25 METER - MILLIMETER WAVE TELESCOPE

MEMO # 15

NATIONAL RADIO ASTRONOMY OBSERVATORY

MEMORANDUM

November 18, 1974

To: L. King
B. Peery
W. Y. Wong
B. Turner

From: J. Payne

Subj: Draft of Proposal for "25-Meter Millimeter Wave Antenna Drive and Control System"

I would appreciate receiving your comments on the subject draft.

Please reply to the Tucson address.

Thank you.

JMP/cjd

Enclosure

25-METER MILLIMETER WAVE ANTENNA DRIVE AND CONTROL SYSTEM

John M. Payne

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25-METER MILLIMETER WAVE ANTENNA DRIVE AND CONTROL SYSTEM

John M. Payne

November 13, 1974

1.0 Introduction

The proposed drive system for the 25-m millimeter wave antenna is conventional in nature and requires no special development or components. The design task is further simplified by the absence of severe wind loads. During the past few years, high-accuracy, angular readout systems have become available and an inductosyn system to meet the required 22-bit position accuracy is now an "off the shelf" item.

A fairly detailed design for the azimuth axis is given and a pointing accuracy (at the readout point) of less than 0.5 arc sec RMS is predicted. The elevation axis design has not been included in detail; due to the lower frictional forces, it is a simpler design.

Similar designs have been undertaken by NRAO for our 36-ft millimeter radio telescope and our 45-ft portable antenna.

The components that have been picked out for this preliminary design may not be the most cost effective, but it is felt that a savings of certainly no greater than 20% would result from an intensive market survey.

2.0 Description of System

A block diagram of the drive system for the azimuth axis is shown in Figure 1.

As mentioned earlier, the telescope rotates on the 95-ft diameter azimuth track on four trucks, each truck having four wheels and two motors. This configuration results in an effective gear ratio between truck wheel and telescope axis of 30:1. Each drive motor is geared to an axle by a 345:1 gearbox resulting in an overall gear reduction of 10,350:1. To eliminate backlash in the gear-trains, the two motors on each truck "buck" or oppose each other over a certain torque range. For high required accelerations, the bucking is eliminated and the motors drive together. In normal tracking conditions, however, pairs of motors will be opposing. Directly coupled to each motor is a tachometer that is used to form a velocity servo loop. This velocity servo loop accepts a commanded velocity, in the form of an analog voltage, which is compared with the tachometer voltage and the difference used to drive the DC motor through a power amplifier. In the case of the azimuth axis, this speed range will vary from 0 to 40°/min or 0-1150 RPM at the motor shaft. The slew rate in elevation is 0-20°/min. To avoid exciting drive train resonances, the bandwidth of this velocity servo system is restricted to a few Hertz.

This drive arrangement is ideal for permanent magnet DC servo motors and transistor amplifiers. Similar drives (although not using wheel and track) have been used on all the Essco antennas and the NRAO designed servo system on the Essco 45-ft antenna.

The drive system may operate in two modes, auto track and manual slew. In the auto track mode the telescope moves to positions commanded by the computer. This position will normally change with time as the radio source moves with respect to the earth. The position commanded by the computer is compared with the actual telescope position in a digital subtractor. The subtraction will take place twenty times per second, the difference between the two positions being outputted from the subtractor as a 12-bit number. This binary number is then converted to an analog voltage and applied to the velocity loop as a velocity command. This forms a closed-position servo loop, in which the output of the digital subtractor is kept close to zero. The departures from this ideal situation and the magnitude of the position error is dealt with in greater detail in the servo design section.

In the manual slew mode the telescope operator may generate velocity commands by means of a joystick control on the console to manually drive the telescope to any desired position. A coarse readout on the control console generated from the 12 most significant bits of the position readout permit the position of the telescope to be read to 0.1° for manual drive.

2.1 Torque Requirements

The maximum torque required of the drive system is the summation of many separate torques. Not all are likely to occur simultaneously, but a conservative design requires the assumption that they will. These torques for the azimuth axis are listed below.

	Torque, ft-lbs
Torque due to circulating wind currents, assumes 6 MPH from worst possible direction	9.7×10^3
Acceleration torque. Torque needed to accelerate drive trains and structure at 0.25°/sec^2	7.18×10^4
Total friction torque at 40°/min	1.33×10^4
Total torque required	9.48×10^4

Assuming reasonable gearbox efficiencies, this comes out to be approximately 1.2 ft-lbs at each motor shaft. This assumes no torque bucking and no safety margin and a motor with at least a continuous rating of 3 ft-lbs would be desirable. A suitable motor is manufactured by the H. K. Porter Company and has a continuous torque rating of 6 ft-lbs. The motor is provided with a brake assembly that is rated at 15 ft-lbs and a tachometer. Complete specifications are given in section 3.0.

The elevation torque requirements are given below:

	Torque, ft-lbs
Torque due to circulating wind currents	9.7×10^3
Acceleration torque	15.4×10^3
Total friction torque	4×10^3
Total torque required	29.1×10^3

Assuming two drive motors, this comes out to be approximately 0.8 ft-lbs per motor. It is convenient to keep both the azimuth and elevation drive motors the same, and this also gives a good safety margin.

2.2 Position Readout

To achieve the pointing accuracy required, at least 22 bits of accuracy are required to the position encoder. This corresponds to 0.31 arc seconds of resolution.

Optical encoders are considered reliable up to 20 bits of resolution, but for greater resolution their use becomes questionable.

Inductosyns offer greater reliability than optical encoders and are made to offer accuracies of up to 24 bits. An inductosyn operates in somewhat the same principle as a synchro, utilizing an inductive coupling principle basically more immune to dust and moisture than an optical encoder. There are three manufacturers of this kind of instrument in the U. S. and two have been contacted for a verbal price quote. It is probably worth mentioning that one of these companies has provided the Smithsonian Institute with a 24-bit system for a multiple mirror array.

The detailed specifications of the inductosyn are dealt with in greater detail in section 3.0.

2.3 Servo Design

2.31 Tachometer Loop

A model of the azimuth drive system is shown in Figure 2. If we assume that the structure is stiff in comparison to the gearbox, i.e., $K_R > K_g$, then the antenna inertia may be transferred to the other side of the gearbox. This assumption leads to the simplified model of Figure 3 showing one-quarter of the azimuth drive, two opposing motors on one truck. An analysis of this model yields the following expressions.

$$\frac{\Theta_L}{\Theta_M} = \frac{2K_g}{J_L S^2 + B_L S + 2K_g}$$

$$\frac{\Theta_M}{V_{in}} = \frac{K \quad (J_L S^2 + B_L S + 2K_g)}{J_M J_L S^4 + (J_M B_L + B_M J_L)S^3 + (J_L K_g + B_M B_L + 2K_g J_M)S^2 + (B_L K_g + 2K_g B_M)S}$$

where S is the operator $\frac{d}{dt}$.

In all these computer generated plots M represents magnitude and P the phase,

These two functions for this antenna are plotted as a function of frequency in the plots shown in Figure 5. We would expect Θ_L to be $\frac{1}{10,350}$ (-80 dB) of Θ_M at low frequencies, peak at the locked rotor frequency with abrupt phase change and then decrease rapidly.

$\frac{\Theta_M}{V_{in}}$ shows an integrator characteristic (gain falling off at 20 dB/decade and phase shift of 90°) at low frequencies with increased phase shift as the locked rotor frequency is approached. The locked rotor frequency of 23 rads/sec (3.66 Hz) is reasonable for this type of structure.

A block diagram of the complete servo system is shown in Figure 4.

