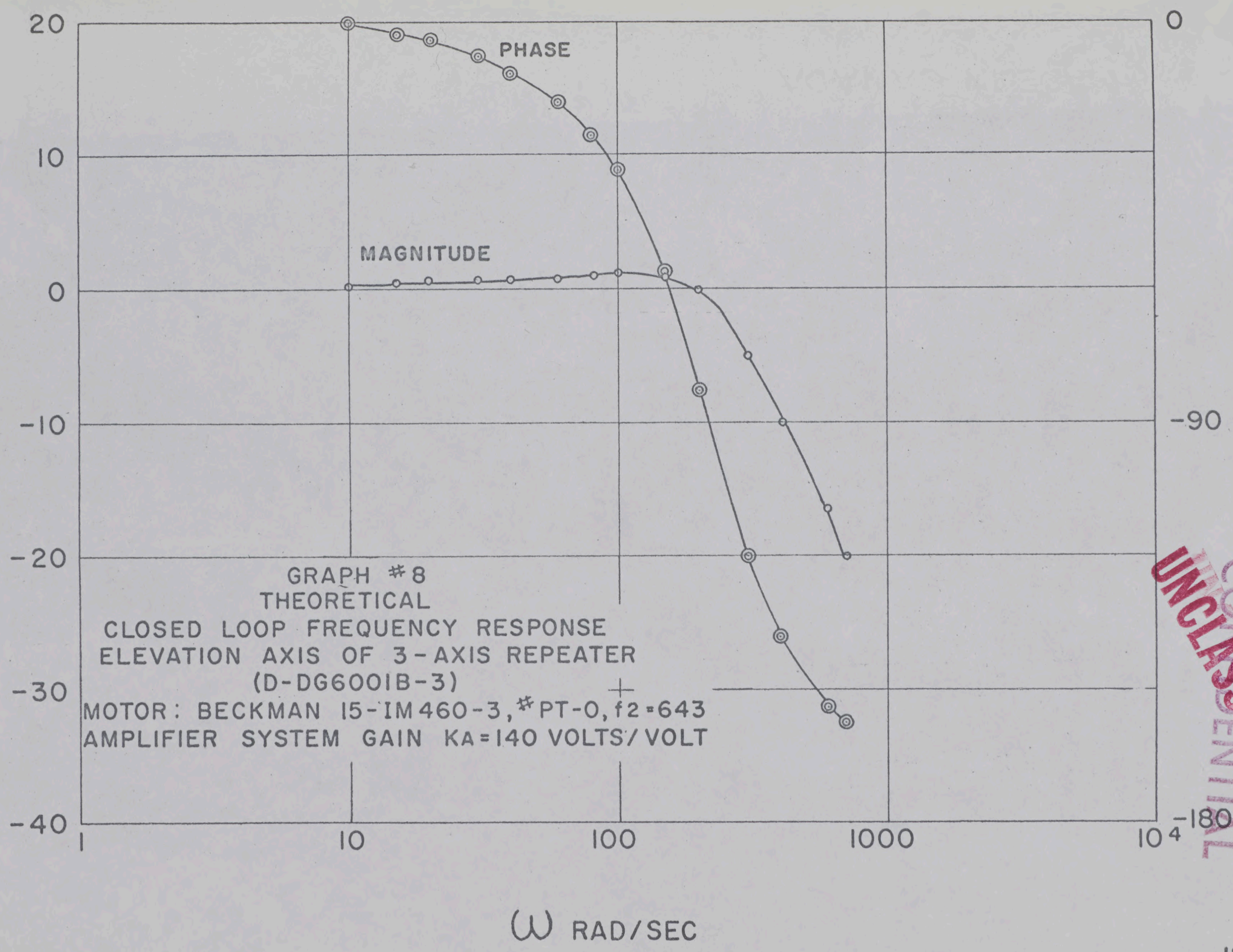

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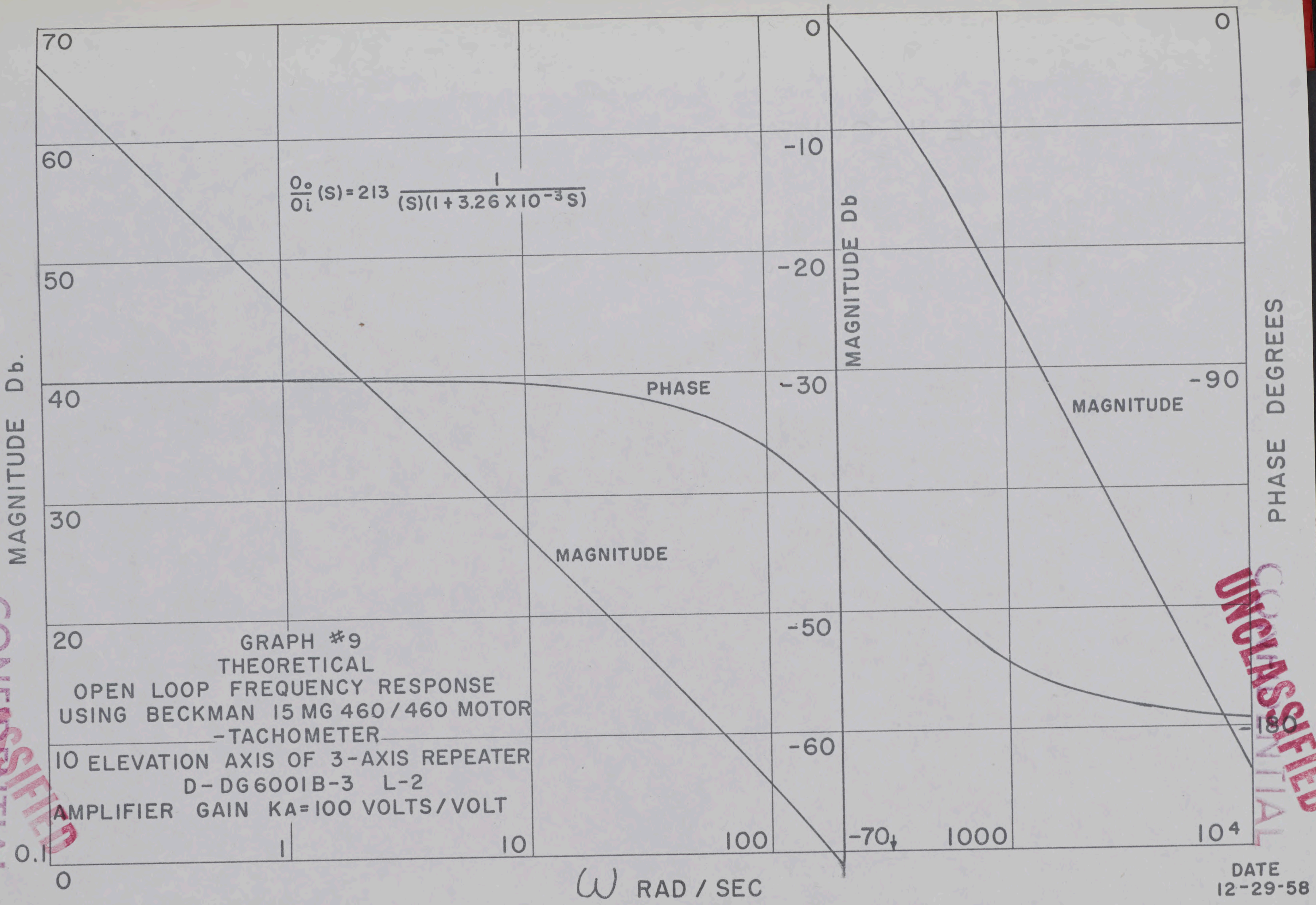
GRAPH #9
THEORETICAL
OPEN LOOP FREQUENCY RESPONSE
USING BECKMAN 15 MG 460/460 MOTOR
-TACHOMETER
ELEVATION AXIS OF 3-AXIS REPEATER
D-DG6001B-3 L-2
AMPLIFIER GAIN KA=100 VOLTS/VOLT
$\frac{O_o}{O_i}(S) = 213 \frac{1}{(S)(1+3.26 \times 10^{-3} S)}$
MAGNITUDE Db.
70
60
50
40
30
20
10
0
0
-10
-20
-30
-50
-60
-70
MAGNITUDE Db
PHASE DEGREES
0
-90
-180
PHASE
MAGNITUDE
MAGNITUDE
0.1
1
10
100
1000
10^4
ω RAD / SEC
DATE
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UNCLASSIFIED

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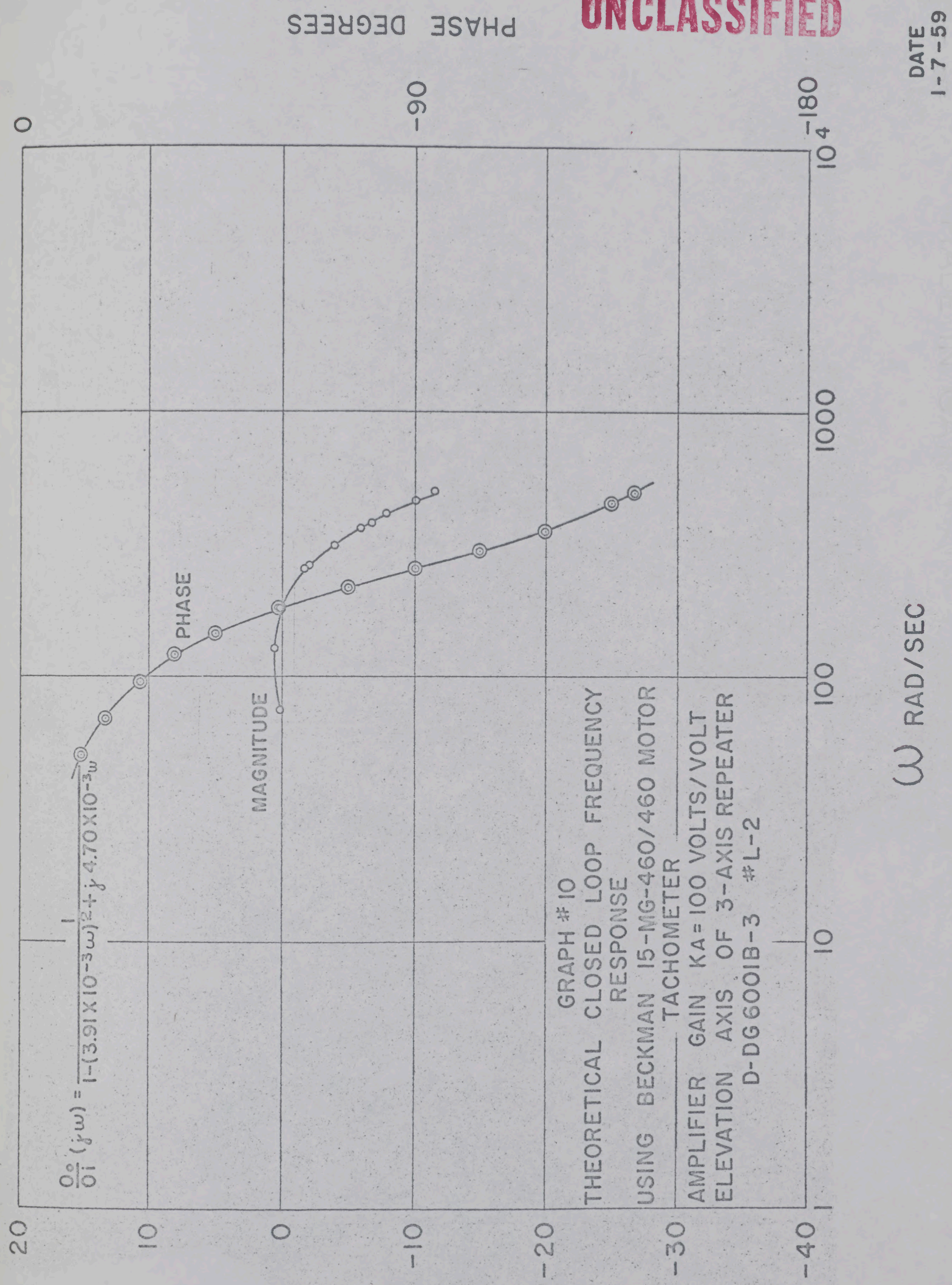

