

AC SPARK PLUG DIVISION General Motors Corporation Milwaukee, Wisconsin					XDE 34-S-529	
PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT					ENGINEERING DESIGN INFORMATION EXHIBIT	
					By A. Laubenstein	
<p style="text-align: right;"><i>Rec'd 10-30-63</i></p> <p>1. SCOPE</p> <p>This specification establishes the preliminary performance requirements for the three Inertial Subsystem Coupling Display Units (CDU) of the APOLLO G&amp;N System, Block I.</p> <p>2. APPLICABLE DOCUMENTS</p> <p>The following documents form a part of this specification to the extent specified herein.</p> <p>APOLLO G&amp;N Specifications</p> <p>PS-1000030 Resolver 1X Transmitter  PS-1000160 Resolver 16X Transmitter  PS-1010341 Resolver 1X Receiver  PS-1010351 Resolver 16X Receiver  ND-1002132 Resolver 1/2X Receiver  ND-1002195 Servo Motor-Generator</p> <p>Drawings</p> <p>1010034 Encoder Electronics  1010035 Motor Drive Amplifier  1010036 Schem. Diagram CDU  1010041 Digital to Analog Conv.  1015550 CDU Gear Box Mech. Schem.  1015560 Inertial Subsystem Mech. Drawing</p> <p>Interface Control Documents</p> <p>ICD 01-50004 D.C. Power Supply  ICD 01-50027 Thermal Environment</p> <p>XDE's</p> <p>XDE 34-S-525 Power Supplies</p>						
Rev.					Page 1 of 42	XDE

## AC SPARK PLUG DIVISION

General Motors Corporation  
Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
DESIGN INFORMATION  
EXHIBITPRELIMINARY PERFORMANCE SPECIFICATION  
INERTIAL COUPLING DISPLAY UNITBy  
A. LaubensteinDate  
8/15/63

## 3. REQUIREMENTS

## 3.1 GENERAL

The three coupling display units of the Inertial Subsystem shall provide a coupling between the AGC or the astronaut and the IMU or the SCS, so that either the computer or the astronaut may drive the CDU gear train and thereby have the CDU resolvers transmit this information to either the IMU or the SCS. The CDU shall also provide the astronaut with a visual readout of the CDU shaft position during any system mode of operation.

Desired angles shall be transmitted by the CDU to the IMU and SCS in analog form while the CDU shall also be capable of following up the IMU gimbal angles and transmitting this information to the computer in digital form.

## 3.2 INPUTS

The CDU loops must maintain adequate performance under the following disturbance, power, and environmental inputs.

## 3.2.1 DISTURBANCE INPUTS -- (Reference ND-1002037)

- a. Acceleration -- 21g max.
- b. Shock -- 15g peak
- c. Vibration -- Section 4.9 of ND-1002037

## 3.2.2 POWER INPUTS

3.2.2.1 GUIDANCE AND NAVIGATION INPUT POWER -- D.C. power will be supplied to the APOLLO Guidance and Navigation equipment from the APOLLO spacecraft. Some of the variations in the D.C. power supply as given in ICD 01-50004 are as follows:

- a. Voltage -- D.C. supply voltage variations in the range of 25 to 30 vdc.
- b. Transients -- 21 to 30 volts D.C. The minimum shall be 21 volts, and it shall return to the specified 25-30 volt level within 0.1 seconds.
- c. Ripple Voltage -- The ripple, if any, shall be at a frequency of 400 cps or greater having a peak to peak excursion of no more than 250 mv.

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8/15/63

3.2.2.2 INERTIAL SUBSYSTEM GENERATED INPUT POWER -- Power will be supplied to the CDU loops from the 28 V 1% 800 $\sim$  / 0°, the 28 V 5% 800 $\sim$   $\angle$ -90°, and the 2.5 v 25.6 Kc sources in the ISS. Some of the characteristics of these supplies, as given in XDE 34-8-525, are as follows.

3.2.2.2.1 28V 1% 800 $\sim$  SUPPLY

- a. Voltage - The amplitude shall be 28 V rms  $\pm$  1%.
- b. Frequency - The frequency shall be 800 $\sim$   $\pm$  2 ppm.
- c. Harmonic Distortion - The harmonic distortion shall be less than 1%.

3.2.2.2.2 28 V 5% 800 $\sim$  SUPPLY

- a. Voltage - The amplitude shall be 28 v rms  $\pm$  5%.
- b. Frequency - The frequency shall be 800 $\sim$   $\pm$  2 ppm.
- c. Harmonic Distortion - The harmonic distortion shall be less than 5%.
- d. Phase Shift - The phase shift shall be 270  $\pm$  10° w.r.t. the 800 $\sim$  1% supply output.

## 3.2.2.2.3 2.5V, 25.6 Kc SUPPLY

- a. Voltage - The amplitude shall be 2.5 v rms  $\pm$  5%.
- b. Frequency - The frequency shall be 25.6 Kc  $\pm$  2 ppm.
- c. Harmonic Distortion - The harmonic distortion shall be less than 5%.

## 3.2.3 ENVIRONMENTAL INPUTS

3.2.3.1 THERMAL ENVIRONMENT -- The thermal environment of the CDU loops shall be as stated in ICD 01-50027.

3.2.3.2 PRESSURE ENVIRONMENT - (to be defined)

3.2.4 DRIVING INPUTS -- The driving inputs to the CDU loop shall be as follows:

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	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

3.2.4.1 COMPUTER PULSES -- Pulses supplied by the computer as an input to the D/A converter in the coarse align, attitude control and entry modes shall have the following characteristics:

- a. Amplitude: 4.8 V  $\pm$  10% P.P.
- b. Width: 3  $\pm$  .5  $\mu$ sec
- c. Rise Time: Less than .1  $\mu$ sec
- d. Frequency: 3200 pps

3.2.4.2 GIMBAL SHAFT POSITION -- The location of the gimbal shaft shall provide an input to the CDU resolvers in the coarse align, manual CDU, fine align, entry and attitude control modes via the gimbal resolvers.

3.2.4.3 SLEW SWITCH -- The slew switch shall provide a constant amplitude 800  $\sim$  signal of zero or pi phase to the MDA in the manual CDU mode.

### 3.3 PERFORMANCE

The static and dynamic performance of the coupling display units, as determined in Section 6, shall be in accordance with the following specifications.

3.3.1 STATIC ACCURACY-- The sixteen speed resolver in-phase electrical output zero shall be defined as the CDU zero position. The one-half and one-speed resolver electrical outputs and the encoder electronics pulse output shall be aligned to this reference. The static accuracy of the CDU outputs referred to the ideal one-speed shaft position, upon completion of the various system functions, shall be as follows.

3.3.1.1 COMPUTER DRIVEN FUNCTION - NORMAL -- (With the AGC position comparison). With the AGC pulse train commanding some desired angle,  $\theta_c$ , into the CDU, the one-speed CDU resolver electrical output accuracy shall be within  $\pm 16$  min.

3.3.1.2 MANUAL OPERATION -- With a manual input into the CDU commanding some desired angle by referring to the dial indications -

- a. The one-speed CDU resolver electrical output accuracy shall be within  $\pm 16$  min.
- b. The dial reading accuracy shall be within  $\pm 1.2$  min.

3.3.1.3 FOLLOWUP FUNCTION -- With the gimbal angle position driving the CDU via the gimbal sixteen-speed resolver -

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<p style="text-align: center;">PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT</p>	<p style="text-align: center;">ENGINEERING DESIGN INFORMATION EXHIBIT</p>	
	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

a. The encoder electronics output shall indicate the gimbal angle within  $\pm 1.1$  min.

b. The dial reading accuracy shall be within  $\pm 1.3$  min.