The open loop Bode plot for the tachometer loop is shown in Figure 6 and has a phase margin of 40°, an entirely acceptable value.

The overall gain of the tachometer loop is 160 RPM/volt.

2.32 Position Loop

The position loop described here is a type II system, that is, it uses two integrators. Such a system has the advantage of having a theoretical zero tracking error at constant velocity while generating a constant torque.

Two integrators in the loop mean an unstable loop unless some means of compensation is employed. In this case a phase advance network is used to give a phase margin of 40°. This is shown in the Bode plot on Figure 7. The closed loop response of the position loop is given in Figure 8. The bandwidth of the loop is 1.0 Hz, once again a very reasonable value.

The response of the system to a position step command of 1 arc minute is shown in Figure 9.

2.33 Anticipated Performance of Tracking System

An analysis of the errors of this type of system usually concentrate on wind generated torques which will, of course, be absent in this case. As mentioned previously, a type II system has theoretically a zero position error under steady tracking conditions and the actual errors will be predominated by stick-slip friction effects. An analysis of this effect is possible but is time consuming, and experience has shown that this type of analysis does not generally give accurate answers. Probably the best guide is the past performance of existing antennas under windless conditions.

Figure 10 shows position errors during tracking for two NRAO antennas, the 36-ft millimeter wave antenna and the 45-ft portable antenna. It will be noticed that the tracking errors in both cases are 5 bits peak to peak, giving an RMS error of approximately 1.25 bits.

With a 22-bit inductosyn we would therefore expect an RMS error of approximately 0.4 arc sec.

Calculations of the effect of varying drag in the cable wrap and the variation in wind currents around the antenna indicate that errors from both these sources will be negligible.

3.0 Component Details

3.1 Inductosyns

Manufacturer	Owens-Illinois, Fecker Systems Division
Transducer	1024-pole, ± 0.5 arc second Inductosyn plates, 2-pole size 15 resolver, preamps and flexible coupling.
Static Accuracy	± 0.5 arc second
Repeatability	0.1 arc second
Weight	≈ 80 pounds
Flexible Coupling/Driving Axis Alignment	
Angular	± 1.5 arc minutes
Axial / Radial } Combined	± .01 inch
End Play	± .01 inch
Electrical Interface	200 ft cable, with no degradation of accuracy.
Digital Conversion Electronics .	All solid-state; SSI, MSI and 5% discrete components
Resolution	2^{-24} revolution (.077 arc sec)
Static Accuracy	± 2^{-23} revolution (± 0.31 arc sec)
Dynamic Accuracy	1 arc sec/rad/sec
Repeatability	2^{-23} revolution
Rate Following	> 30°/sec
Package Configuration	7" x 19" enclosed chassis. Front panel controls, rear panel connectors. Illuminated PB switches, except for rotary Self Test Function switch.
Power Requirements	115 V, 60 Hz at 2 amps.

3.2 Motor Specifications

Manufacturer	H. K. Porter Model #DFT4 K7708.
Frame Size	Nema 56.
Torque Constant	5.36 in-lbs/amp.
Back EMF	63.4 V/1000 RPM.
Inertia	0.1043 in-lbs-sec^2.
Armature Resistance	0.54 ohm.
Voltage at Peak Torque	54 volts.
Static Friction	2.85 in-lbs.
Viscous Friction	0.082 in-lbs/rad/sec.
Insulation	Class F.
Tachometer Outpout	31.5 V/1000 RPM.
Inductance	2.43 mH.

3.3 Amplifier Specifications

Manufacturer	Control Systems Research.
Model Number	NC 202.
Current Rating	± 20 A constant, 40 A peak.
Maximum Output Voltage	± 115 V.
Bandwidth	1 kHz.
Mode of Operation	Current driver.
Power Supply	220 V, 3 phase.

3.4 Brake Specifications

Manufacturer	Stearns, Inc.
Model Number	1-055-752-5.
Torque Rating	15 ft-lbs.

3.4 Brake Specifications (continued):

Moment of Inertia .... 0.0126 lb ft^2

These brakes are designed to interface directly to the motor.

4.0 Cost Estimate

The following is a material cost estimate for the major part of the control system. The estimate includes spare parts and is in 1974 dollars.

	Cost K$
Position readout system for two axes and one spare	$ 51.0
Motors for both axes and two spares	10.98
Brakes for both axes and two spares	4.20
DC amplifiers for both axes and two spares	18.08
Control panel and coarse readout	3.00
Miscellaneous electronics	5.00
Cabling and hardware	5.00
Total	$ 97.26
Contingency approximately 20%	$122.0

The estimated labor required to construct such a system is given below:

	Months
Engineering time	2
Technician time	6
Installations	2

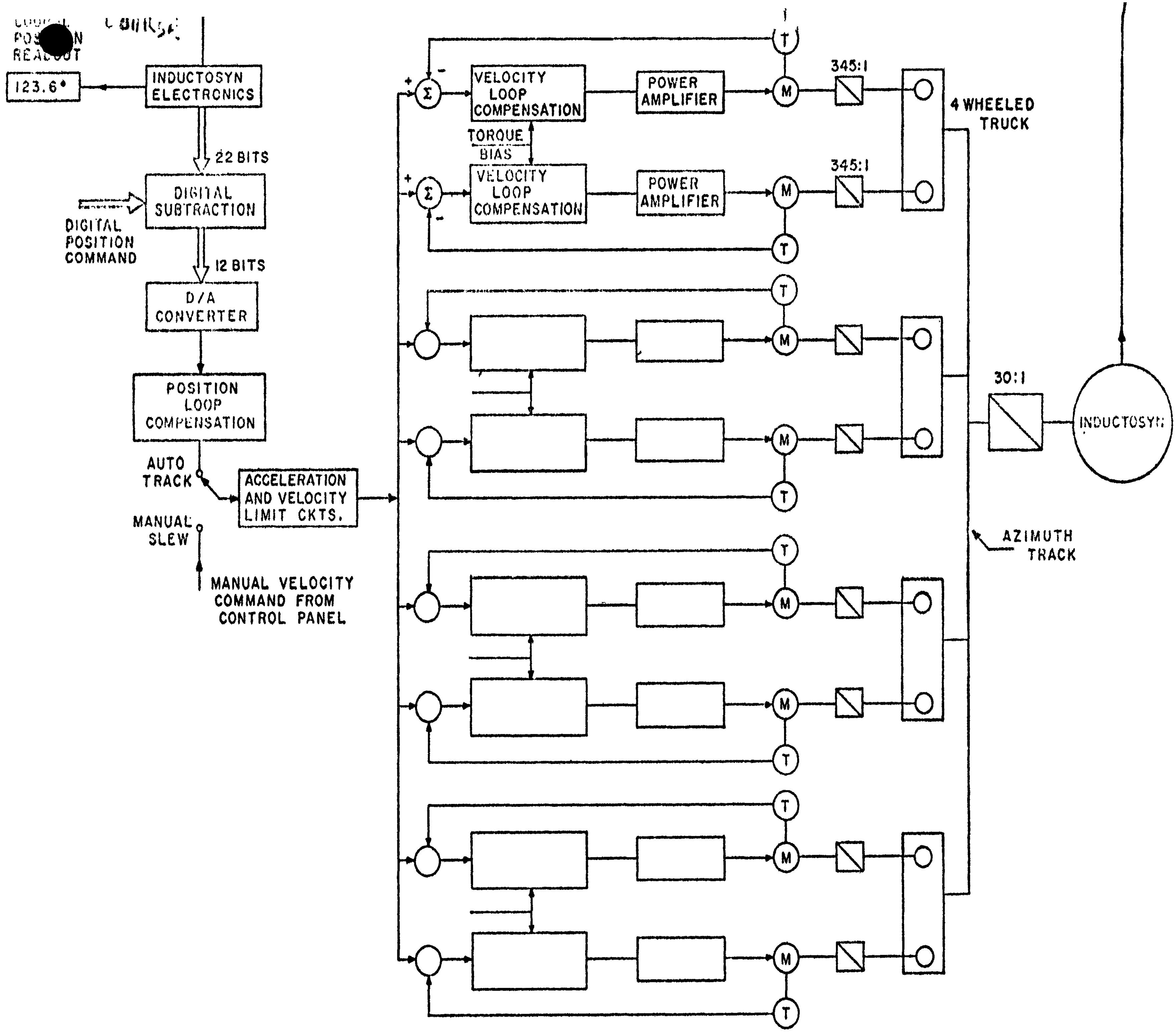


FIG. 1 BLOCK DIAGRAM OF AZIMUTH DRIVE

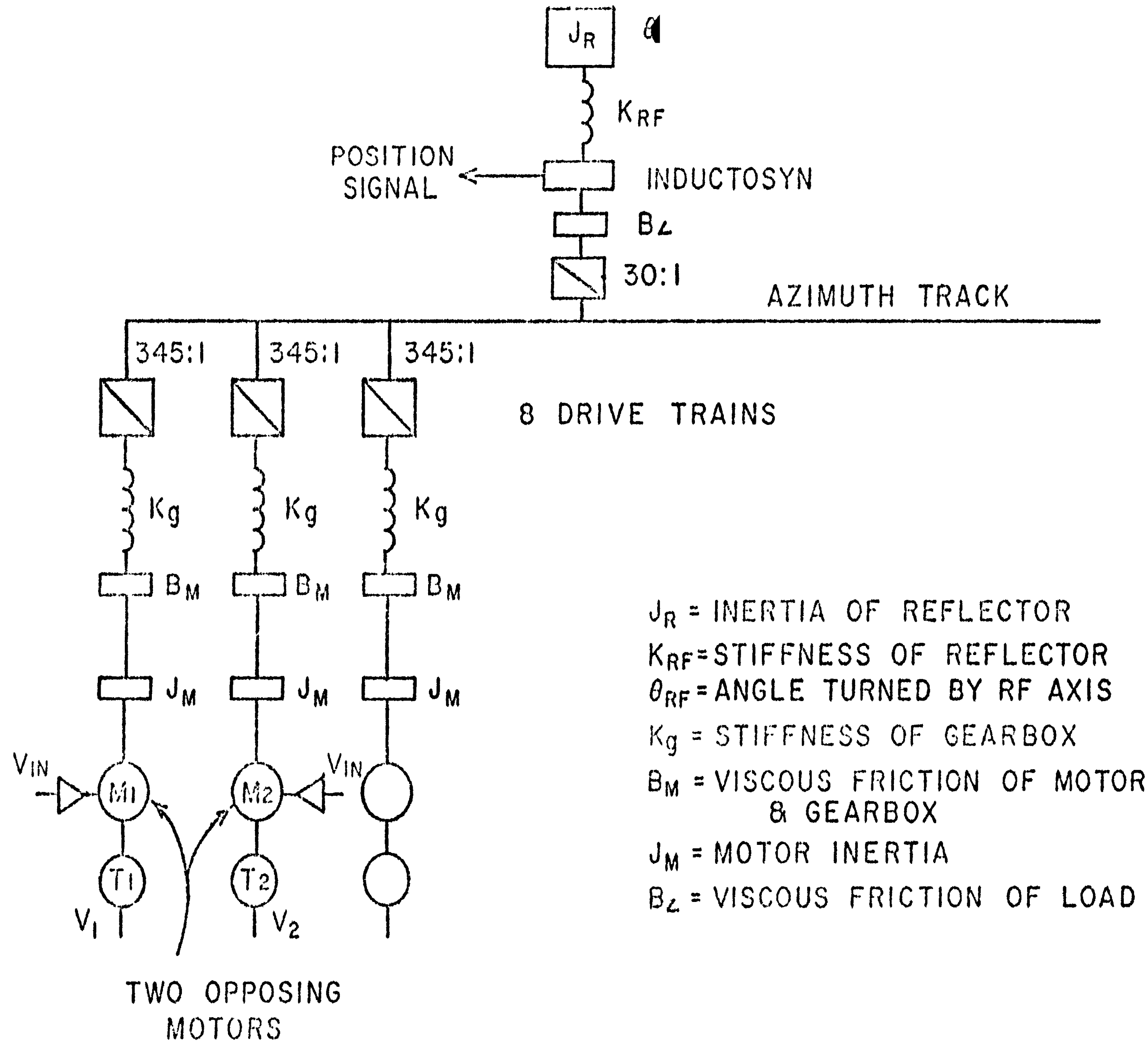
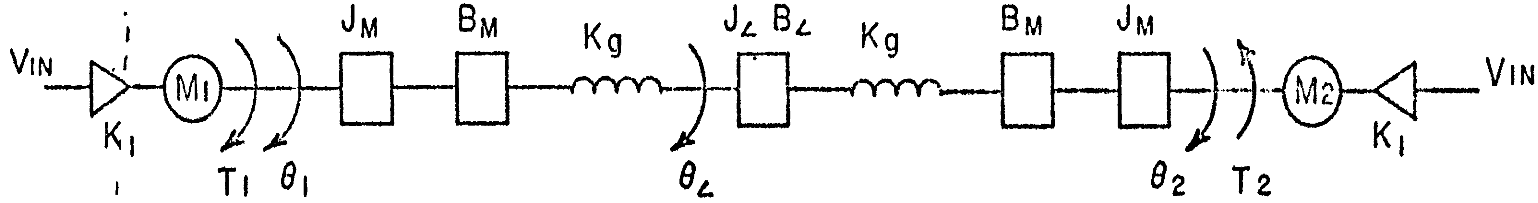


FIG. 2 MODEL OF ONE AXIS OF DRIVE SYSTEM



T_1 = TORQUE FROM MOTOR 1

T_2 = TORQUE FROM MOTOR 2

θ_1 = ANGLE TURNED BY MOTOR 1

θ_2 = ANGLE TURNED BY MOTOR 2

θ_L = ANGLE TURNED BY LOAD

B_L = VISCOUS FRICTION OF LOAD (REFERRED TO MOTOR)