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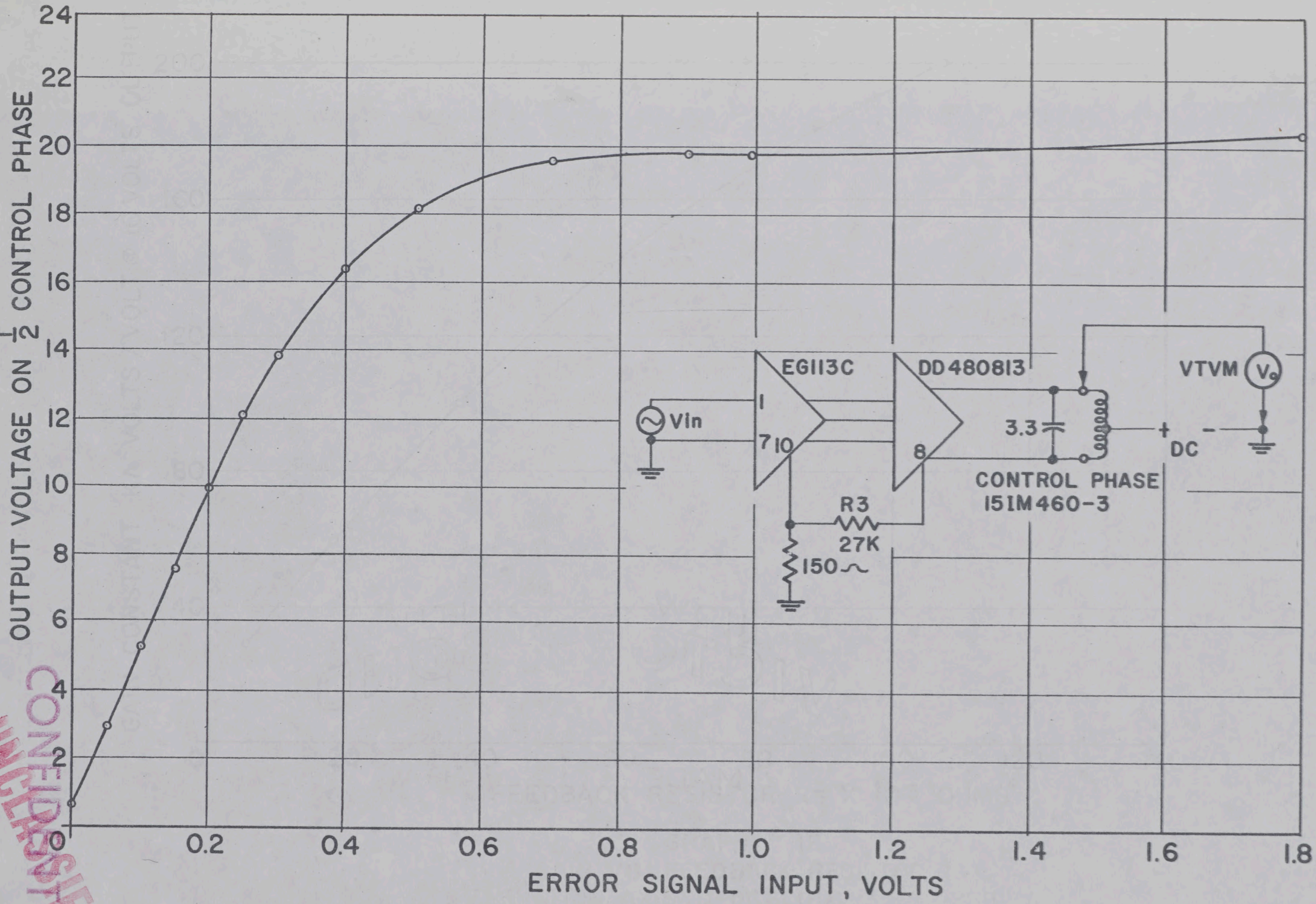

GRAPH # 11

GAIN: AMPLIFIER SYSTEM OF 3-AXIS REPEATER MODULE D-DG6001B-3 #L-2 INDICATED GAIN CONSTANT KA = 110 (@ 5 VOLTS OUTPUT)

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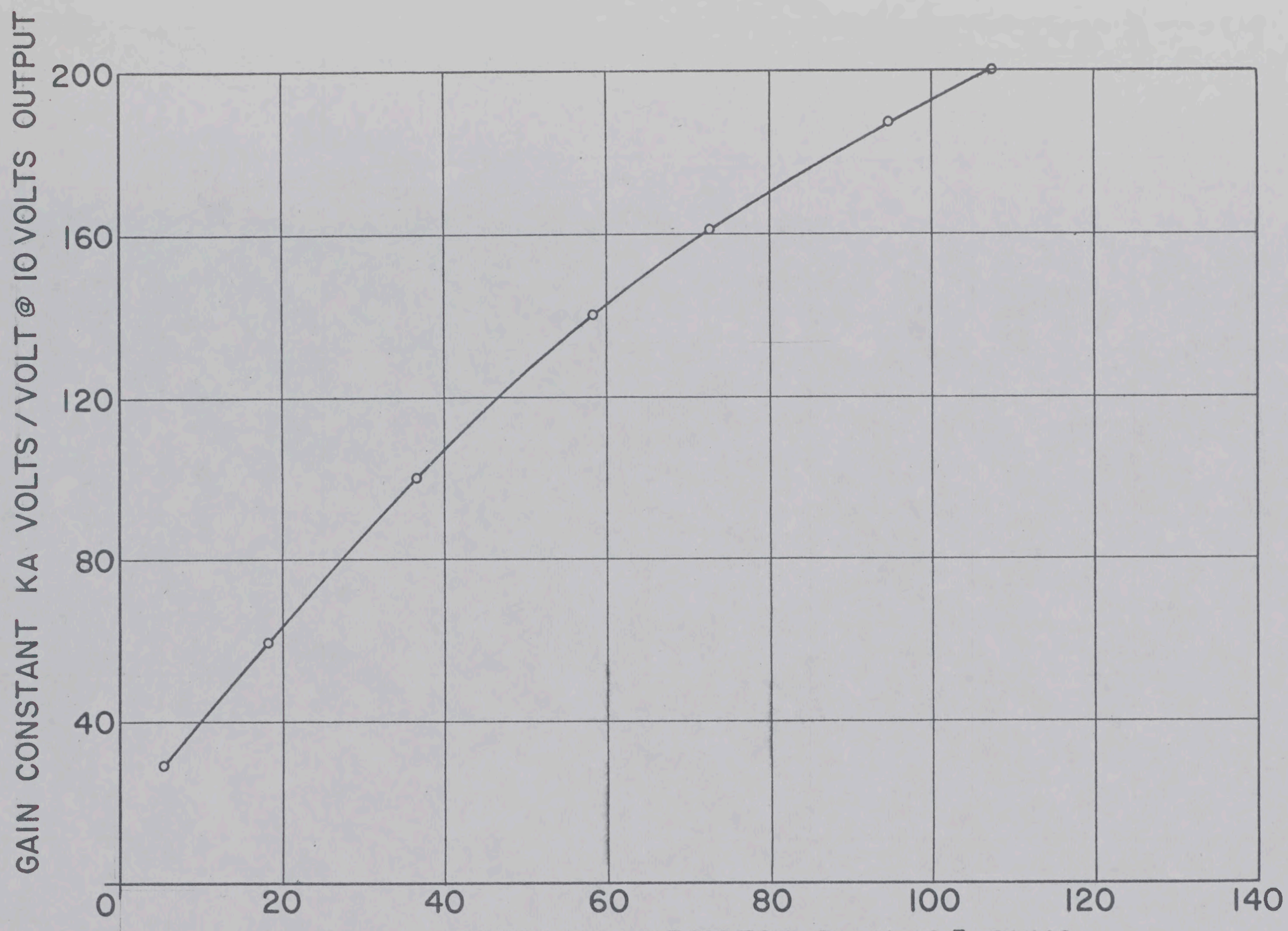
UNCLASSIFIED



GRAPH # 12
GAIN VS. FEEDBACK RESISTOR R3
ELEVATION AXIS D-DG6001B-3, L-2 SERIES
LOAD MOTOR: BECKMAN 151M460-3 #PT-0
R_2 = 150 OHMS

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1-5-59

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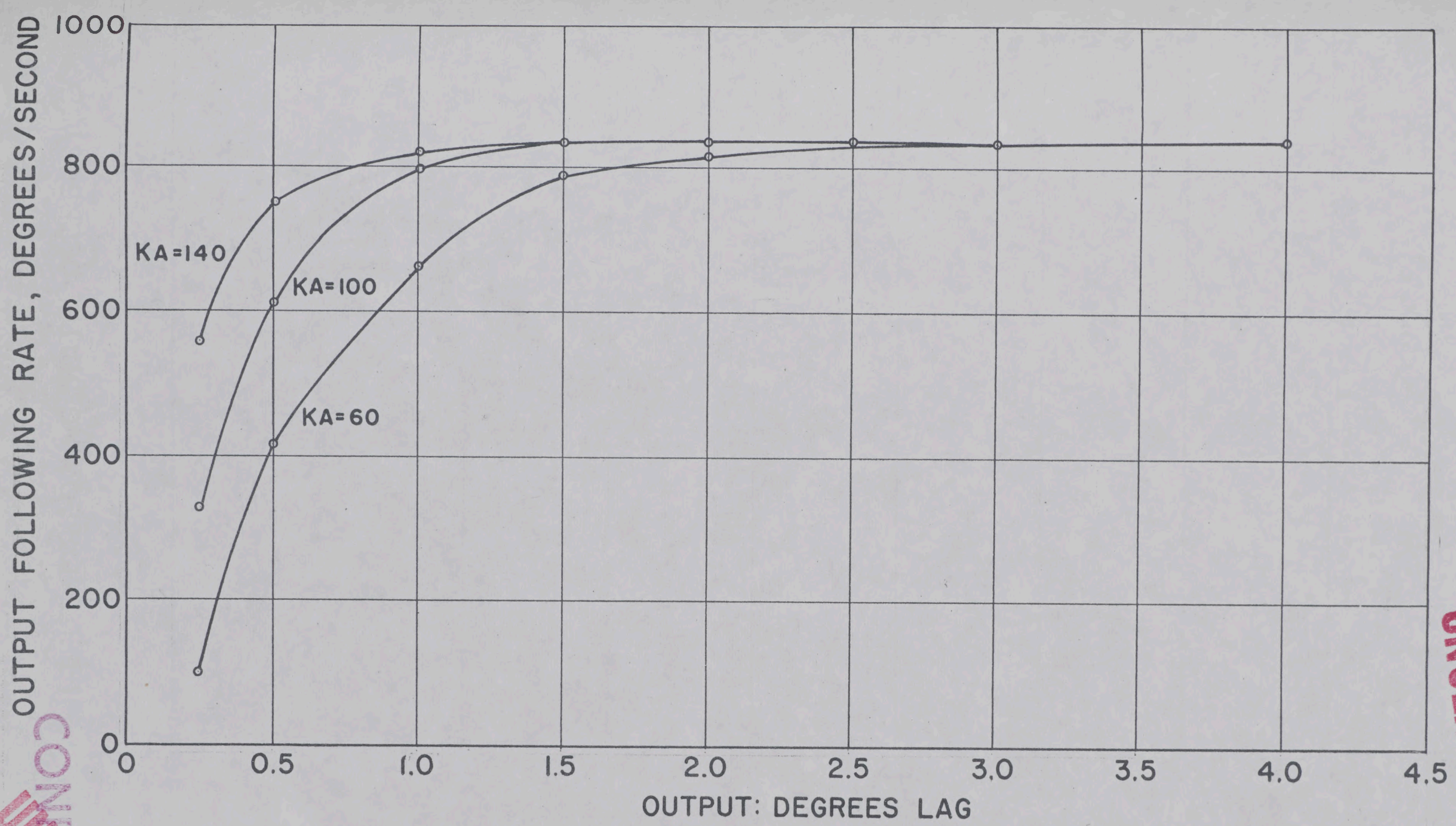