3.3.1.4 COMPUTER DRIVEN FUNCTION - ENTRY -- (With the AGC position comparison). With the AGC commanding some desired angle,  $\theta_c$ , the sixteen-speed CDU resolver output accuracy shall be within  $\pm 17$  min.

3.3.2 MAXIMUM SETTling TIME -- The worst case or maximum time for each mode to come within tolerance of its final value shall be as follows:

a. Zero Encode - 30 secs. max. from any initial shaft position.

b. Coarse Align or Attitude Control - (20 secs.) max. for  $\pm 180$  degree command.

c. Manual CDU - 15 secs. max. for  $\pm 180$  degree command. (Slewing 10 secs., rundown 1.5 secs., and thumbing 3.5 secs.).

d. Fine Align - 2.5 secs. max. for a  $5^\circ$  offset between the gimbal and the CDU Shaft and 0.5 secs. max. for a 4 min. offset between the gimbal and the CDU shaft.

e. Entry - 2.5 secs. max. to move the sixteen-speed CDU shaft  $\pm 180^\circ$ .

3.3.3 DYNAMIC LAG ERRORS -- The CDU shaft nominal velocity lag in the "fine align" mode shall be as follows:

a. 0.05 sec. - sixteen-speed control

b. 0.90 sec. - one-speed control

The switch from sixteen-speed to one-speed control occurs when the input velocity is between 1.5 and 1.6 degrees per second.

3.3.4 FREQUENCY RESPONSE -- The CDU loops shall exhibit the following frequency response characteristics in the various operating modes.

#### 3.3.4.1 ZERO ENCODE MODE

a. Phase margin:  $80^\circ$  min. under both 1/2 and 16 speed cont.

b. Gain margin: 40 db min. under 1/2 X control  
20 db min. under 16 X control

c. 3 db bandwidth: 22 cps nom. under 16X control  
.8 cps nom. under 1/2X control

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<p style="text-align: center;"><b>PRELIMINARY PERFORMANCE SPECIFICATION</b> <b>INERTIAL COUPLING DISPLAY UNIT</b></p>	<p><b>ENGINEERING DESIGN INFORMATION EXHIBIT</b></p>	
	<p>By <b>A. Laubenstein</b></p>	<p>Date <b>8/15/63</b></p>

### 3.3.4.2 FINE ALIGN MODE

- a. Phase margin: 80° min. under both 1 and 16 speed control
- b. Gain margin: 40 db min. under 1X control  
20 db min. under 16X control
- c. 3 db bandwidth: 20 cps nom. under 16X control  
1.3 cps nom. under 1X control

### 3.3.4.3 COARSE ALIGN MODE

- a. Phase margin: 80° min.
- b. Gain margin: 30 db min.
- c. 3 db bandwidth: 3.6 cps nominal

## 3.4 COMPONENTS

The components which make up the three inertial subsystem coupling display units are identical for the outer, middle and inner gimbals. The interconnection of these components to form the CDU Loop is seen in Figure 1. Pertinent performance characteristics of the major components are as follows:

**3.4.1 MOTOR-GENERATOR** -- The servo motor-generator shall be an 800 cycle ac unit and shall drive the CDU gear train and produce a feedback signal proportional to the output shaft rate. (Ref. ND-1002195).

- a. Motor voltage constant at rated control voltage - 34.4 rad/sec. volt. nominal.
- b. Motor voltage constant at low control voltage - 68.8 rad/sec/volt nominal.
- c. Motor-generator time constant - 0.415 sec. nominal
- d. Generator sensitivity -  $9.55 \times 10^{-3}$  volts/rad/sec. nominal
- e. Starting voltage - 0.9 volts rms max.
- f. Generator total rms null - 8.0 mv max.
- g. Rotor inertia -  $5.5 \pm 20\%$  gm cm<sup>2</sup>
- h. Damping constant -  $13.27 \frac{\text{gm cm}^2}{\text{sec}}$  nominal

**3.4.2 MOTOR SHAFT LOAD** - The inertia load of the CDU shaft and gearing referred to the motor shaft shall be nominally 20.5 gm. cm<sup>2</sup>.

- a. Nominal motor-generator loaded time constant at rated control voltage - 1.96 secs.
- b. Nominal motor-generator loaded time constant at low control voltage - 3.92 secs.
- c. Motor starting voltage, loaded - 1.5 v rms max.

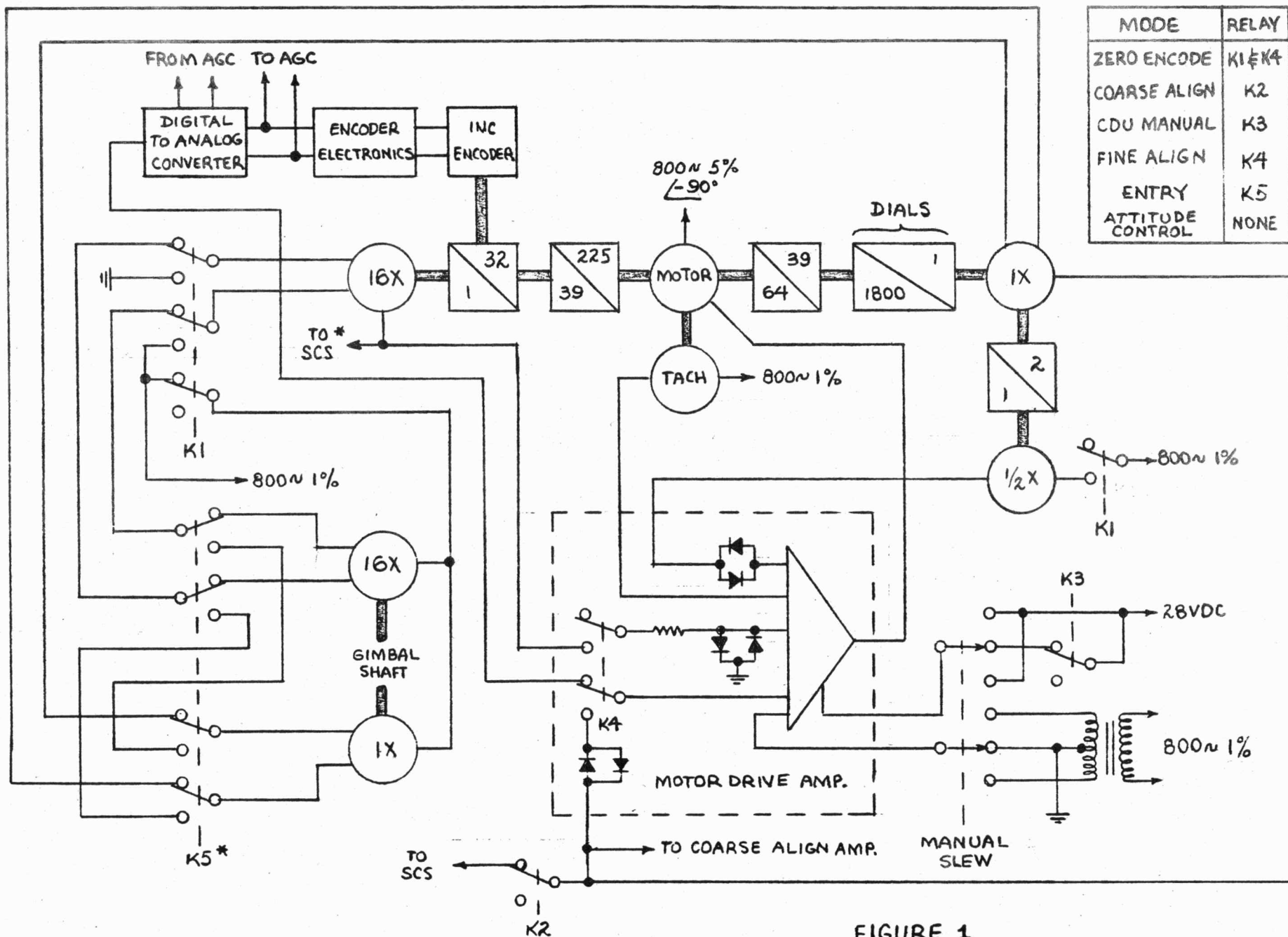


FIGURE 1  
CDU LOOP MECHANIZATION DRWG.