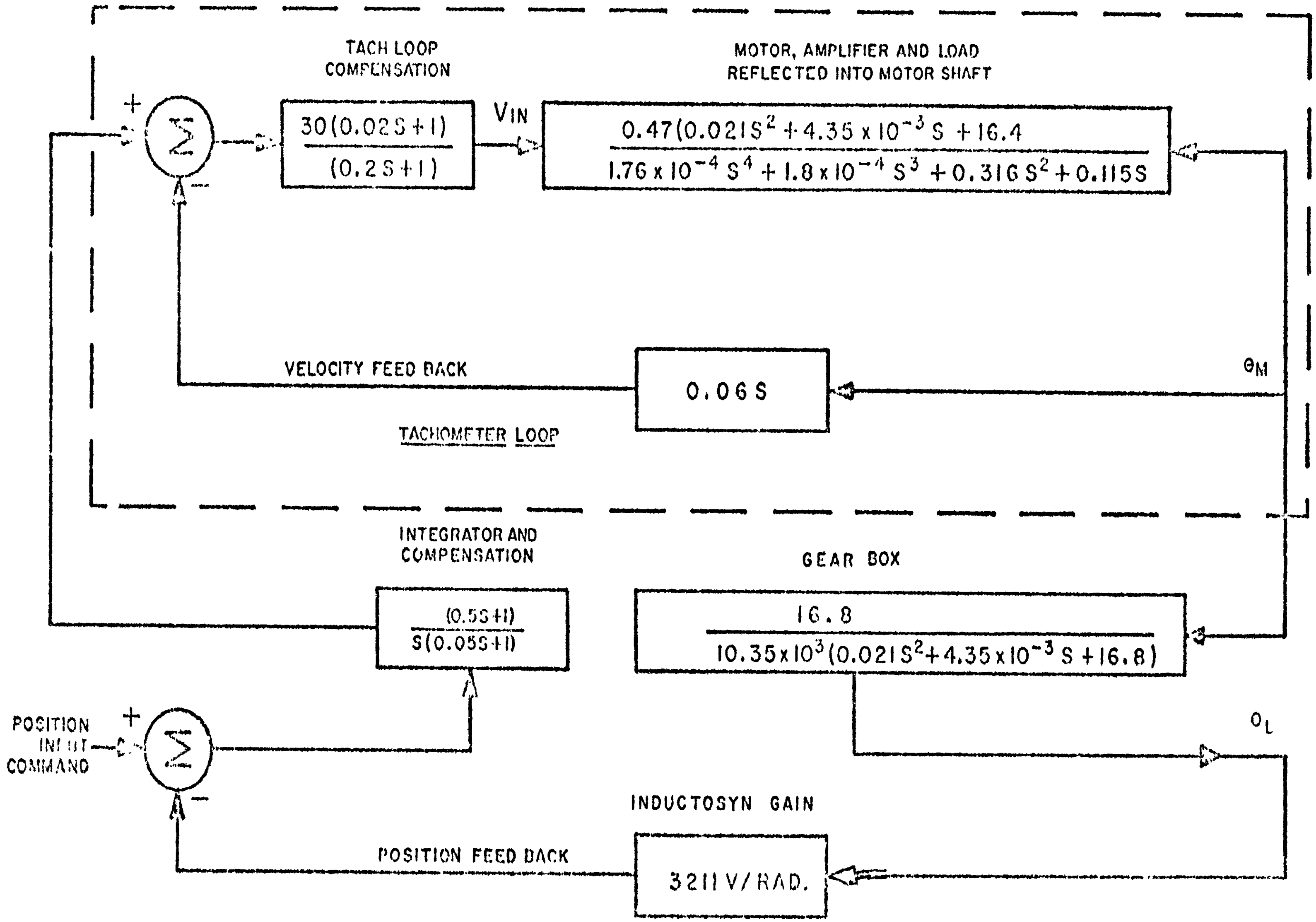
B_M = VISCOUS FRICTION OF MOTOR

J_L = LOAD INERTIA (REFERRED TO MOTOR)

K_g = GEARBOX STIFFNESS (REFERRED TO MOTOR)

K_1 = AMPS/VOLT OF AMPLIFIER

FIG. 3 SIMPLIFIED MODEL OF ONE AXIS



BLOCK DIAGRAM OF SERVO SYSTEM

FIG. 4

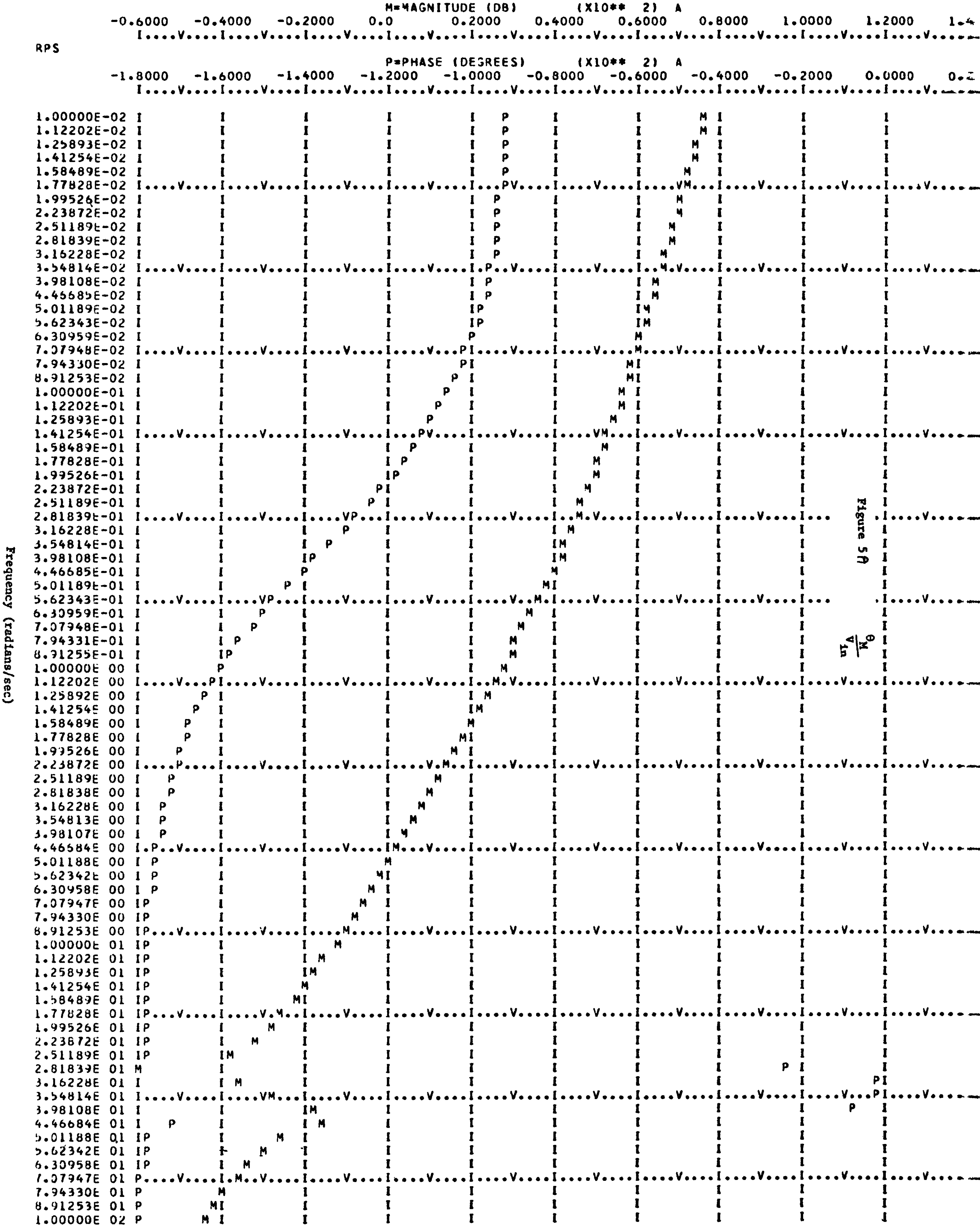
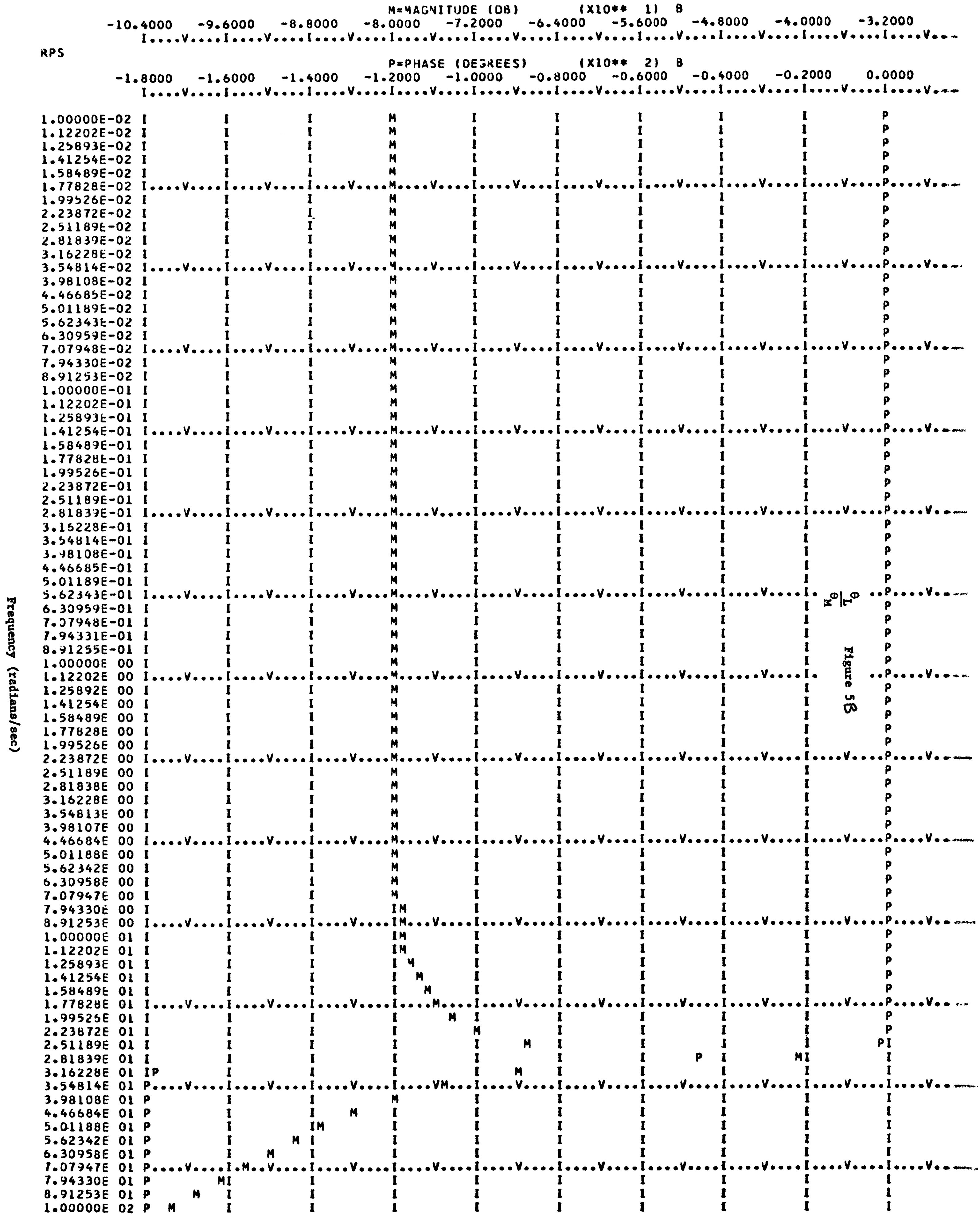