GRAPH #13
FOLLOWING RATE OF D-DG6001B-3
#L-2 ELEVATION AXIS
MOTOR PT-O 151M460-3
AMPLIFIER SYSTEM GAINS AS INDICATED

DATE
12-31-58

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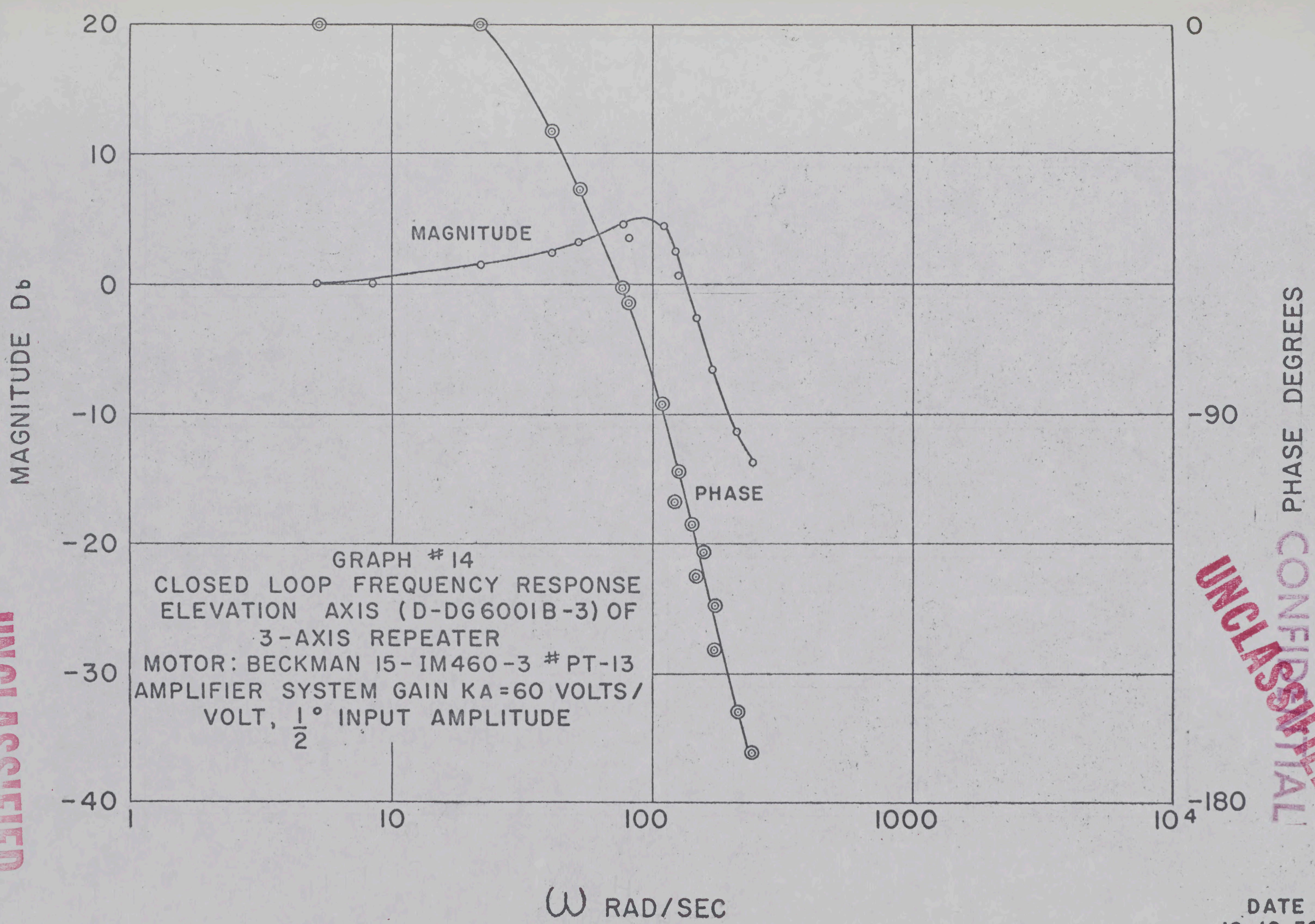
UNCLASSIFIED
CONFIDENTIAL
UNCLASSIFIED



GRAPH # 14
CLOSED LOOP FREQUENCY RESPONSE
ELEVATION AXIS (D-DG6001B-3) OF
3-AXIS REPEATER
MOTOR: BECKMAN 15-IM460-3 # PT-13
AMPLIFIER SYSTEM GAIN KA=60 VOLTS/VOLT, $\frac{1}{2}$° INPUT AMPLITUDE

DATE
12-19-58

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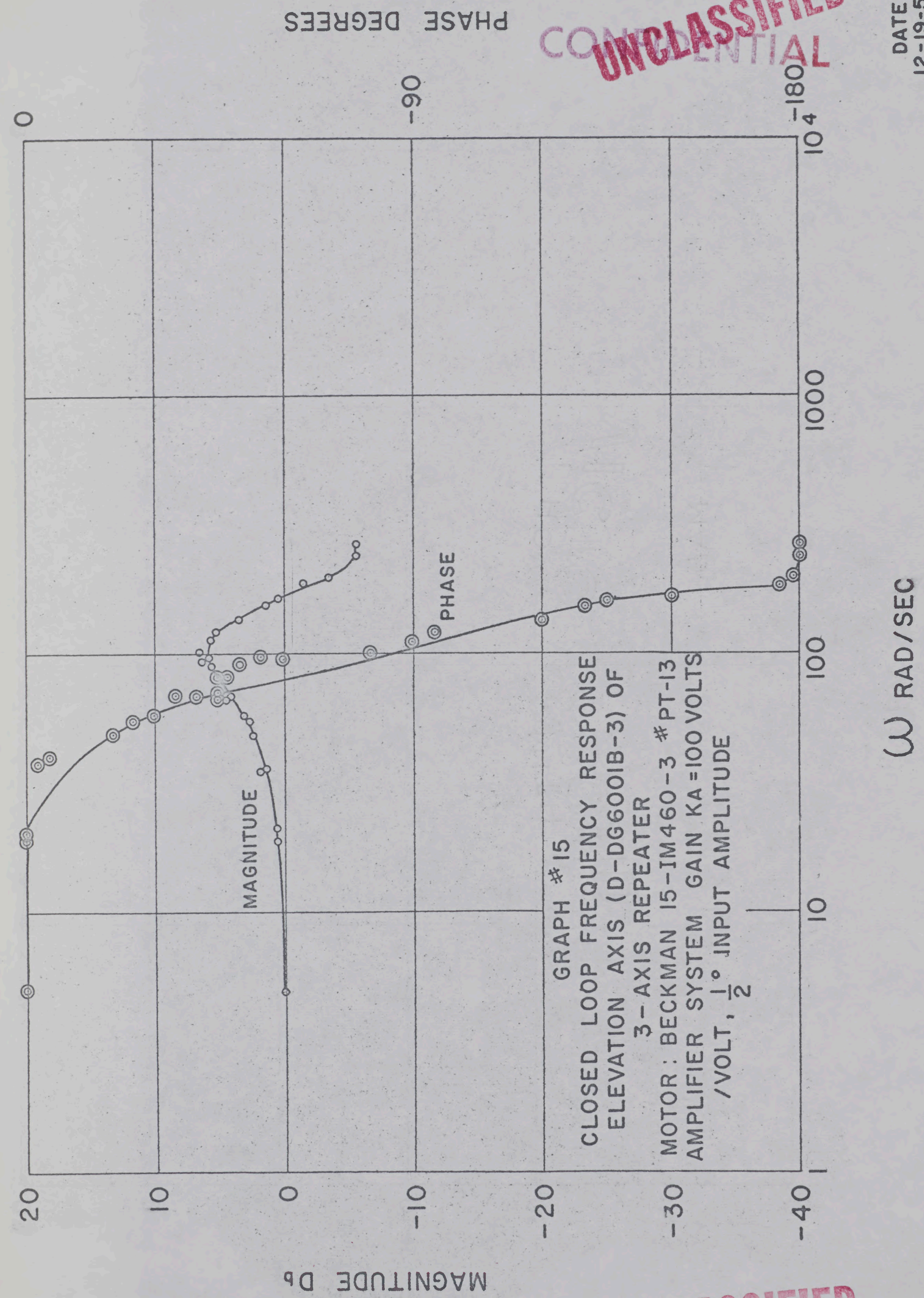
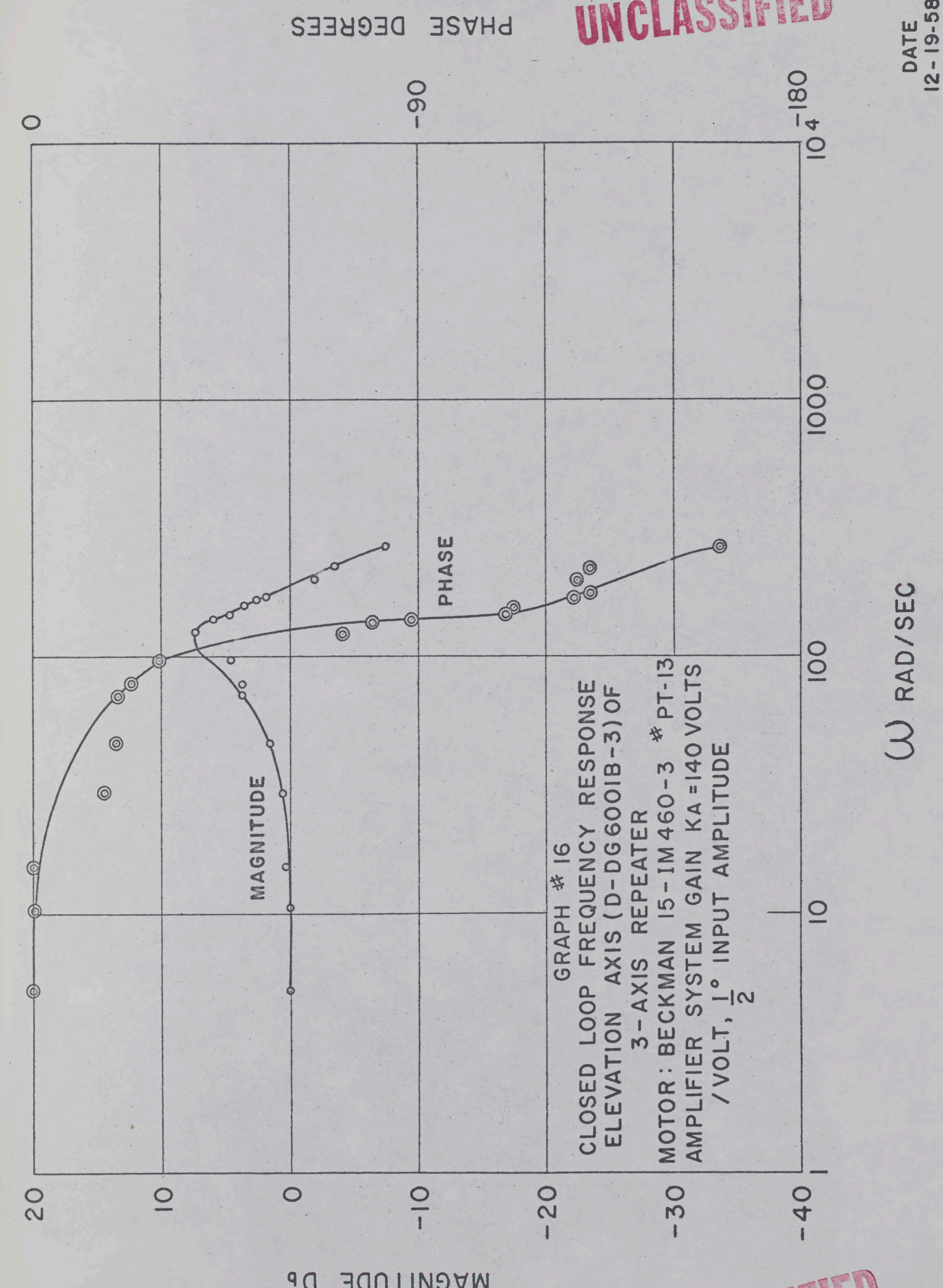
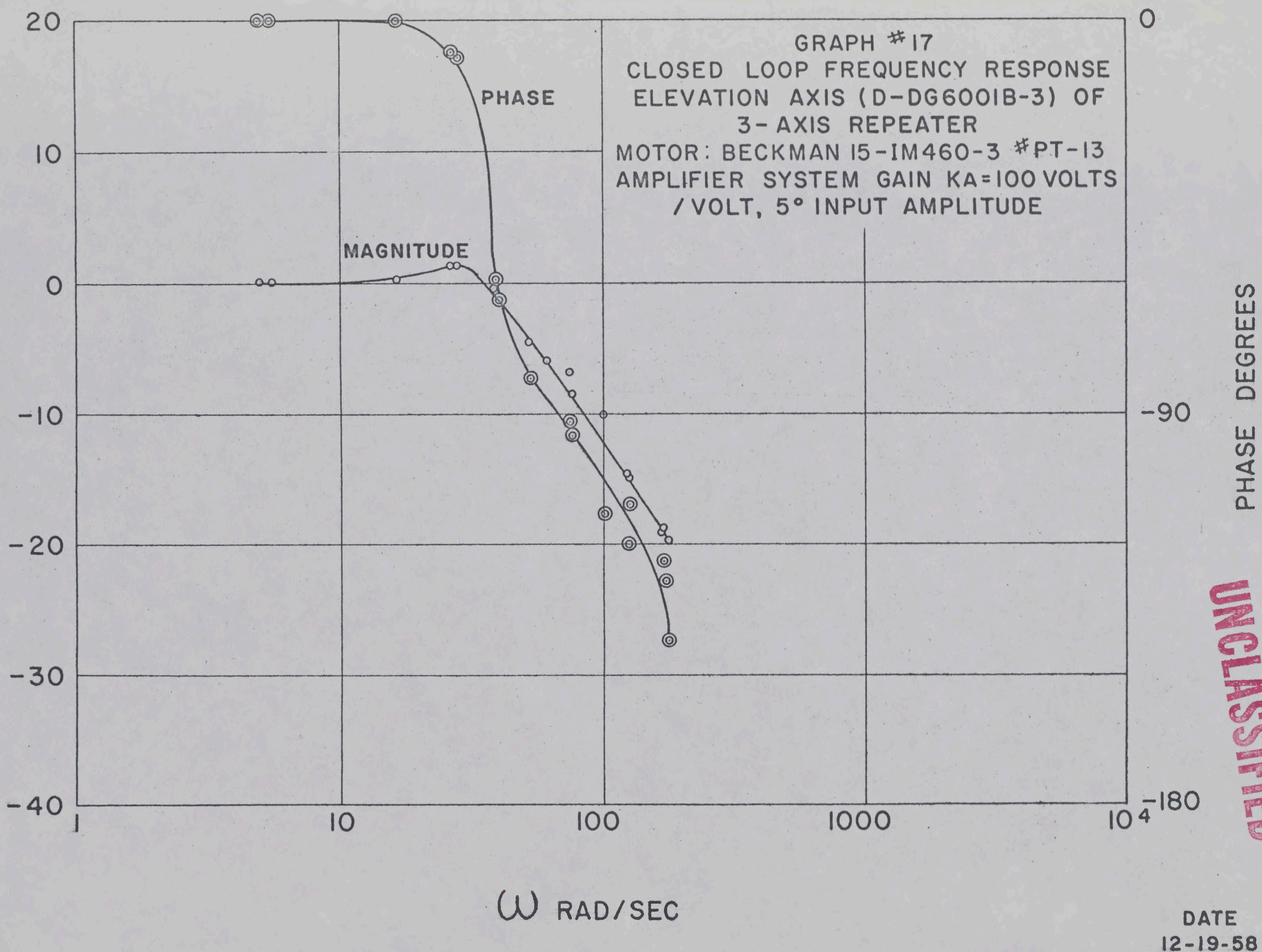
DATE 12-19-58