\* THESE ARE PRESENT ON  
OUTER GIMBAL CDU ONLY

<p style="text-align: center;"><b>AC SPARK PLUG DIVISION</b> General Motors Corporation Milwaukee, Wisconsin</p>	<p style="text-align: center;"><b>XDE</b> 34-S-529</p>	
<p style="text-align: center;"><b>PRELIMINARY PERFORMANCE SPECIFICATION</b> <b>INERTIAL COUPLING DISPLAY UNIT</b></p>	<p style="text-align: center;"><b>ENGINEERING</b> <b>DESIGN INFORMATION</b> <b>EXHIBIT</b></p>	
	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

3.4.3 MOTOR DRIVE AMPLIFIER -- The motor drive amplifier shall accept inputs from the digital to analog converter, the selector circuit, the generator and the slew switch and amplify the respective error signals to the motor. (Ref. Dwg. 1010035).

- a. Gain (main channel) -  $1000 \pm 10\%$  volt/volt
- b. Nominal time constants -  $1.325 \times 10^{-3}$  sec. and  $3.61 \times 10^{-4}$  sec.
- c. Nominal saturation level - 33 volts
- d. Max. allowable quadrature at the summing point - 100 mv rms.
- e. Gain (feedback channel) -  $667 \pm 10\%$  volt/volt
- f. Quadrature rejection - 30 db nominal

3.4.4 SELECTOR CIRCUIT -- The selector circuit shall provide passive switching between the one-half speed and sixteen speed resolvers in the "Zero Encode" mode and between the one speed and sixteen speed resolvers in the "Fine Align" mode. The nominal diode switching level shall be 0.5 volts.

3.4.5 DIGITAL TO ANALOG CONVERTER -- The DAC shall convert the number of incremental angle pulses from the AGC and the incremental encoder into an 800 cycle square wave whose amplitude is proportional to the algebraic summation of the input and feedback pulses. (Ref. Dwg. 1010041).

- a. Nominal Scale Factor - 30 mv peak-peak square wave out  
pulse in
- b. Nominal decay time constant - 10 sec.
- c. Nominal saturation level (output) - 10 volts peak-peak
- d. Input pulse rate - 3200 pps.
- e. Min. pulse amplitude - 1.5 volts

3.4.6 INCREMENTAL ENCODER AND ELECTRONICS -- The incremental encoder shall be an electro-magnetic device which modulates a carrier at a rate proportional to the CDU shaft speed. This rate shall be converted to a pulse rate in the encoder electronics. Together, the encoder and electronics shall quantize the CDU output shaft rotation and they shall have the following characteristics. (Ref. Dwg. 1010034).

- a. Number of encoder teeth - 64
- b. Scale factor -  $(2)^6$  pulses/rev.
- c. Granularity -  $2\pi$  rad.  $\approx 39.55 \frac{\text{sec}}{(2)^{15}}$
- d. Min. pulse amplitude - 1.5 volts



AC SPARK PLUG DIVISION General Motors Corporation Milwaukee, Wisconsin						XDE 34-S-529	
PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT						ENGINEERING DESIGN INFORMATION EXHIBIT	
						By A. Laubenstein	
<p>3.4.7 RESOLVER TRANSFORMER - SIXTEEN SPEED -- The sixteen speed resolver shall increase the loop static gain near null in the "zero encode" and "fine align" modes. (Ref. PS-1010351).</p> <p>a. Transformation ratio - <math>1 \pm 1\%</math>  b. Total angular error - 1.0 min. max.  c. Phase shift - <math>2.0^\circ \pm 0.5^\circ</math>  d. Total null - 28 mv max.</p> <p>3.4.8 RESOLVER TRANSFORMER - ONE SPEED -- The one-speed resolver shall compare the CDU shaft angle to the appropriate gimbal angle and produce an error signal proportional to the sine of their difference. (Ref. PS-1010341).</p> <p>a. Transformation ratio - <math>1 \pm 1\%</math>  b. Total angular error - 3 min., max.  c. Phase shift - <math>6.5^\circ \pm 0.5^\circ</math>  d. Total null - 28 mv max.</p> <p>3.4.9 RESOLVER TRANSMITTER - ONE HALF SPEED -- The one-half speed resolver shall be used to eliminate the false nulls when zeroing the CDU shaft. (Ref. ND-1002132).</p> <p>a. Transformation ratio - <math>1 \pm 2\%</math>  b. Total angular error - 3 min, max.  c. Phase shift - <math>7.5^\circ \pm 1^\circ</math>  d. Total null - 28 mv, max.</p> <p>3.4.10 RESOLVER TRANSMITTER - SIXTEEN SPEED -- The sixteen-speed resolver transmitters shall be located between the IMU gimbals and shall transmit gimbal angle information to the CDU in the form of electrical signals proportional to the sine of sixteen times the gimbal angles. (Ref. PS-1000160).</p> <p>a. Transformation ratio - <math>1 \pm 3\%</math>  b. Total angular error - 20 sec. max.  c. Phase shift - <math>5.5^\circ \pm 1.5^\circ</math>  d. Total null - 20 mv. max.</p> <p>3.4.11 RESOLVER TRANSMITTER - ONE SPEED -- The one-speed resolver transmitters shall be located between the IMU gimbals and shall transmit gimbal angle information to the CDU in the form of electrical signals proportional to the sine of the gimbal angles. (Ref. PS-1000030).</p>							
Rev.						Page 9 of 42	XDE

<p style="text-align: center;">AC SPARK PLUG DIVISION General Motors Corporation Milwaukee, Wisconsin</p>	<p style="text-align: center;">XDE 34-8-529</p>	
<p style="text-align: center;">PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT</p>	<p style="text-align: center;">ENGINEERING DESIGN INFORMATION EXHIBIT</p>	
	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

- a. Transformation ratio -  $1 \pm 1\%$
- b. Total angular error - 5 min, max.
- c. Phase shift -  $3^\circ \pm 0.5^\circ$
- d. Total null - 28 mv. max.

#### 4. QUALITY ASSURANCE PROVISIONS

##### 4.1 GENERAL

In order to verify the performance requirements of Section 3, the following shall be demonstrated.

##### 4.2 MAXIMUM TIME TO ZERO

The maximum time for the CDU to zero to within  $\pm 0.02$  degrees from any initial position shall be less than 30 seconds. (The worst case will occur for an initial position around 355 or 356 degrees).

##### 4.3 STATIC ACCURACY - ZEROING

In the Zero Encode Mode, the following characteristics shall be demonstrated.

4.3.1 SIXTEEN-SPEED RESOLVER NULLS -- The sixteen-speed resolver nulls at the selector circuit input shall be less than 6 mv in phase, less than 35 mv quadrature and less than 35 mv. total 800 cycle when measured with the Phase Angle Voltmeter.

4.3.2 ONE HALF-SPEED RESOLVER NULLS -- The one-half speed resolver nulls at the selector circuit input shall be less than 35 mv. in phase, less than 35 mv. quadrature and less than 50 mv. total 800 cycle when measured with the Phase Angle Voltmeter.