M=MAGNITUDE (DB) (X10** 2) A
-0.6000 -0.4000 -0.2000 0.0 0.2000 0.4000 0.6000 0.8000 1.0000 1.2000
P=PHASE (DEGREES) (X10** 2) A
-1.8000 -1.6000 -1.4000 -1.2000 -1.0000 -0.8000 -0.6000 -0.4000 -0.2000 0.0000
RPS
Frequency (radians/sec)
$\frac{\theta_M}{V_{in}}$

Figure 5A


M=MAGNITUDE (DB) (X10** 1) B
-10.4000 -9.6000 -8.8000 -8.0000 -7.2000 -6.4000 -5.6000 -4.8000 -4.0000 -3.2000
RPS
P=PHASE (DEGREES) (X10** 2) B
-1.8000 -1.6000 -1.4000 -1.2000 -1.0000 -0.8000 -0.6000 -0.4000 -0.2000 0.0000
1.00000E-02
1.12202E-02
1.25893E-02
1.41254E-02
1.58489E-02
1.77828E-02
1.99526E-02
2.23872E-02
2.51189E-02
2.81839E-02
3.16228E-02
3.54814E-02
3.98108E-02
4.46685E-02
5.01189E-02
5.62343E-02
6.30959E-02
7.07948E-02
7.94330E-02
8.91253E-02
1.00000E-01
1.12202E-01
1.25893E-01
1.41254E-01
1.58489E-01
1.77828E-01
1.99526E-01
2.23872E-01
2.51189E-01
2.81839E-01
3.16228E-01
3.54814E-01
3.98108E-01
4.46685E-01
5.01189E-01
5.62343E-01
6.30959E-01
7.07948E-01
7.94331E-01
8.91255E-01
1.00000E 00
1.12202E 00
1.25892E 00
1.41254E 00
1.58489E 00
1.77828E 00
1.99526E 00
2.23872E 00
2.51189E 00
2.81838E 00
3.16228E 00
3.54813E 00
3.98107E 00
4.46684E 00
5.01188E 00
5.62342E 00
6.30958E 00
7.07947E 00
7.94330E 00
8.91253E 00
1.00000E 01
1.12202E 01
1.25893E 01
1.41254E 01
1.58489E 01
1.77828E 01
1.99526E 01
2.23872E 01
2.51189E 01
2.81839E 01
3.16228E 01
3.54814E 01
3.98108E 01
4.46684E 01
5.01188E 01
5.62342E 01
6.30958E 01
7.07947E 01
7.94330E 01
8.91253E 01
1.00000E 02
Frequency (radians/sec)
$\frac{\theta_L}{\theta_M}$
Figure 5B