PHASE DEGREES
0
-90
-180
MAGNITUDE Db
20
10
0
-10
-20
-30
-40
1
10
100
1000
10⁴
ω RAD/SEC
MAGNITUDE
PHASE
GRAPH # 16
CLOSED LOOP FREQUENCY RESPONSE
ELEVATION AXIS (D-DG6001B-3) OF
3-AXIS REPEATER
MOTOR: BECKMAN 15-IM 460-3 # PT-13
AMPLIFIER SYSTEM GAIN KA = 140 VOLTS / VOLT, 1/2° INPUT AMPLITUDE
DATE
12-19-58



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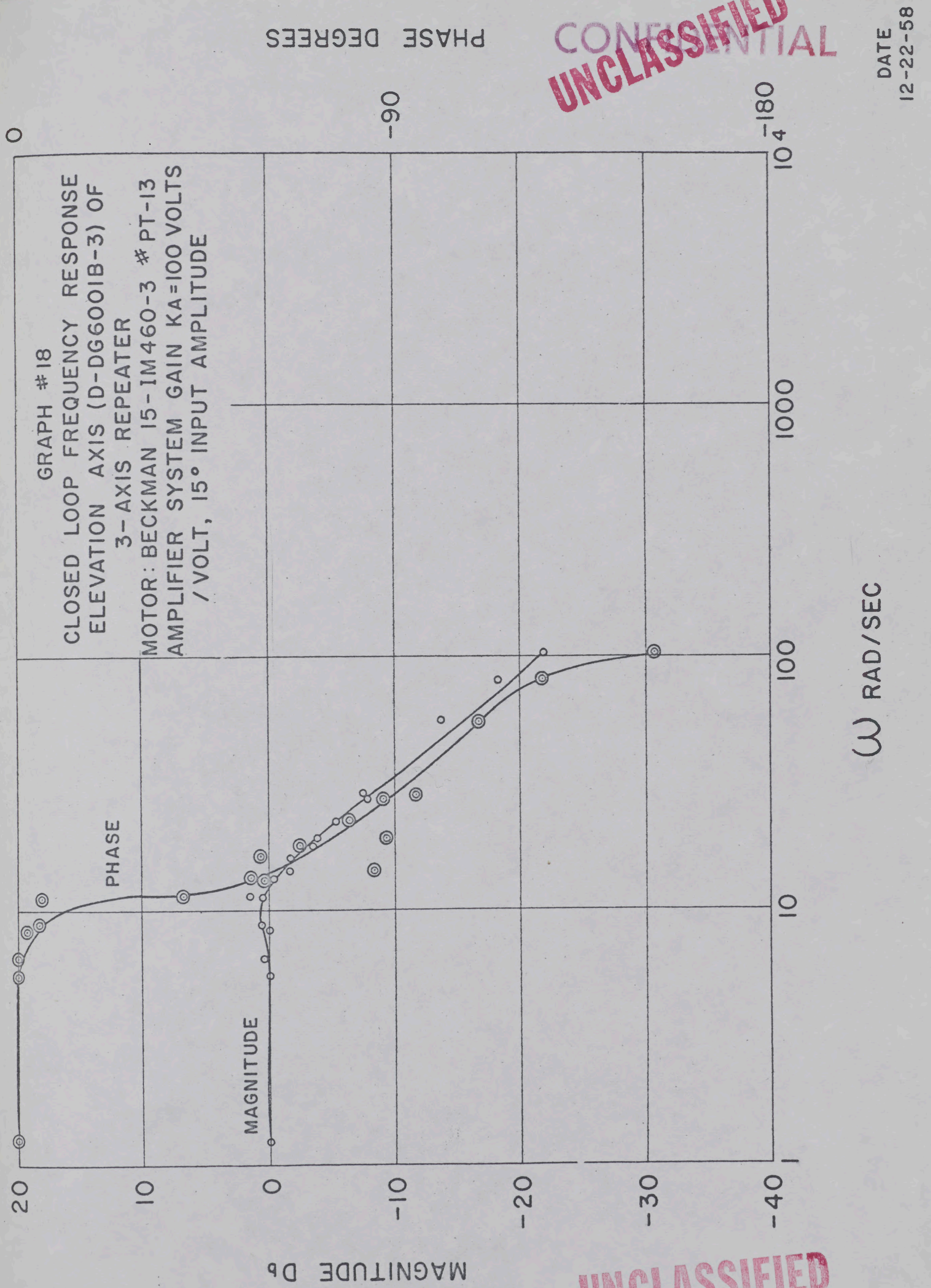

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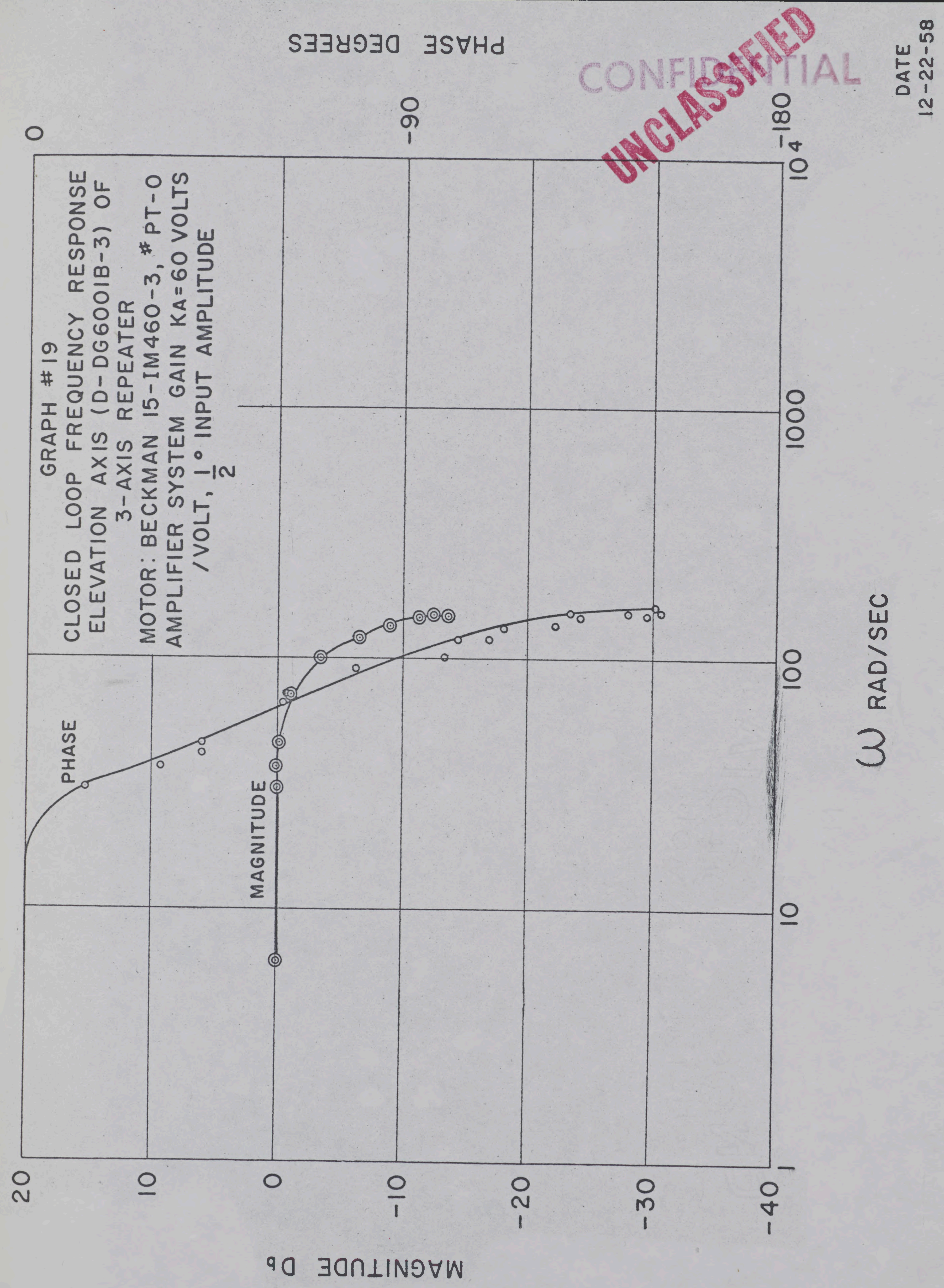