4.3.3 MECHANICAL READOUT -- The mechanical readout shall be  $0.0 \pm 0.009$  degrees.

4.4 ENCODER PULSE CENTERING -- Depending upon the initial alignment, the first  $\Delta\theta$  pulse at the AGC interface shall occur when the sixteen-speed resolver output level is  $19.78 \pm 8$  mv. for an increasing dial count and  $59.33 \pm 8$  mv. for a decreasing dial count or when the sixteen-speed resolver output level is  $59.33 \pm 8$  mv. for an increasing dial count and  $19.78 \pm 8$  mv. for a decreasing dial count.

AC SPARK PLUG DIVISION General Motors Corporation Milwaukee, Wisconsin	<b>XDE</b> 34-8-529	
	ENGINEERING DESIGN INFORMATION EXHIBIT	
PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT	By	Date
	A. Laubenstein	8/15/63

#### 4.5 ENCODER ELECTRONICS OUTPUT CHARACTERISTICS

The encoder electronics output pulses ( $\Delta\theta$  pulses) shall have the following characteristics at the AGC interface:

- a. Polarity - Positive with respect to the reference.
- b. Pulse amplitude -  $6 \pm 3$  volts with respect to the reference.
- c. Undershoot - 4 volts maximum.
- d. Pulse duration - 0.5 to 8.0 microseconds at 90% amplitude.
- e. Rise time - less than 20% of the pulse width, 10 to 90% amplitude.
- f. Fall time - less than 20% of the pulse width, 10 to 90% amplitude.
- g. Noise - less than 1.0 volt peak.

#### 4.6 CDU REPEATING ACCURACY

The CDU repeating accuracy shall be as specified in Table I. The steady state sixteen-speed resolver total null at each cardinal and inter-cardinal point shall be less than 35 mv. as measured on the Digital Voltmeter.

ANGLE NO.	CDU 1X RESOLVER ANGLE	DIAL INDICATION	ENCODER PULSES FROM ZERO
1	0	$0^\circ \pm 0.02^\circ$	0
2	$\pm 45/16$	$\pm 2.813^\circ \pm 0.02^\circ$	$\pm 256 \pm 1$
3	$\pm 90/16$	$\pm 5.625^\circ \pm 0.02^\circ$	$\pm 512 \pm 1$
4	$\pm 135/16$	$\pm 8.438^\circ \pm 0.02^\circ$	$\pm 768 \pm 1$
5	$\pm 180/16$	$\pm 11.250^\circ \pm 0.02^\circ$	$\pm 1024 \pm 1$
6	$\pm 225/16$	$\pm 14.063^\circ \pm 0.02^\circ$	$\pm 1280 \pm 1$
7	$\pm 270/16$	$\pm 16.875^\circ \pm 0.02^\circ$	$\pm 1536 \pm 1$
8	$\pm 315/16$	$\pm 19.688^\circ \pm 0.02^\circ$	$\pm 1792 \pm 1$
9	$\pm 360/16$	$\pm 22.500^\circ \pm 0.02^\circ$	$\pm 2048 \pm 1$
10	$\pm 45^\circ$	$\pm 45.000^\circ \pm 0.02^\circ$	$\pm 4096 \pm 1$
11	$\pm 90^\circ$	$\pm 90.000^\circ \pm 0.02^\circ$	$\pm 8192 \pm 1$
12	$\pm 135^\circ$	$\pm 135.000^\circ \pm 0.02^\circ$	$\pm 12288 \pm 1$
13	$\pm 180^\circ$	$\pm 180.000^\circ \pm 0.02^\circ$	$\pm 16384 \pm 1$
14	$\pm 225^\circ$	$\pm 225.000^\circ \pm 0.02^\circ$	$\pm 20480 \pm 1$
15	$\pm 270^\circ$	$\pm 270.000^\circ \pm 0.02^\circ$	$\pm 24576 \pm 1$
16	$\pm 315^\circ$	$\pm 315.000^\circ \pm 0.02^\circ$	$\pm 28672 \pm 1$

TABLE I

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<p style="text-align: center;"><b>PRELIMINARY PERFORMANCE SPECIFICATION</b> <b>INERTIAL COUPLING DISPLAY UNIT</b></p>	<p><b>ENGINEERING DESIGN INFORMATION EXHIBIT</b></p>	
	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

#### 4.7 DYNAMIC REPEATING

With a 1.0 deg. angular difference between the IMU gimbal angle and the CDU shaft position, the time to travel 63% of the angular difference after "fine align" loop closure shall be less than 0.55 seconds. The sixteen-speed resolver error signal shall be used to record this transient on the strip recorder.

#### 4.8 DYNAMIC POSITIONING

With the CDU in a "computer driven" mode configuration and 16 pulses put into the DAC, the DAC output as recorded on the strip recorder shall decrease to 37% of its peak value in less than 0.3 seconds.

#### 4.9 DAC DRIFT

With no input pulses applied to the DAC when in a "computer driven" mode configuration, the CDU dial indications shall not change more than 1.0 degrees per second.

#### 4.10 TACHOMETER NULLS

The null voltages of the tachometer when in the "manual CDU" mode configuration as measured at the input to the quadrature rejection circuit in the MDA shall be less than 4 mv. in phase, less than 8 mv. quadrature, and less than 11 mv. total 800 cps as indicated on the PAV.

#### 4.11 ENCODER AND ELECTRONICS BANDWIDTH

The minimum bandwidth of the encoder electronics shall be such that no pulses are lost when the CDU motor is driving at its maximum rate.

#### 4.12 CDU MANUAL OPERATION

When the CDU slew switch is depressed to the "increase" position, the CDU dial shall indicate an increasing angular change of at least 20 degrees per second. When the CDU slew switch is depressed to the "decrease" position, the CDU dial shall indicate a decreasing angular change of at least 20 degrees per second. The CDU shall indicate an increasing and decreasing angle when manually turning the "fine adjust thumbwheel" in an increasing and decreasing direction.

#### 5. PREPARATION FOR DELIVERY

Not applicable.

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<p style="text-align: center;">PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT</p>	<p style="text-align: center;">ENGINEERING DESIGN INFORMATION EXHIBIT</p>	
	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

## 6. ANALYSIS

### 6.1 INTRODUCTION

In this preliminary analysis, only nominal component parameters have been considered, and therefore, the results indicate only the inherent capability of the CDU to meet the requirements of Section 3.

The analysis consists of defining the components and then analyzing the loops of combined components as they appear in the various system operating modes. Whereas the components are defined by their standard transfer functions, using nominal parameters, or their non-linear output versus input plots, the static and dynamic performance of the loops will be determined by whichever analysis technique fits the particular situation.

### 6.2 COMPONENT CHARACTERISTICS

The individual component transfer functions and characteristics are defined as follows.