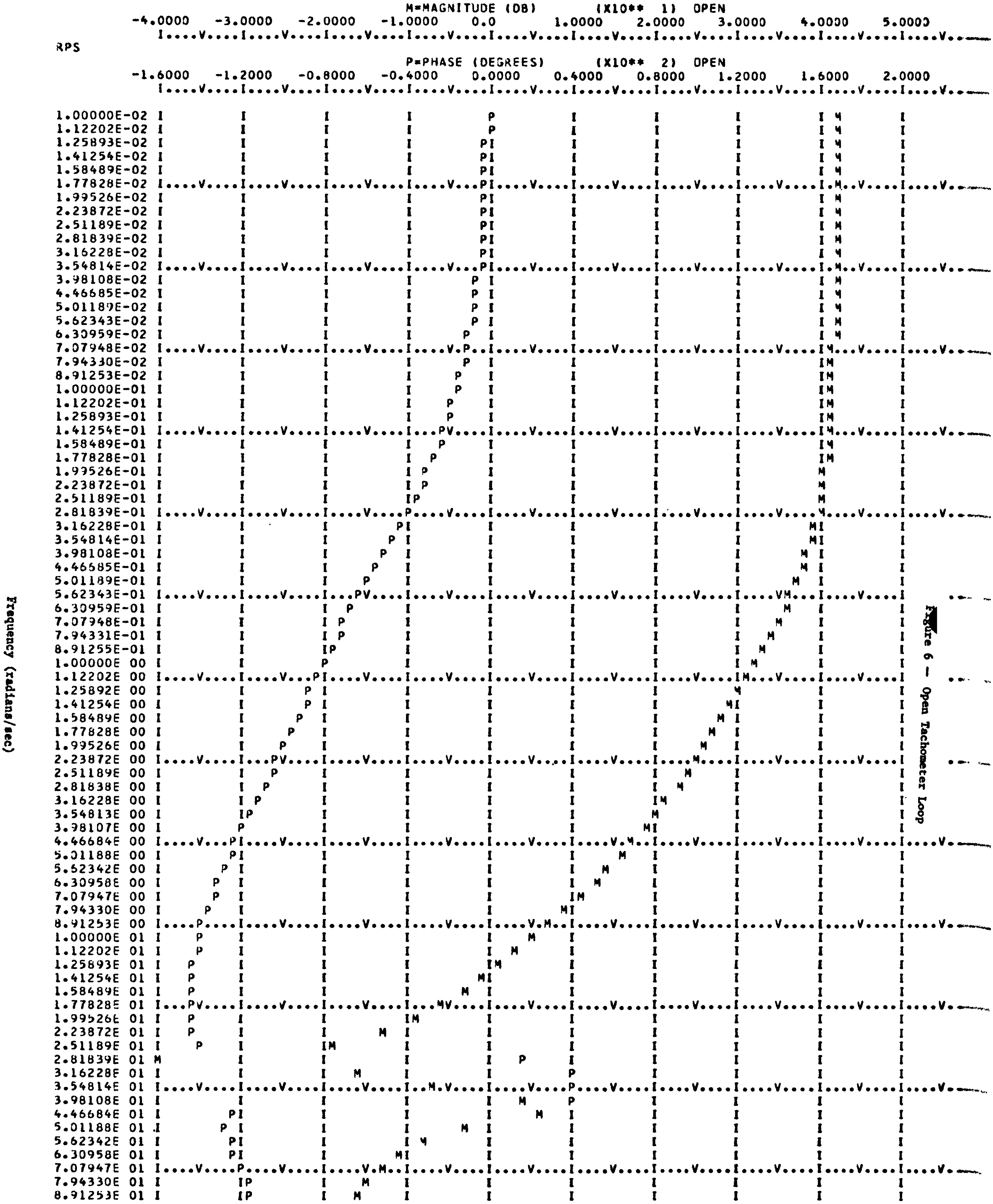


Figure 6 — Open Tachometer Loop

1 PROCESSED ROOTS FOR CLOS MULTIPLIER = (1.6823845E 00)*10** 2

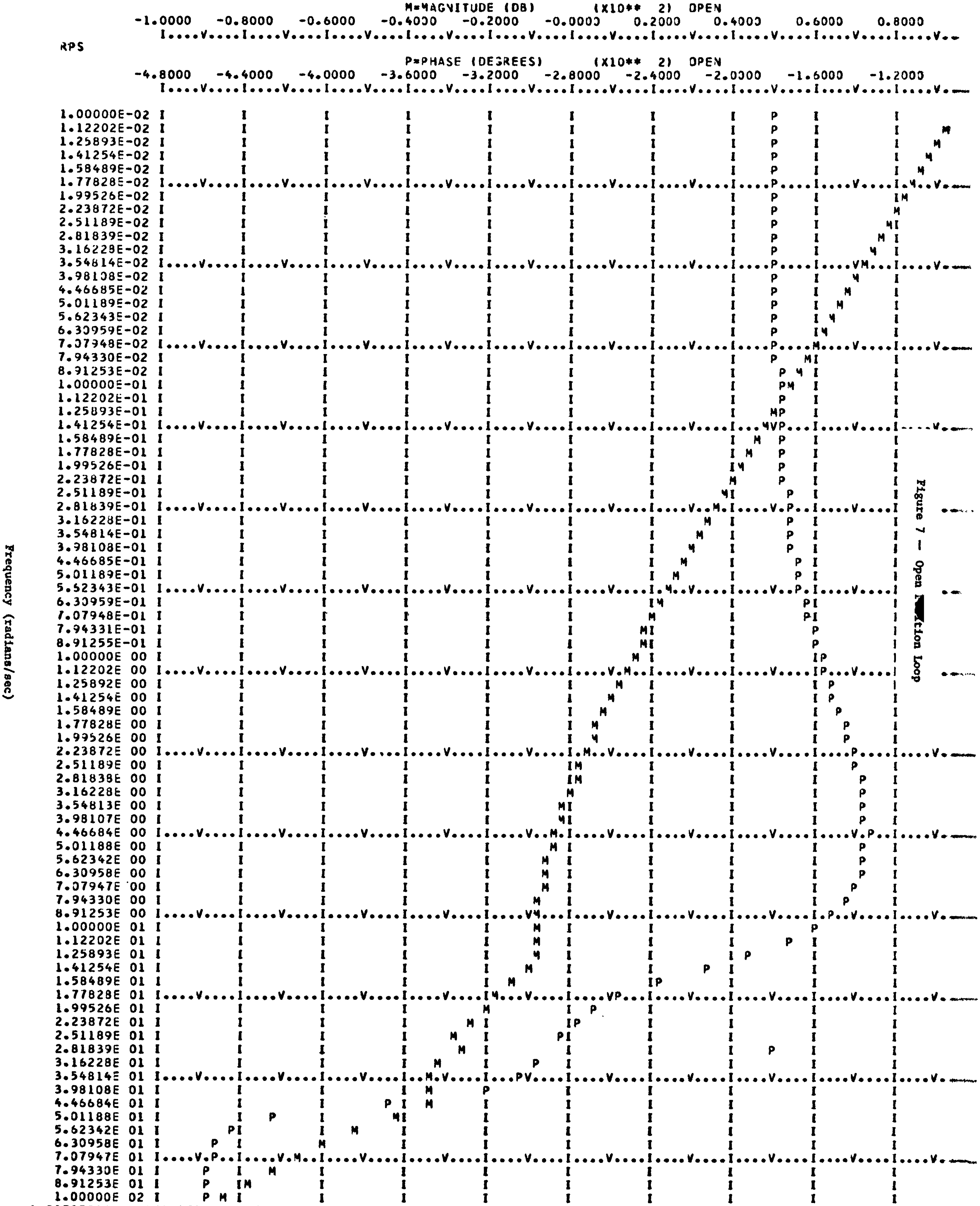
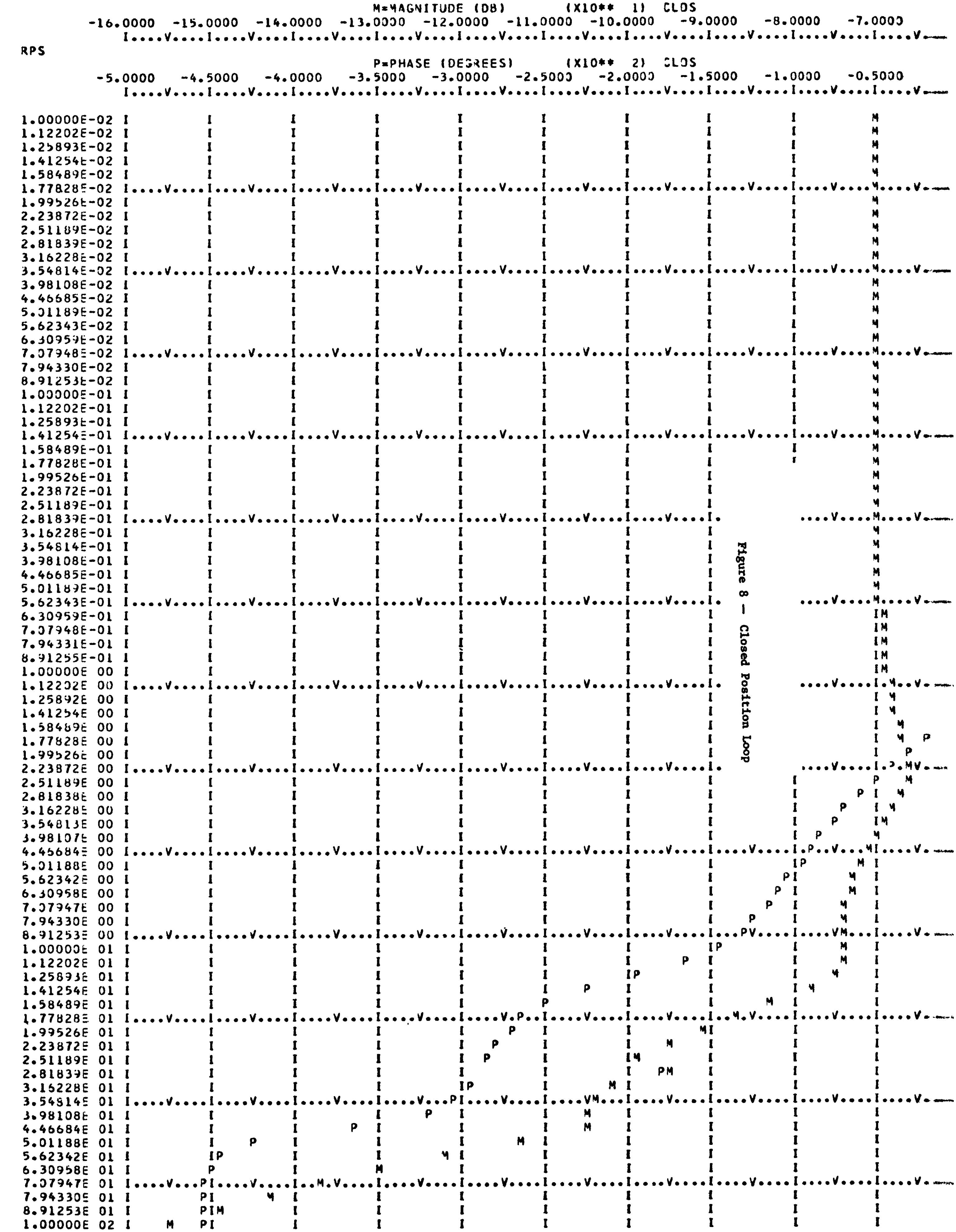