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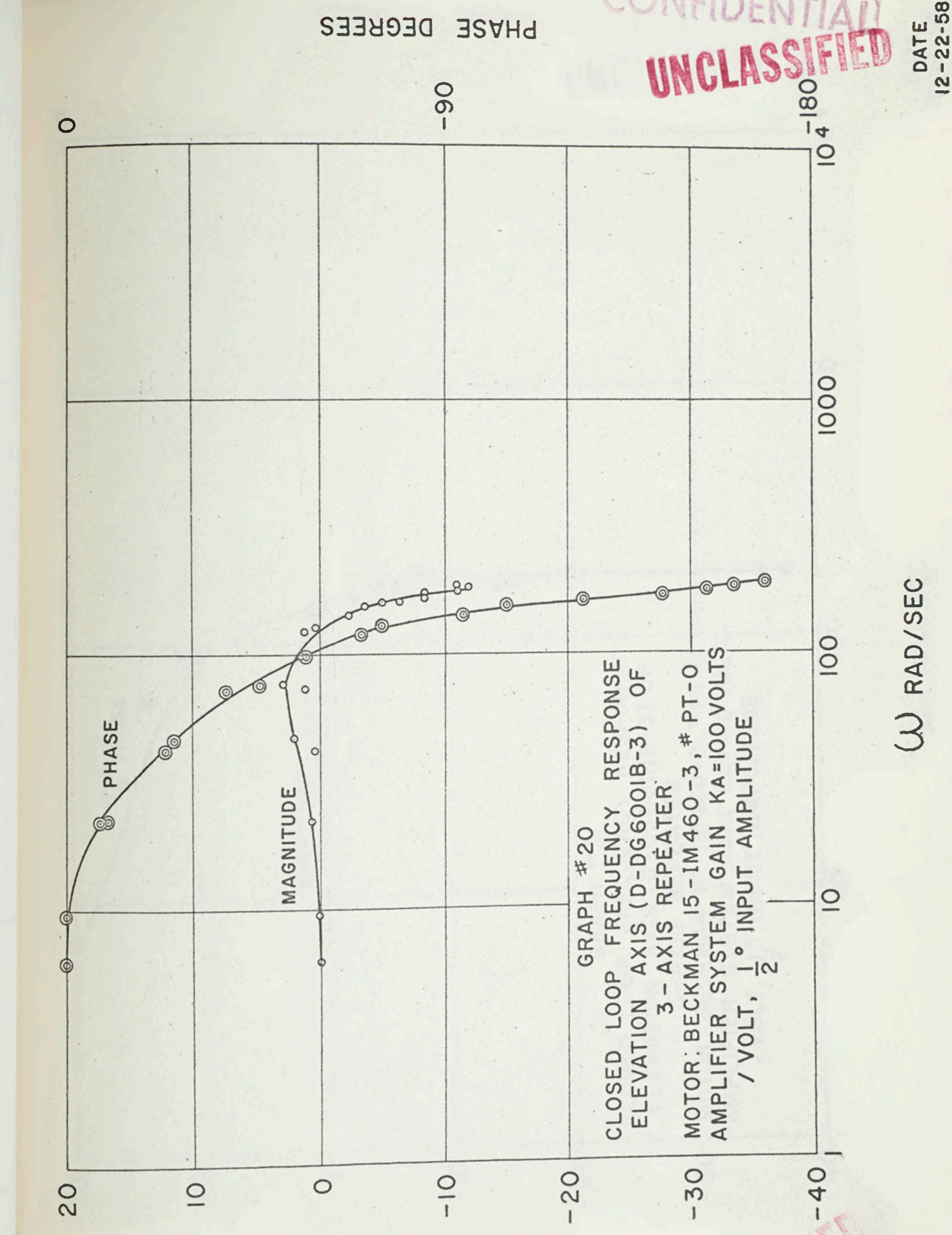

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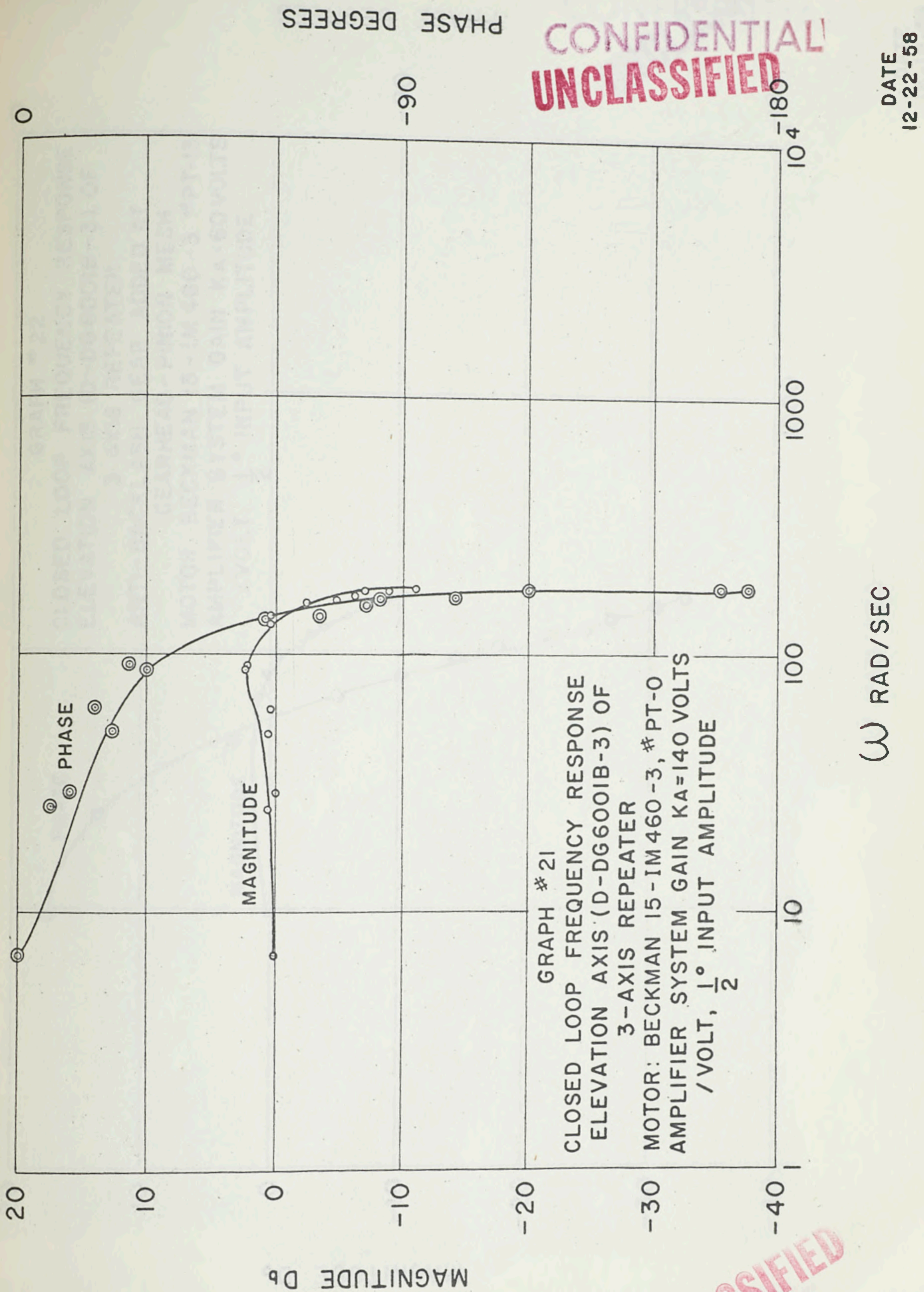

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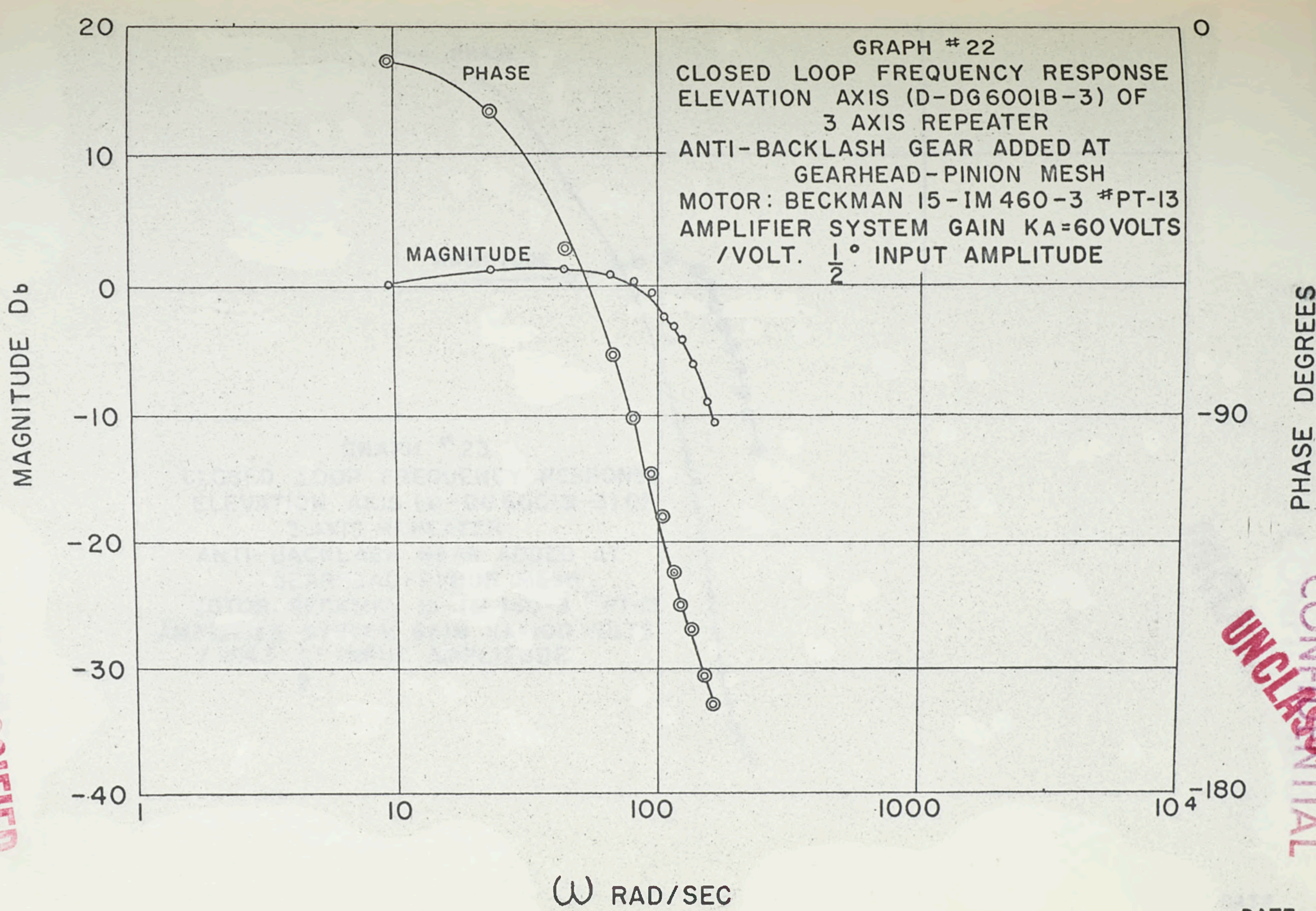