6.2.1 SERVO MOTOR -- The servo-motor converts the various CDU error signals into the appropriate shaft angle and velocity. The amplifier output presents a constant voltage source to the motor.

$$\frac{\theta_m (S)}{E_1 (S)} = \frac{K_1/K_2}{S \left[ \frac{J_e}{K_2} S + 1 \right]}$$

$$J_e = J_{\text{rotor}} + J_{\text{flywheel}} + J_{\text{load referred}}$$

$$J_r = 5.5 \text{ gm. cm.}^2$$

$$J_f = 15 \text{ gm. cm.}^2$$

$$J_1 = 5.5 \text{ gm. cm.}^2$$

$$K_1 = 456 \frac{\text{dyne cm.}}{\text{volt}}$$

$$K_2 = 13.27 \text{ dyne cm. sec.}$$

<p style="text-align: center;">AC SPARK PLUG DIVISION General Motors Corporation Milwaukee, Wisconsin</p>	<p><b>XDE</b> 34-S-529</p>	
<p>PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT</p>	<p style="text-align: center;">ENGINEERING DESIGN INFORMATION EXHIBIT</p>	
	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

## 6.2.1 (Continued)

At rated control voltage,

$$\frac{\Theta_m (S)}{E_1 (S)} = \frac{34.4}{S(1.96S+1)} \frac{\text{Rad.}}{\text{Volt}}$$

Since the slopes of the motor torque-speed curves decrease with motor control voltage, a more accurate expression for small values of control voltage would be

$$\frac{\Theta_m (S)}{E_1 (S)} = \frac{68.8}{S(3.92S+1)} \frac{\text{Rad.}}{\text{Volt}}$$

6.2.2 SERVO GENERATOR -- The generator provides a negative feedback signal proportional to the motor shaft speed.

$$\frac{E_o (S)}{\Theta_m (S)} = K_T S$$

$$K_T = 1.0 \frac{\text{mv}}{\text{rpm}} = 9.55 \times 10^{-3} \frac{\text{volt}}{\text{rad/sec}}$$

$$\frac{E_o (S)}{\Theta_m (S)} = 9.55 \times 10^{-3} S \frac{\text{volt}}{\text{rad/sec}}$$

6.2.3 MOTOR DRIVE AMPLIFIER -- The motor drive amplifier is a high gain push-pull amplifier.

For the input channels,

$$\frac{E_o (S)}{E_1 (S)} = \frac{1000}{\left(\frac{S}{755} + 1\right) \left(\frac{S}{2770} + 1\right)}$$

For the feedback channel,

$$\frac{E_o (S)}{E_1 (S)} = \frac{667}{\left(\frac{S}{755} + 1\right) \left(\frac{S}{2770} + 1\right)}$$

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	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

6.2.4 DIGITAL TO ANALOG CONVERTER -- The DAC converts AGC and encoder incremental angle pulses into an amplitude modulated square wave which feeds the amplifier in the computer driven modes.

$$\frac{E_o(S)}{N(S)} = \frac{K}{(S+1)} \frac{\text{volts rms}}{\text{pulse}}$$

In this approximation, N represents an impulse of a strength equivalent to the summation of the strengths of a string of impulses coming at a rate much faster than the decay time of the unit.

$$K \approx 13.5 \times 10^{-3} \frac{\text{volt sec.}}{\text{pulse}}$$

$$\tau = 10 \text{ sec.}$$

$$\frac{E_o(S)}{N(S)} = \frac{13.5 \times 10^{-2}}{10S + 1} \frac{\text{volt rms}}{\text{pulse}}$$

6.2.5 INCREMENTAL ENCODER AND ELECTRONICS -- The encoder and associated electronics quantize the CDU shaft rotation and transmit incremental angle pulses to the AGC and the DAC. The phase relationship between the two pickoffs determines the direction of shaft rotation.

$$\frac{F(S)}{\theta_e(S)} = 10.2 \frac{\text{pulses}}{\text{rad.}}$$

6.2.6 RESOLVER TRANSFORMER-16X -- The "sixteen-speed" resolver transformer is a size 11 one-speed resolver mounted on the sixteen-speed shaft, and it converts angular error measurements into electrical signals. It is used to increase the loop gain near null in "zero encode" and "fine align".

$$e = 28 \sin 16\phi$$

Because of system loading,

$$e_i = 25.8 \sin 16\phi$$

For small angles,

$$\frac{e_i}{\phi} \approx 413 \frac{\text{volts}}{\text{rad.}}$$

## AC SPARK PLUG DIVISION

General Motors Corporation  
Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
DESIGN INFORMATION  
EXHIBITPRELIMINARY PERFORMANCE SPECIFICATION  
INERTIAL COUPLING DISPLAY UNITBy  
A. LaubensteinDate  
8/15/63

6.2.7 RESOLVER TRANSFORMER 1X-- The one speed resolver transformer converts the angular error between the 1X CDU shaft and the gimbal angle into an electrical signal.

$$e = 28 \sin \phi$$

Because of system loading,

$$e_1 = 24.2 \sin \phi$$

For small angles,

$$\frac{e_1}{\phi} \approx \frac{24.2 \text{ volts}}{\text{rad.}}$$

6.2.8 RESOLVER TRANSFORMER  $\frac{1}{2}$ X -- The "one half speed" resolver transformer is a one-speed resolver mounted on the one half speed shaft, and it is used to eliminate the possible false null in the system. It converts CDU shaft position to an electrical error signal which will drive the shaft toward zero.

$$e = 28 \sin \frac{\phi}{2}$$

For small angles,

$$\frac{e}{\phi} \approx \frac{14 \text{ volts}}{\text{rad.}}$$

6.2.9 RESOLVER TRANSMITTER - 1X -- The one speed resolver transmitters convert the gimbal angles into electrical signals.

$$e = 28 \sin A$$

Because of system loading,

$$e_1 = 26 \sin A$$

For small angles,

$$\frac{e_1}{A} \approx \frac{26 \text{ volts}}{\text{rad.}}$$

6.2.10 RESOLVER TRANSMITTER - 16X -- The sixteen speed resolver transmitters convert sixteen times the gimbal angles into electrical signals.

$$e = 28 \sin 16A$$

Because of system loading,

$$e_1 = 26 \sin 16A$$

For small angles,

$$\frac{e_1}{A} \approx \frac{416 \text{ volts}}{\text{rad.}}$$



## AC SPARK PLUG DIVISION

General Motors Corporation  
Milwaukee, Wisconsin

XDE 34-8-529

ENGINEERING  
DESIGN INFORMATION  
EXHIBITPRELIMINARY PERFORMANCE SPECIFICATION  
INERTIAL COUPLING DISPLAY UNITBy  
A. LaubensteinDate  
8/15/63

6.2.11 SELECTOR CIRCUIT -- The selector circuit provides passive switching between the coarse and fine resolver outputs. In "fine align", the switching occurs between the 1X and 16X resolvers and in "zero encode", the switching occurs between the 1/2X and 16X resolvers.

In the "zero encode" mode, the SC output goes to zero every  $\Delta\theta=2\pi$  radians. Near the nulls, the output voltage versus the one-speed shaft angle is shown below.

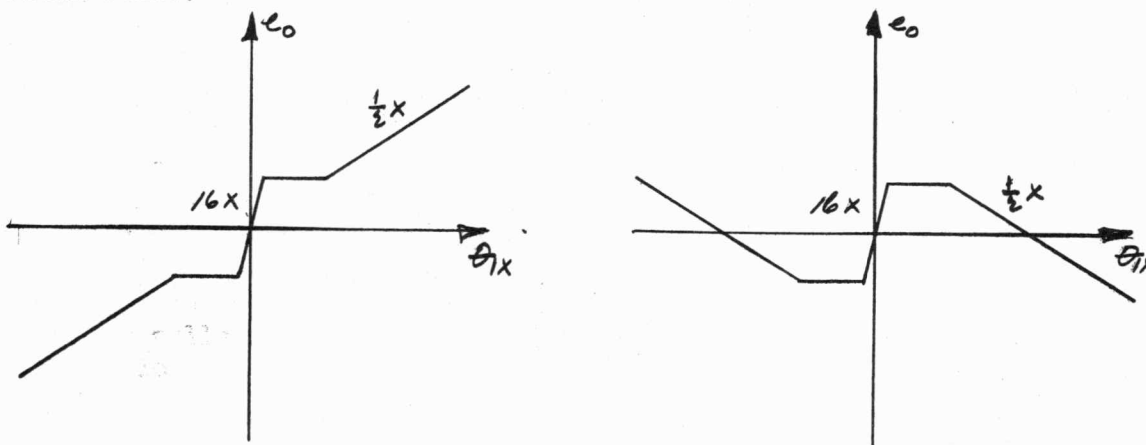


Figure 2

SELECTOR CIRCUIT OUTPUT vs. ONE SPEED SHAFT  
ANGLE NEAR NULLS -- ZERO ENCODE

The diodes conduct at approximately 0.5 volts. The switching occurs at

$$25.8 \sin(16\theta) = 0.5 \quad \theta \approx 4.16 \text{ min.}$$

$$28 \sin\left(\frac{\theta}{2}\right) = 0.5 \quad \theta \approx 2.05 \text{ deg.}$$

$$e_o = 413 \theta \quad (\theta \leq 4.16 \text{ min.})$$

$$e_o = 0.5 \quad (4.16 \text{ min.} \leq \theta \leq 2.05 \text{ deg.})$$

$$e_o = 0.5 + 14 \left(\theta - \frac{1}{14}\right) \quad (\theta \geq 2.05 \text{ deg.})$$