Figure 7 — Open [redacted]tion Loop

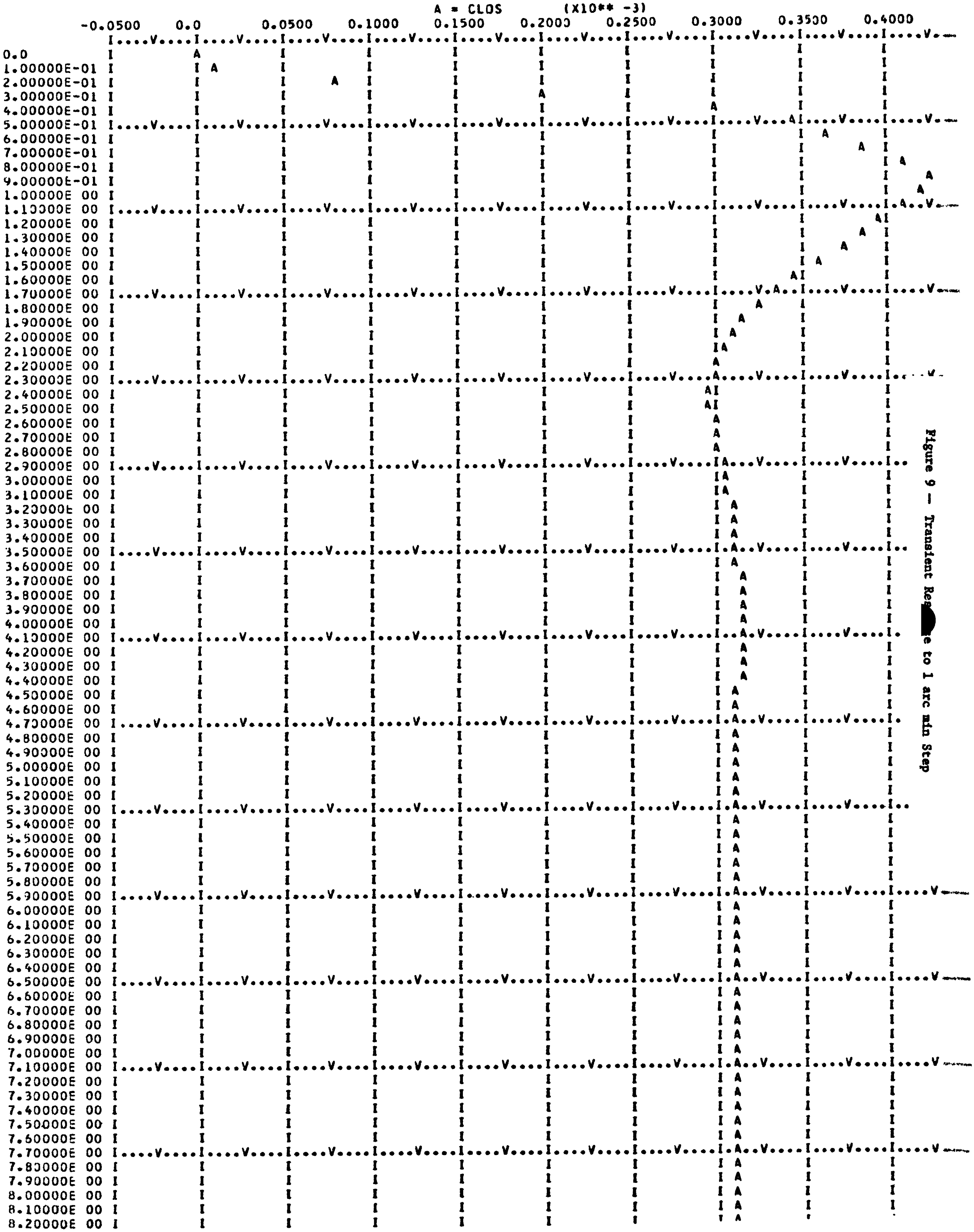
1 PROCESSED ROOTS FOR CLOS MULTIPLIER = (1.3003922E 00)*10** 2



Frequency (radians/sec)