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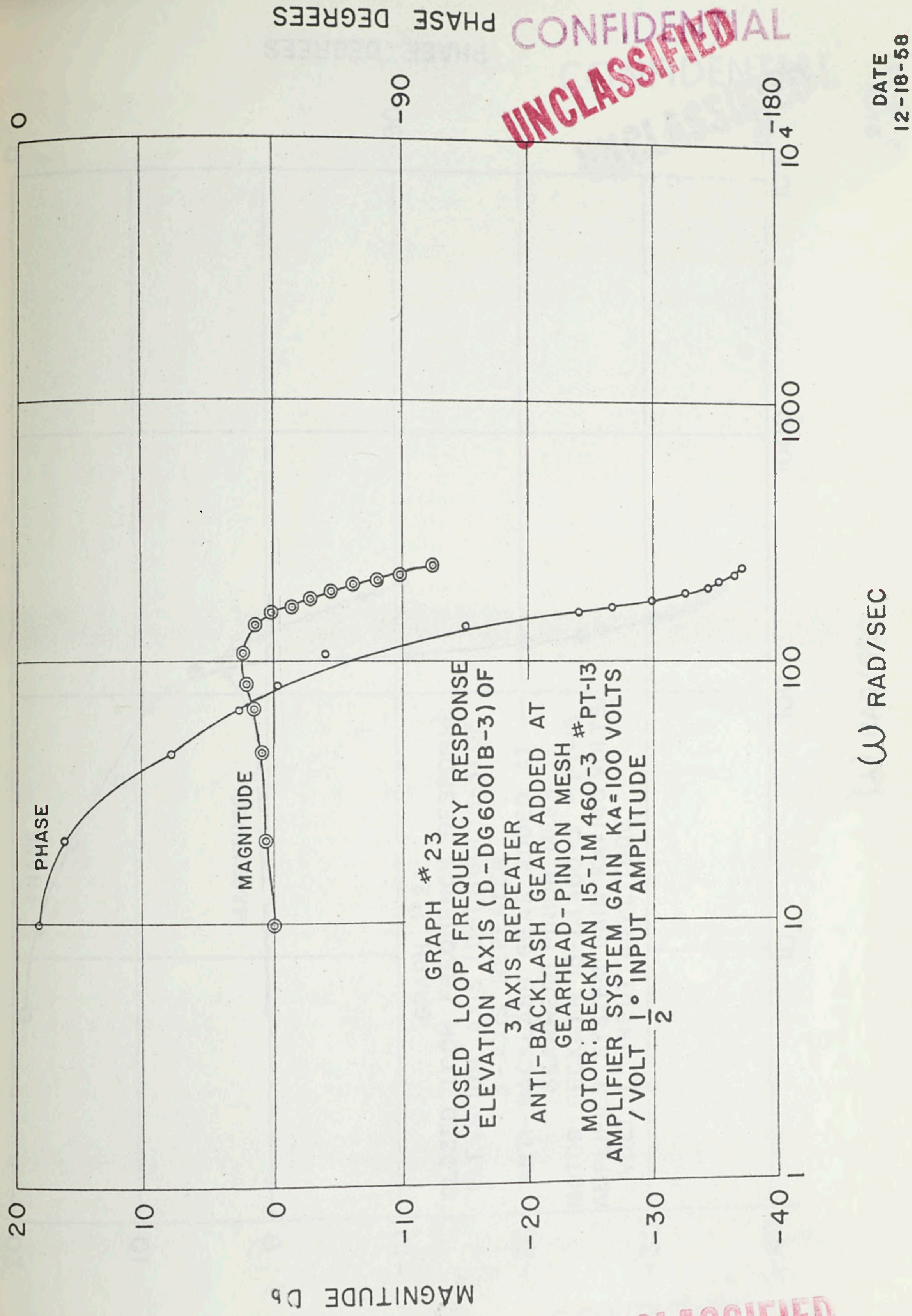

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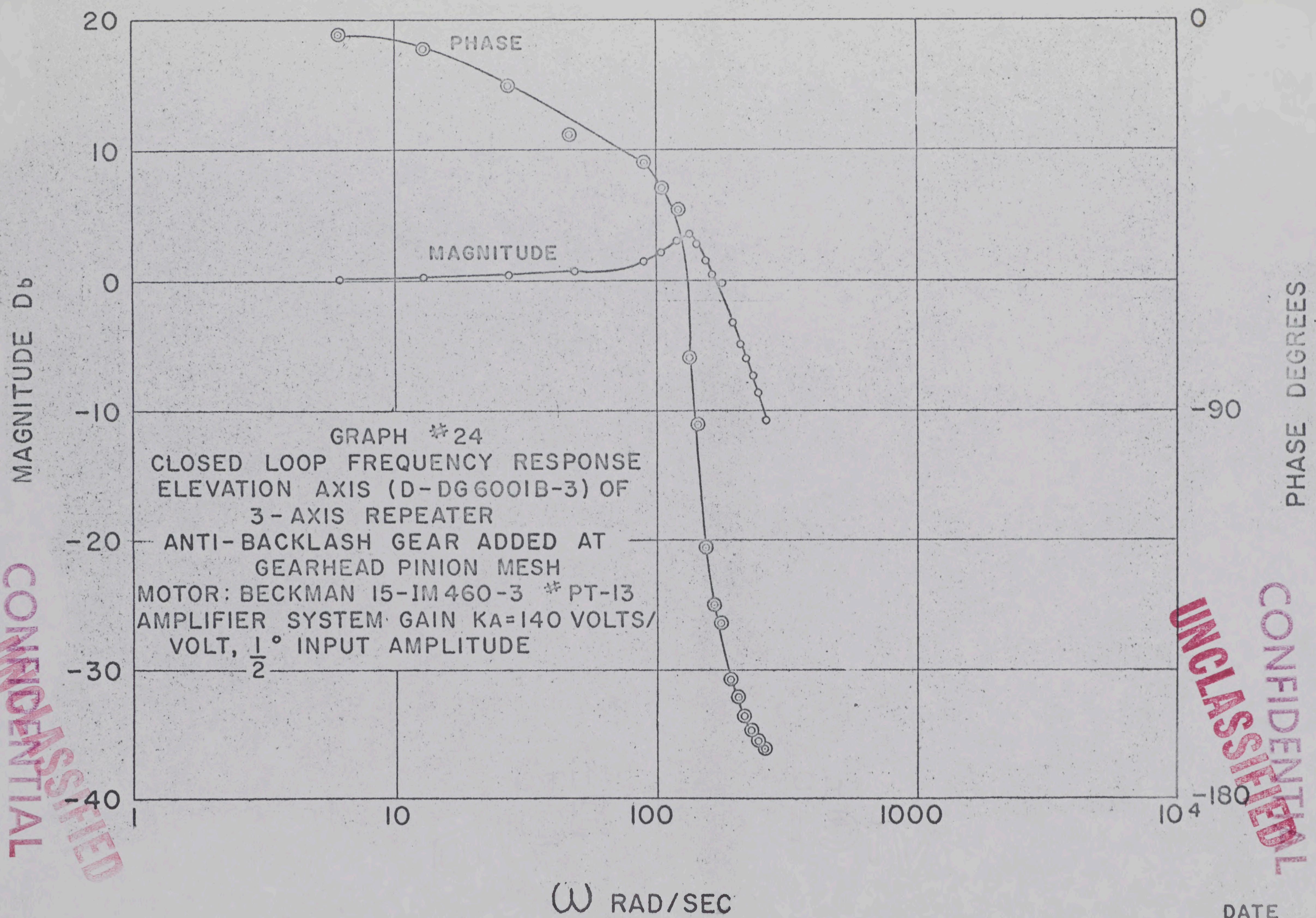

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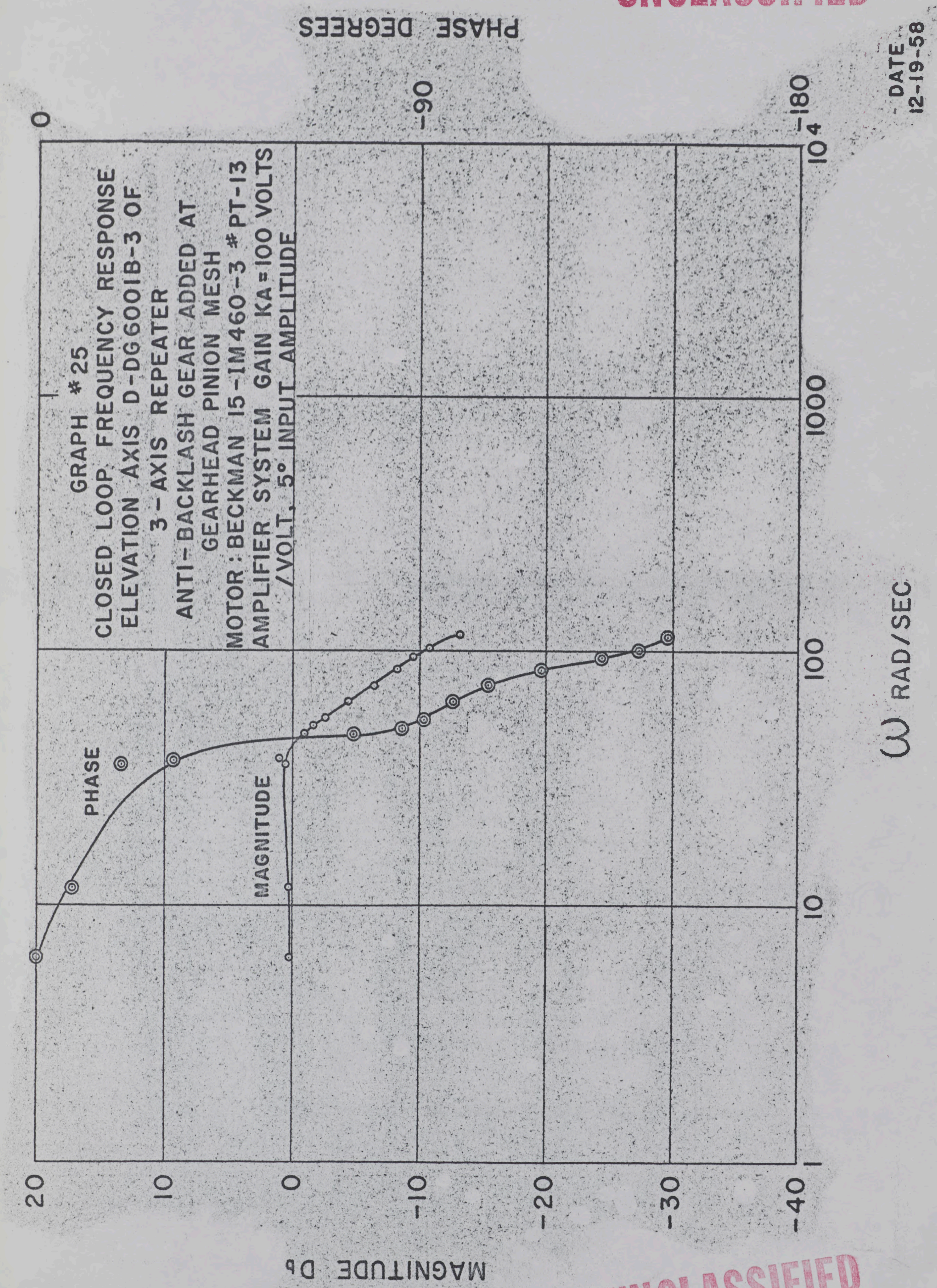

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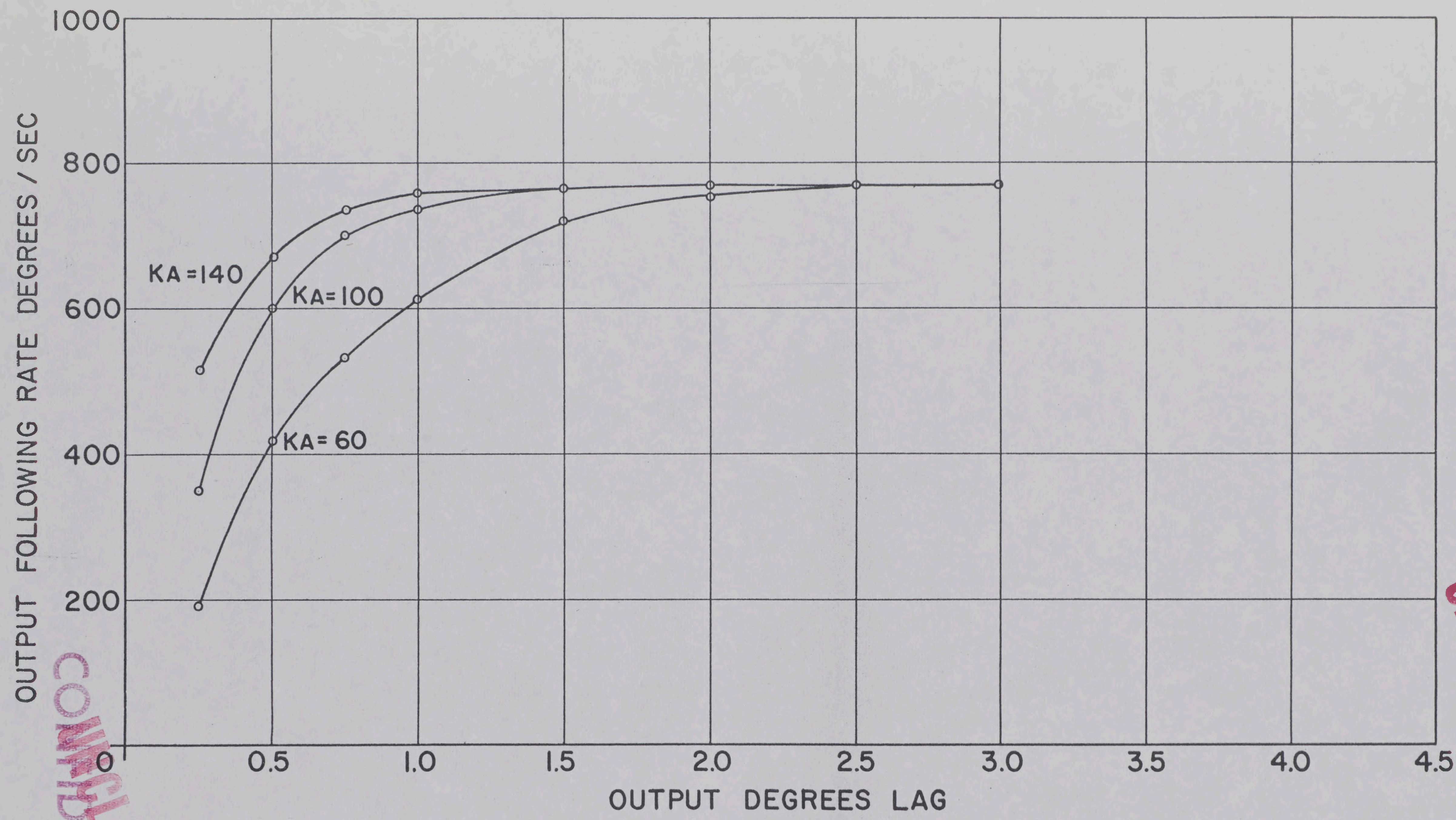