In the "fine align" mode, the SC output goes to zero every  $\Delta(\theta-A) = \pi$  radians. The desired null occurs at  $(\theta-A) = N\pi$  where  $N=0, +2, +4, \dots$ . A false null occurs at  $(\theta-A) = N\pi$  where  $N=\underline{+1}, \underline{+3}, \underline{+5}, \dots$ . However, if the system has been properly coarse aligned, the possibility of a false null occurring in "fine align" is very remote.

**AC SPARK PLUG DIVISION**  
 General Motors Corporation  
 Milwaukee, Wisconsin

**XDE** 34-S-529

**ENGINEERING  
 DESIGN INFORMATION  
 EXHIBIT**

**PRELIMINARY PERFORMANCE SPECIFICATION  
 INERTIAL COUPLING DISPLAY UNIT**

By  
 A. Laubenstein

Date  
 8/15/63

6.2.11 (Continued)

Near the nulls, the output voltage versus the difference between the gimbal and the one-speed CDU shaft angles is shown below.

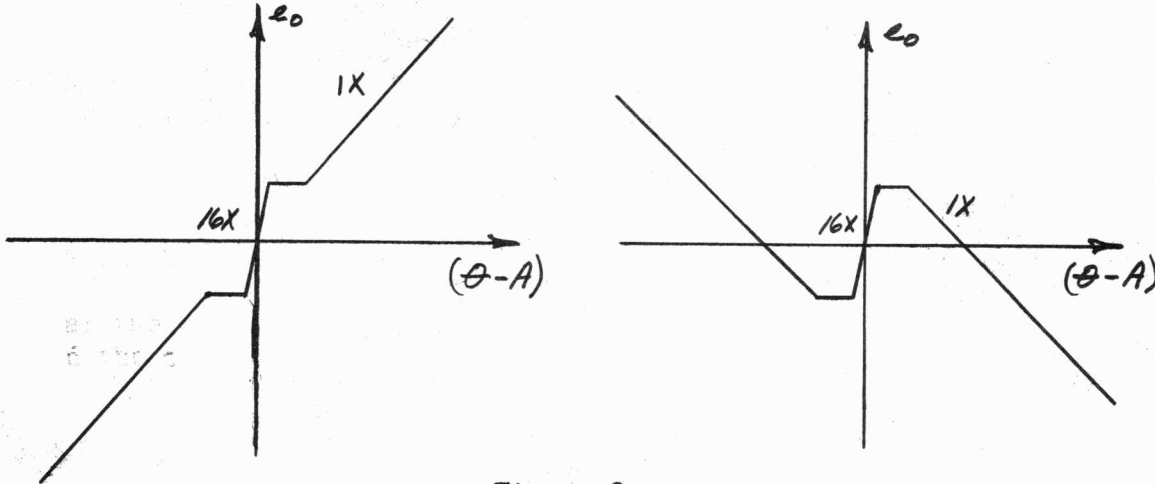


Figure 3

**SELECTOR CIRCUIT OUTPUT vs. ONE SPEED ERROR  
 NEAR NULLS -- FINE ALIGN**

The diodes conduct at approximately 0.5 volts. The switching occurs at,

$$25.8 \sin 16 (\theta - A) = 0.5 \quad (\theta - A) \approx 4.16 \text{ min.}$$

$$24.2 \sin (\theta - A) = 0.5 \quad (\theta - A) \approx 1.185 \text{ deg.}$$

$$e_o = 413 (\theta - A) \quad (\theta - A) \leq 4.16 \text{ min.}$$

$$e_o = 0.5 \quad 4.16 \text{ min.} < (\theta - A) \leq 1.185 \text{ deg.}$$

$$e_o = 0.5 + 28 \left[ \frac{(\theta - A) - 1.185}{28} \right] \quad (\theta - A) \geq 1.185 \text{ deg.}$$

AC SPARK PLUG DIVISION

General Motors Corporation  
Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
DESIGN INFORMATION  
EXHIBIT

PRELIMINARY PERFORMANCE SPECIFICATION  
INERTIAL COUPLING DISPLAY UNIT

By  
A. Laubenstein

Date  
8/15/63

6.3 LOOP ANALYSIS -- The function and the performance of the CDU changes considerably in the various system modes of operation. Basically, there are three separate CDU modes; the computer driven mode as in "coarse align", attitude control", and "entry"; the follow up mode as in "zero encode" and "fine align" and the slewing mode. These various loop arrangements must necessarily be analyzed separately.

6.3.1 LOOP DYNAMIC RESPONSES -- The equations and the frequency and time response plots that follow show the CDU dynamics in the various modes. The equations and plots are the result of mathematical analysis techniques applied to simplified loop representations and also an analog computer simulation containing all pertinent nonlinearities.

6.3.1.1 INNER LOOP -- The basic inner loop, consisting of the amplifier and the motor-generator remains intact in all the CDU modes and is as follows.

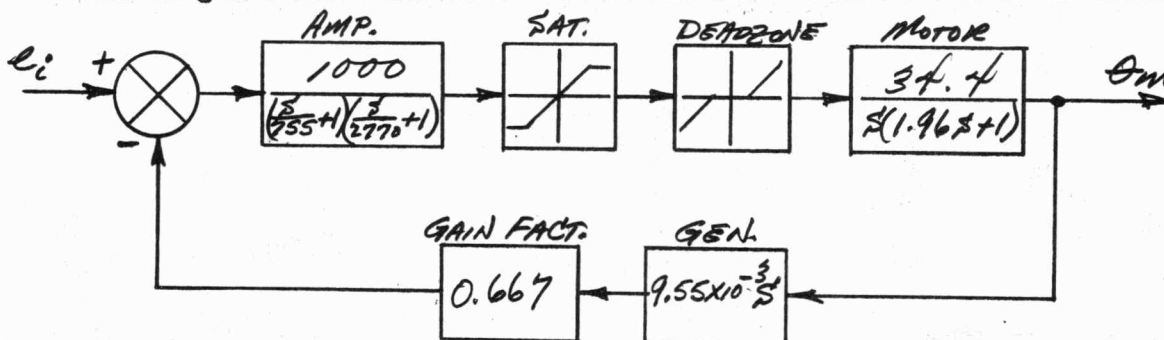


Figure 3

INNER LOOP

A simplified over-all transfer function may be obtained by neglecting the nonlinearities.

$$\frac{\theta_m(s)}{e_i(s)} = \frac{156.5}{s \left( \frac{s}{143} + 1 \right) \left( \frac{s}{573} + 1 \right) \left( \frac{s}{2810} + 1 \right)}$$

Using the motor transfer function for small motor control voltages,

$$\frac{\theta_m(s)}{e_i(s)} = \frac{157}{s \left( \frac{s}{147} + 1 \right) \left( \frac{s}{568} + 1 \right) \left( \frac{s}{2810} + 1 \right)}$$

AC SPARK PLUG DIVISION  
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XDE 34-S-529

ENGINEERING  
 DESIGN INFORMATION  
 EXHIBIT

PRELIMINARY PERFORMANCE SPECIFICATION  
 INERTIAL COUPLING DISPLAY UNIT

By  
 A. Laubenstein

Date  
 8/15/63

6.3.1.1 (Continued)

Since the overall loop transfer function does not change appreciably with the slope of the motor torque-speed curves, a nominal inner loop transfer function will be used in the analysis that follows.

$$\frac{\theta_m(s)}{e_1(s)} = \frac{157}{s \left( \frac{s}{145} + 1 \right) \left( \frac{s}{570} + 1 \right) \left( \frac{s}{2810} + 1 \right)}$$

6.3.1.2 SLEWING MODE -- With the addition of some gearing and the encoder and its electronics, the basic inner loop represents the CDU in the slewing mode of operation.