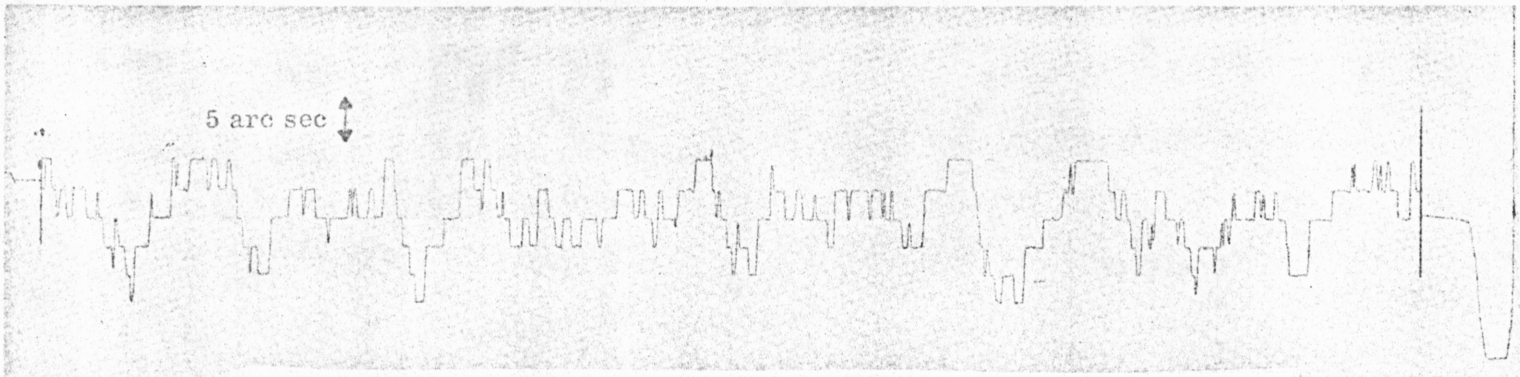
Figure 8 — Closed Position Loop

1 PROCESSED ROOTS FOR CLOS MULTIPLIER = (1.3003922E 00)*10** 2

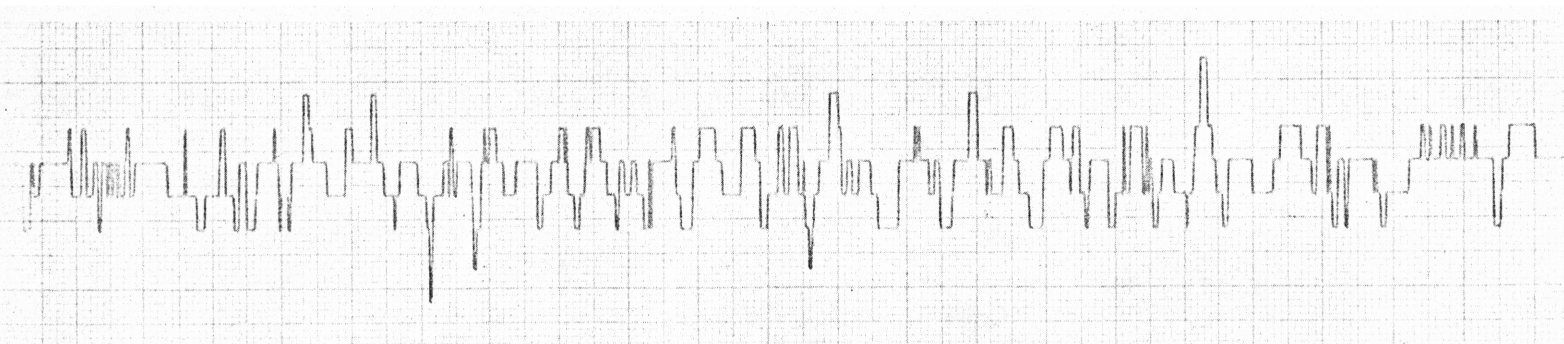


Time, seconds.

Figure 9 — Transient Re[illegible]e to 1 arc min Step



45-ft Tracking Error, 1 bit = 4.94 arc sec, 5 bits p/p error.



36-ft Tracking Error, 1 bit = 1.24 arc sec, 5 bits p/p error.

Figure 10

Stick-Slip operation in servo is mainly the results of the difference between static friction and dynamic friction.

Type 0 (Type II ?) position servo system shows the existance of a stick-slip problem at low tracking speed.

Difference betwe Type I servo (velocity) and Type 0 servo (position)

Type I servo has error integration function thus produce no positional (or tracking) error.

Type 0 servo will show the tracking error. because the error integration function is minimized, limit cycle is magnified!

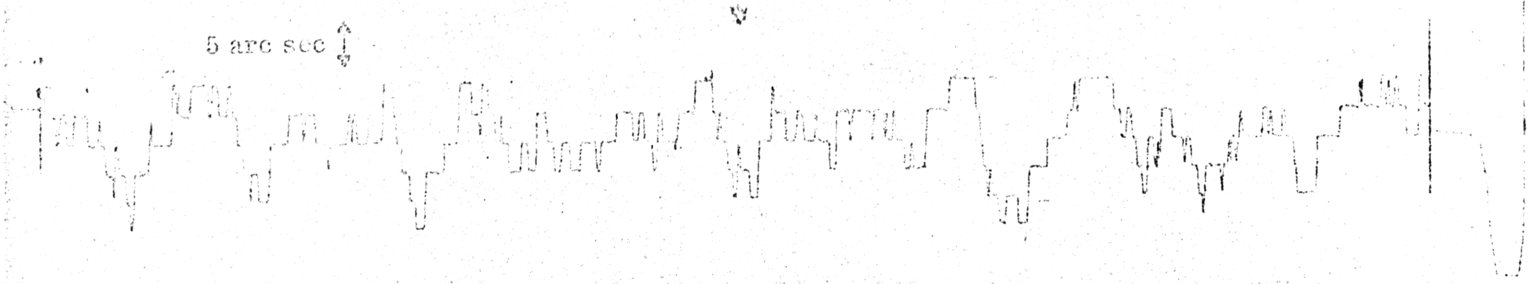
Servo characteristics:

Load inertia, F_S, F_D — Not practical to modify

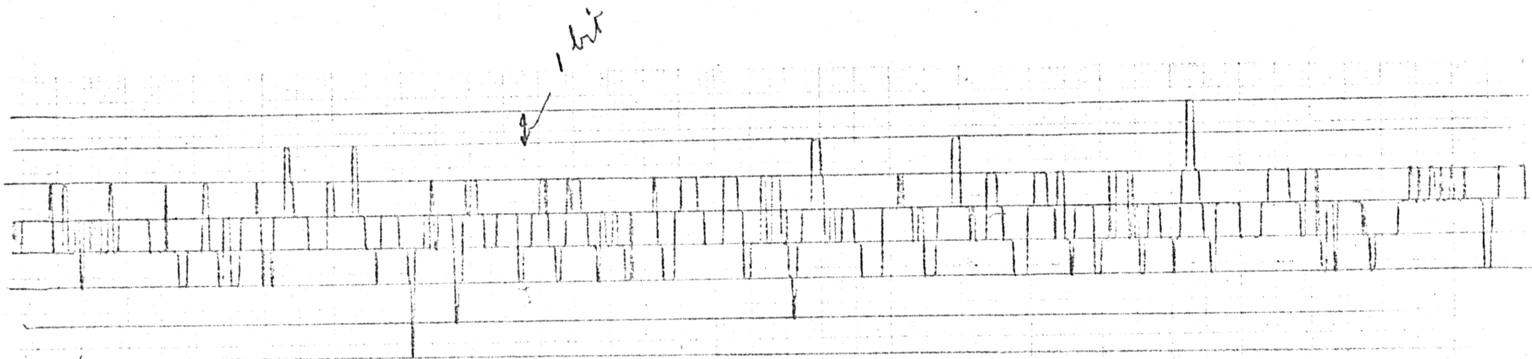
Gain, damping, f_n (servo) — To be modified.

Demands: Limit cycle freq. and amplitude are far from the close lopp frequency

Limit cycle operation: load oscillating around the true position by alternatively overshooting in each direction. Either during tracking or at steady state.



45-ft Tracking Error, 1 bit = 4.94 arc sec, 5 bits p/p error.



36-ft Tracking Error, 1 bit = 1.24 arc sec, 5 bits p/p error.

Figure 10