GRAPH # 26
FOLLOWING RATE OF DG6000-G BREADBOARD
MOTOR: 15-IM460-3 #PT-0, f_2=643
AMPLIFIER SYSTEM GAINS (KA) AS INDICATED

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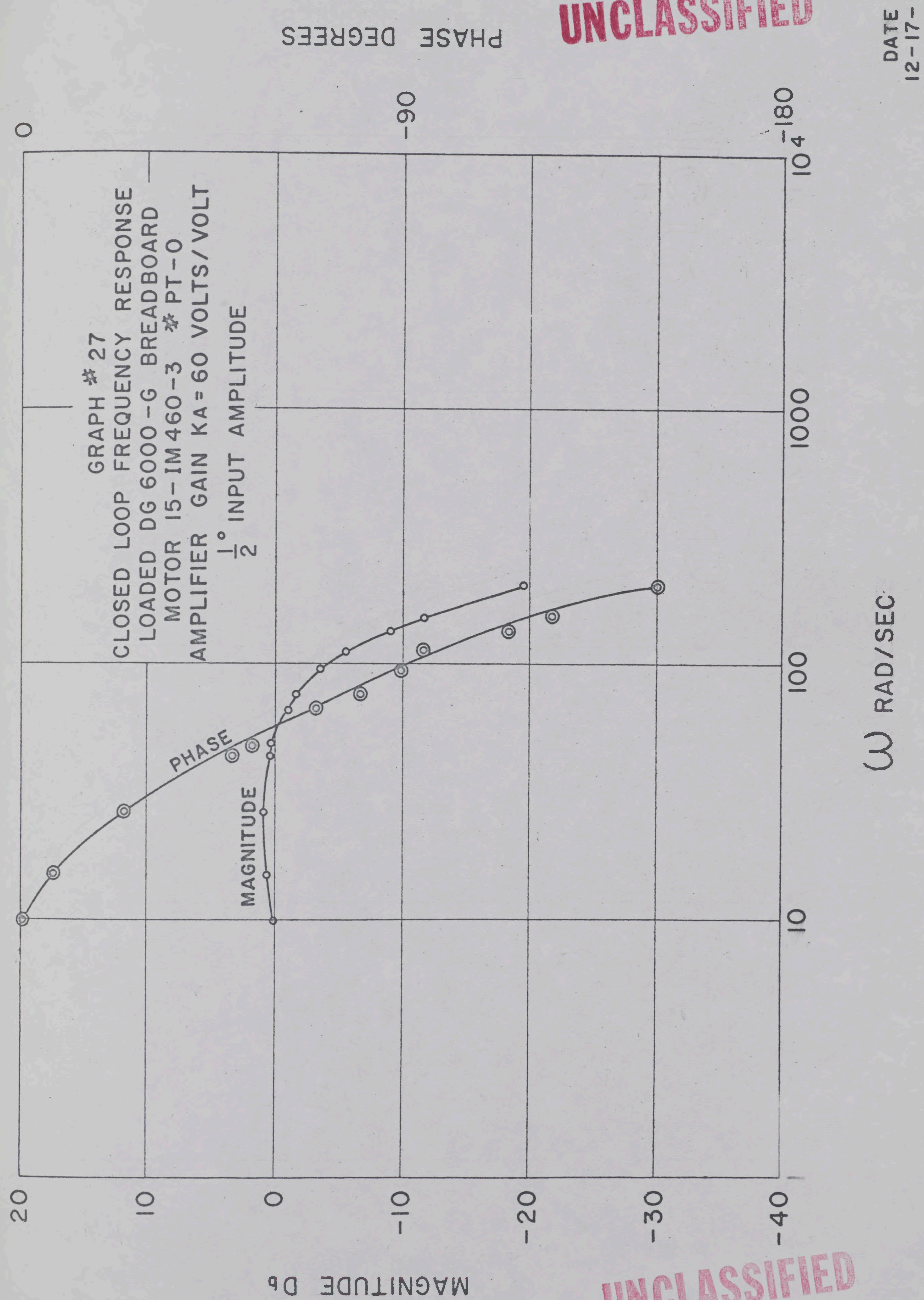

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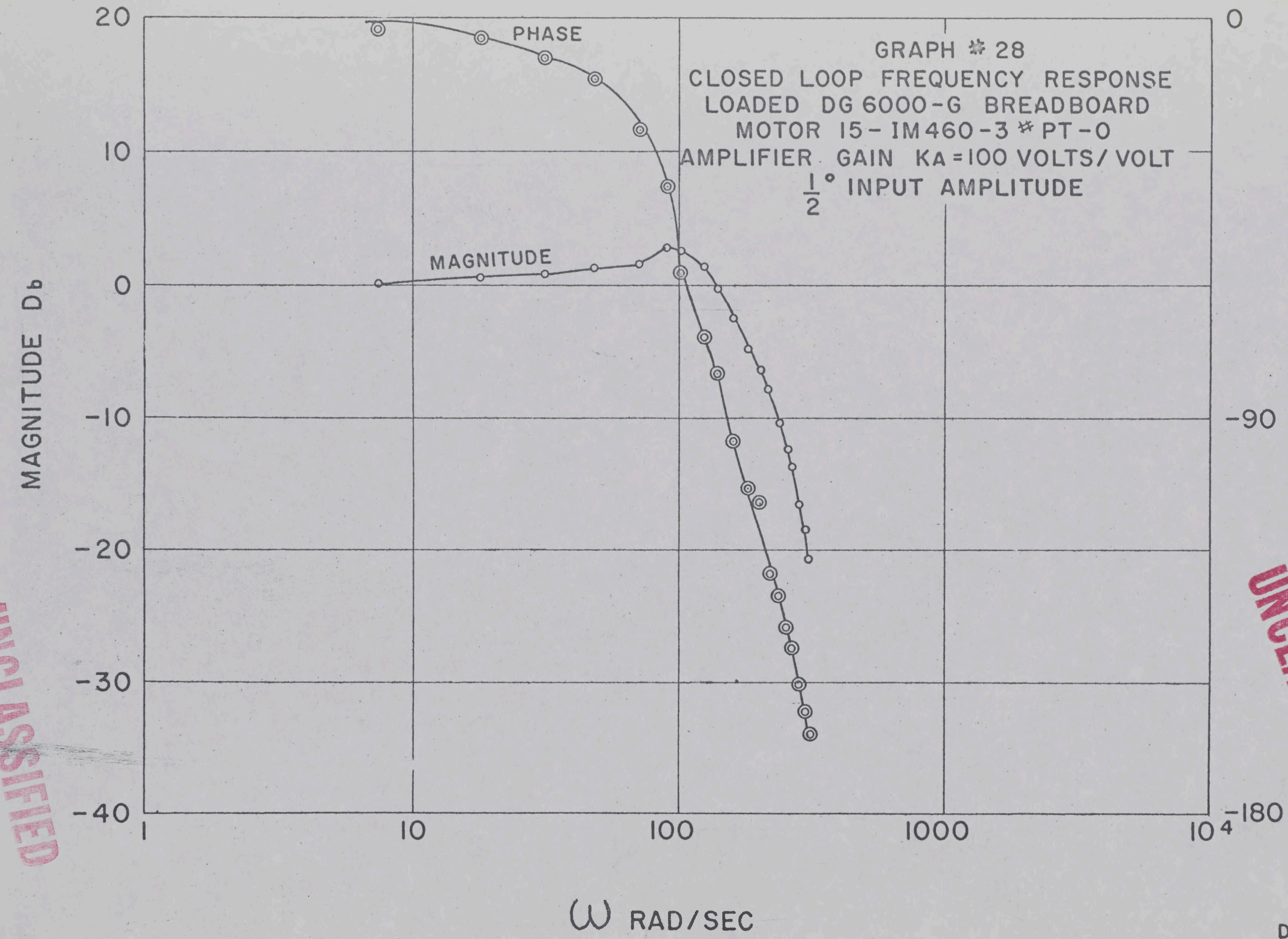

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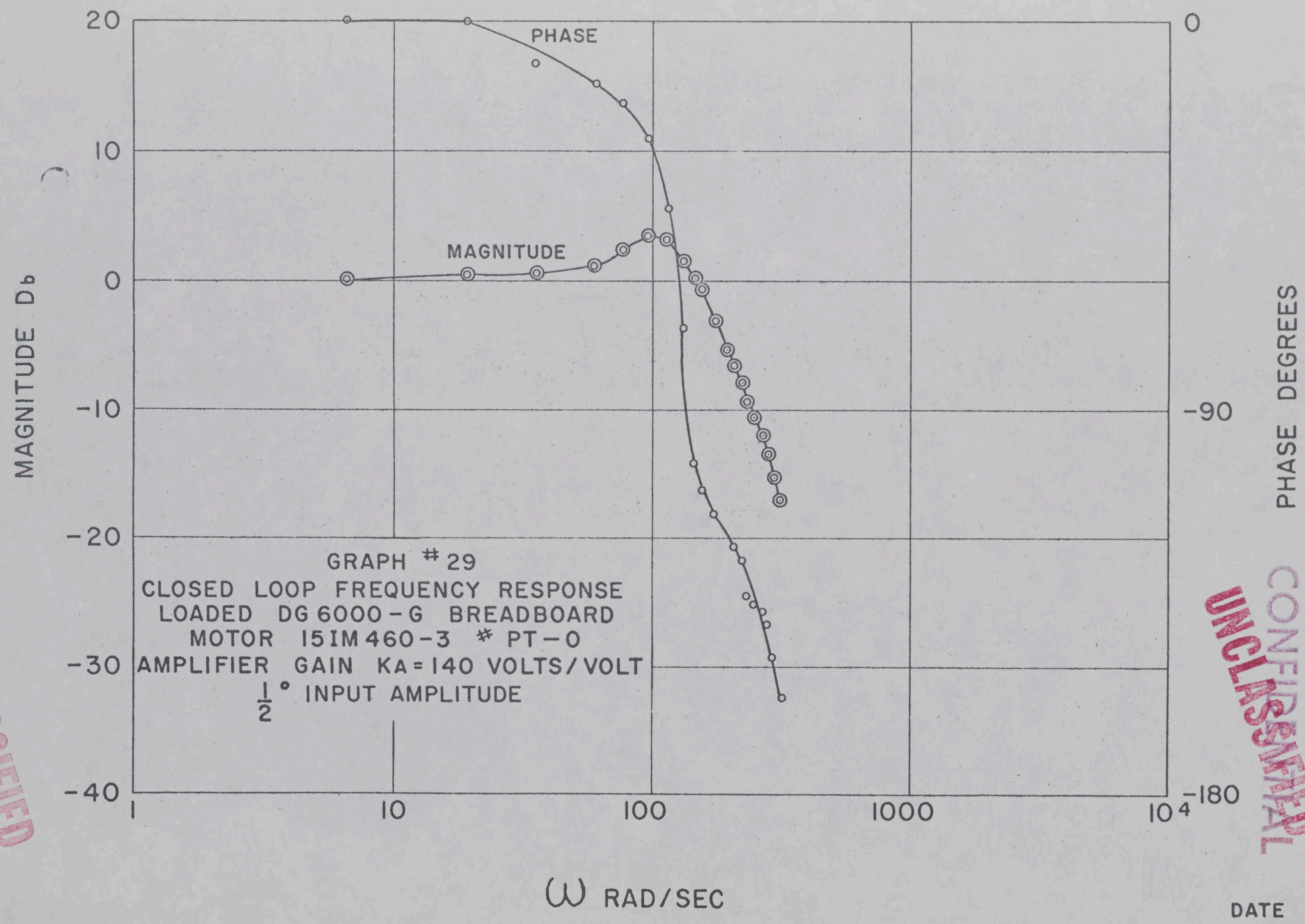