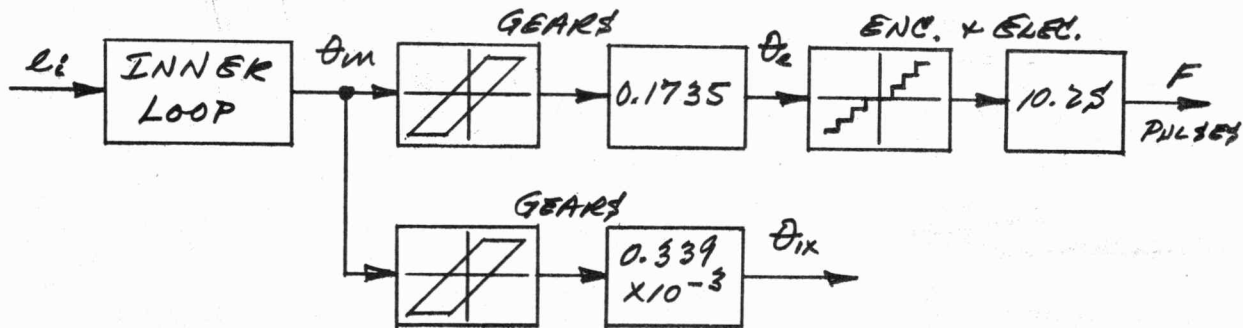


Figure 5

SLEWING MODE

When the slew switch is depressed, an 800 cycle 12.7 volt signal is applied to the amplifier summing point. This is sufficient to saturate the amplifier as long as it is applied. Under this condition, the inner loop is effectively broken, and the CDU can be represented as follows.

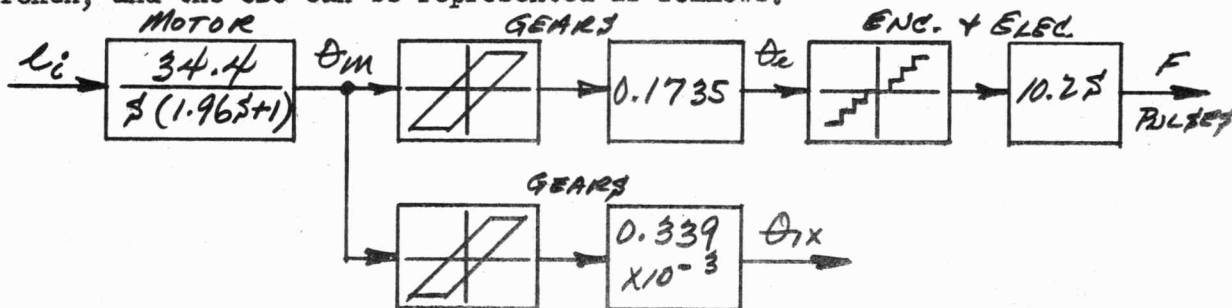


Figure 6

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<p style="text-align: center;">PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT</p>	<p style="text-align: center;">ENGINEERING DESIGN INFORMATION EXHIBIT</p>	
	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

### 6.3.1.2 (Continued)

The input voltage will be the amplifier saturated output, nominally 33 volts, minus a nominal 2 volt loaded motor deadzone.

As long as the input is applied,

$$\frac{\theta_m (S)}{e_1 (S)} = \frac{34.4}{S (1.96 X+1)} \frac{\text{rad.}}{\text{volt}}$$

and neglecting any backlash, the maximum output shaft speeds are

$$W_m \text{ max.} = 1065 \frac{\text{rad.}}{\text{sec}} = 10,180 \text{ rpm}$$

$$W_{1X} \text{ max.} = 0.361 \frac{\text{rad.}}{\text{sec}} = 3.45 \text{ rpm}$$

$$= 20.7 \frac{\text{deg.}}{\text{sec}}$$

Encoder Rate Max. = 1880 pps

From the above and the computer simulation, it is seen that the maximum time to slew the one speed shaft 180 degrees is from 9-12 seconds depending upon the amplifier saturation and motor deadzone values used.

The one-speed CDU shaft will stop within 1.5 seconds after the slew switch is released and overshoot about 3 degrees.

The total time to complete the function in this mode for a command of  $\pm 180$  degrees is the 9-12 seconds slewing time, the rundown time, and the time required for the operator to "thumb" the shaft to the desired position.

**6.3.1.3 FOLLOW-UP MODES** -- In the "zero encode" and "fine align" modes of operation, the CDU is driven such that its actuating error-signal is eliminated. The actuating error signal is proportional to the sine of the one-half and sixteen speed CDU shaft angles in "zero encode" and the sine of the difference between the one speed CDU and gimbal angles and the sixteen speed CDU and gimbal angles in "fine align". The CDU shaft, therefore, drives to zero in the "zero encode" mode and repeats the gimbal angle in the "fine align" mode.

AC SPARK PLUG DIVISION  
 General Motors Corporation  
 Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
 DESIGN INFORMATION  
 EXHIBIT

PRELIMINARY PERFORMANCE SPECIFICATION  
 INERTIAL COUPLING DISPLAY UNIT

By  
 A. Laubenstein

Date  
 8/15/63

6.3.1.3 (Continued)