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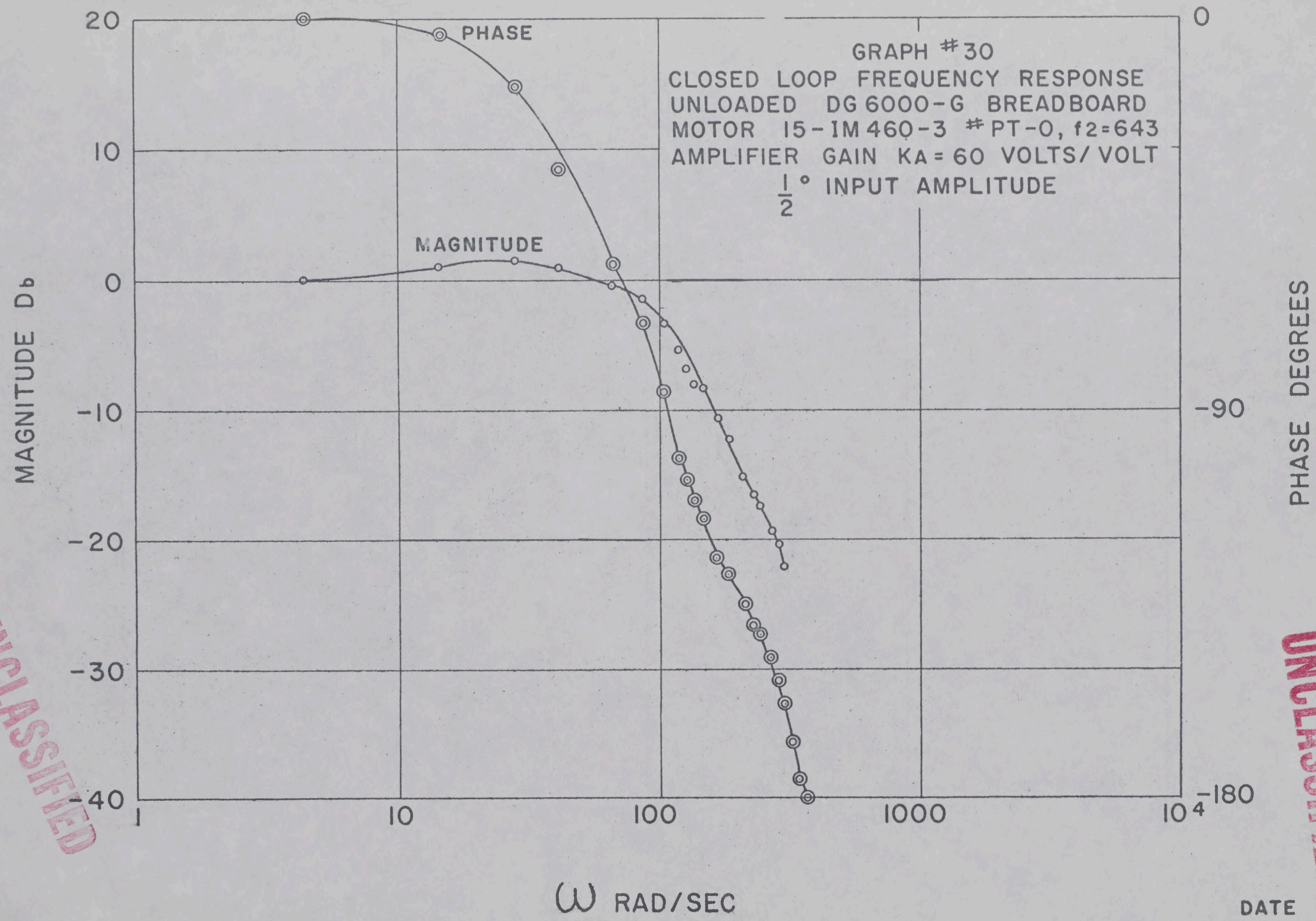

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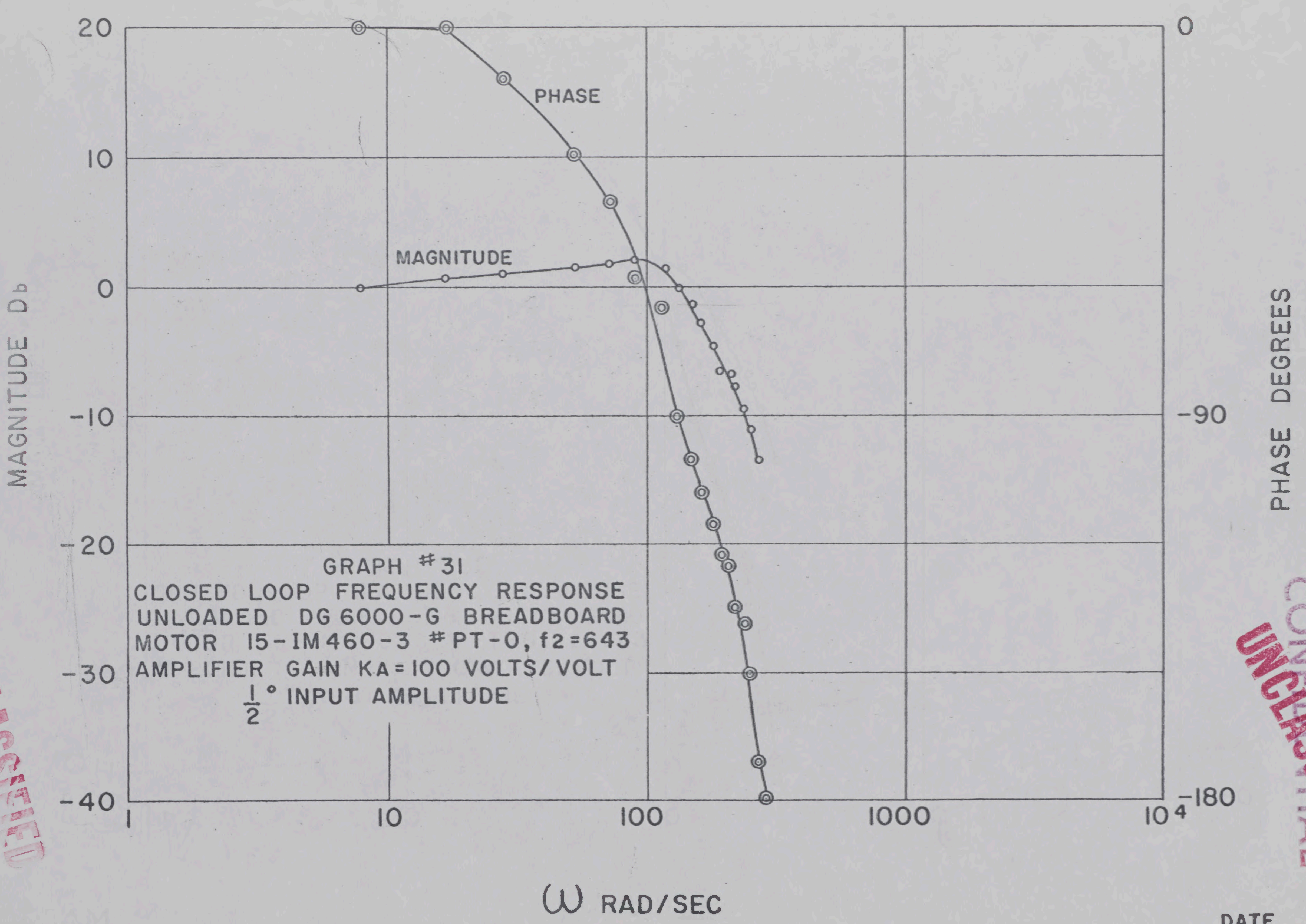

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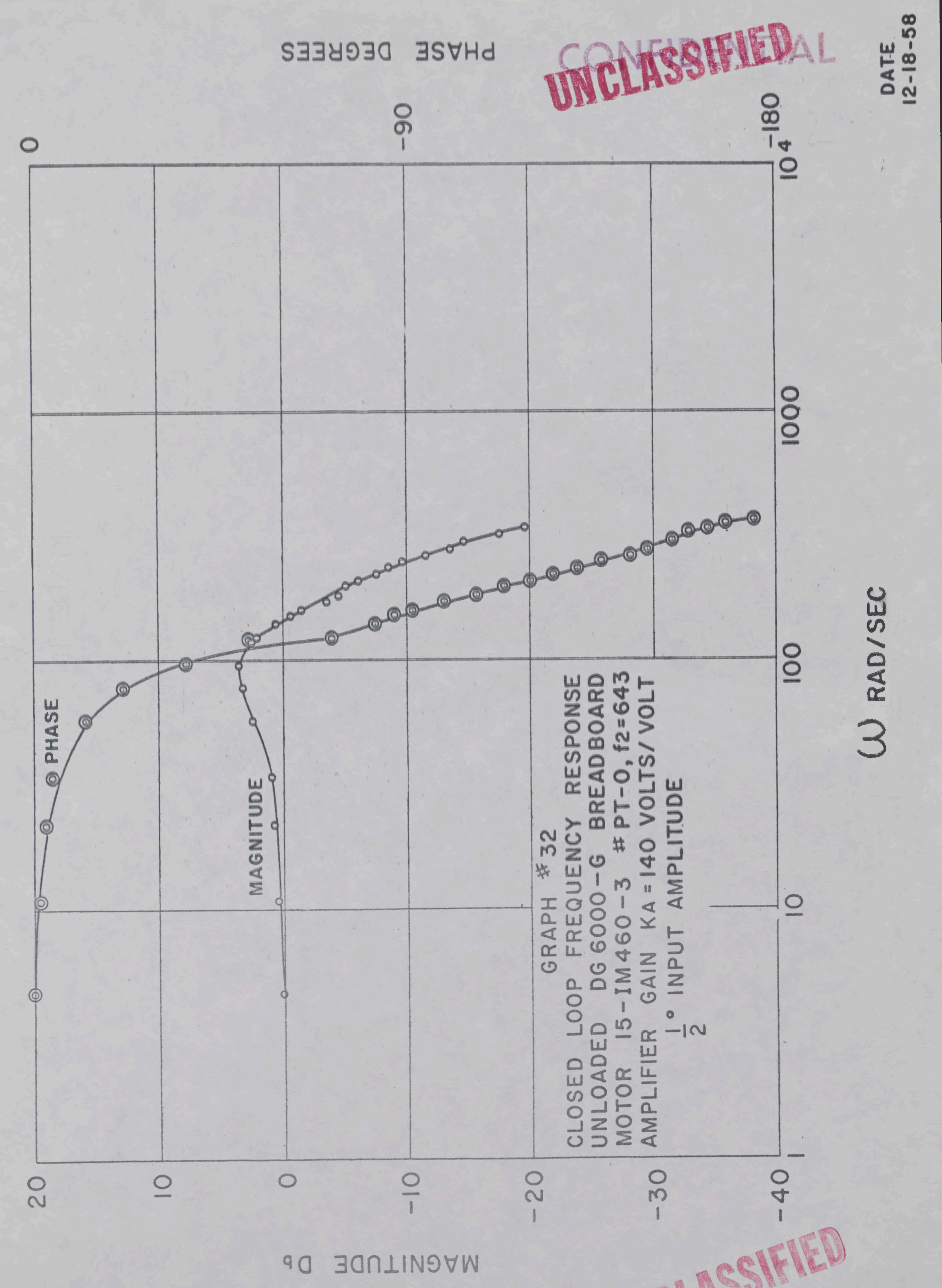

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TITLE: Termination Report on 3 AXIS Repeater for ASTRA/CF 105

RETENTION

(1) The attached document has been incorporated in the Technical Reference Library as Item 15-105 and is tentatively indexed as follows:

(I) Fire Control System - ASTRA

(II) A/C CF 105

(III) Report - Termination

(IV)

(V)

(VI)

Any requests for loan of this document or changes to the tentative index should be minuted on the reverse of this form for action on completion of circulation.

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