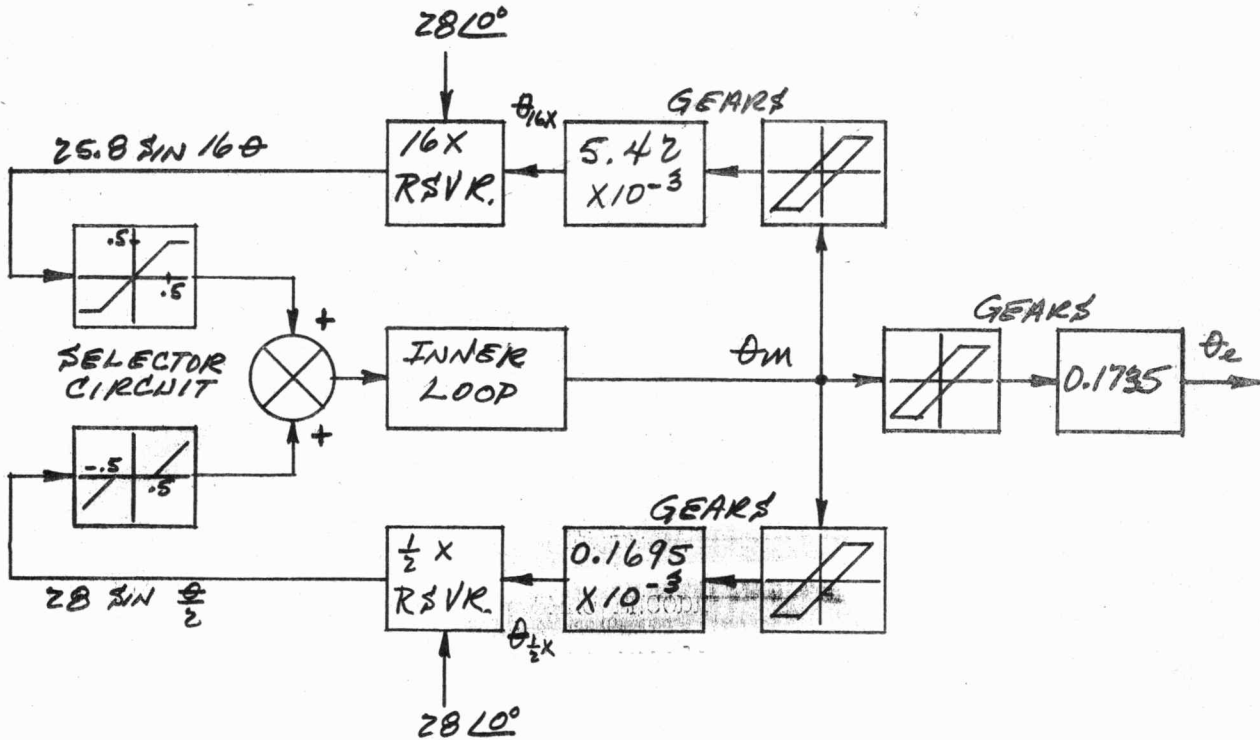


Figure 7

ZERO ENCODE

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XDE 34-S-529

ENGINEERING  
 DESIGN INFORMATION  
 EXHIBIT

PRELIMINARY PERFORMANCE SPECIFICATION  
 INERTIAL COUPLING DISPLAY UNIT

By  
 A. Laubenstein

Date  
 8/15/63

6.3.1.3 (Continued)

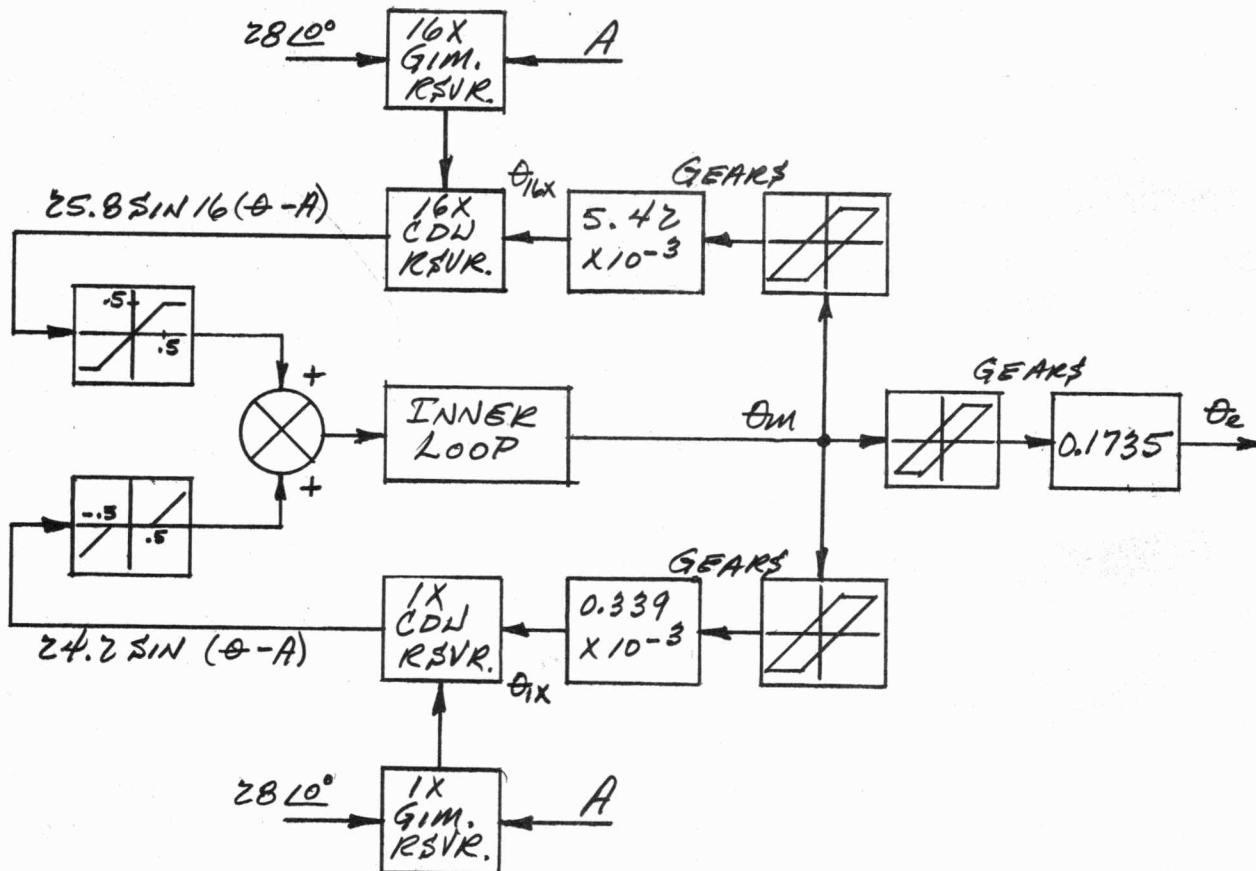


Figure 8

FINE ALIGN

Approximate expressions for the loop dynamic responses can be obtained for small angular errors by replacing the resolvers with their linear approximations, replacing the selector circuit by a two position switch, and neglecting the remaining nonlinearities.

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 General Motors Corporation  
 Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
 DESIGN INFORMATION  
 EXHIBIT

By  
 A. Laubenstein

Date  
 8/15/63

6.3.1.3 (Continued)

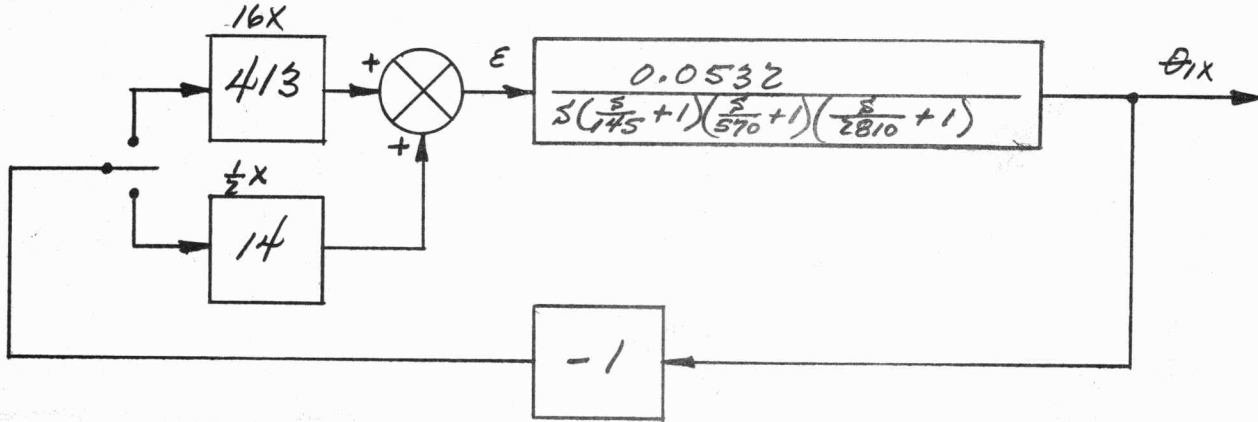


Figure 9

ZERO ENCODE

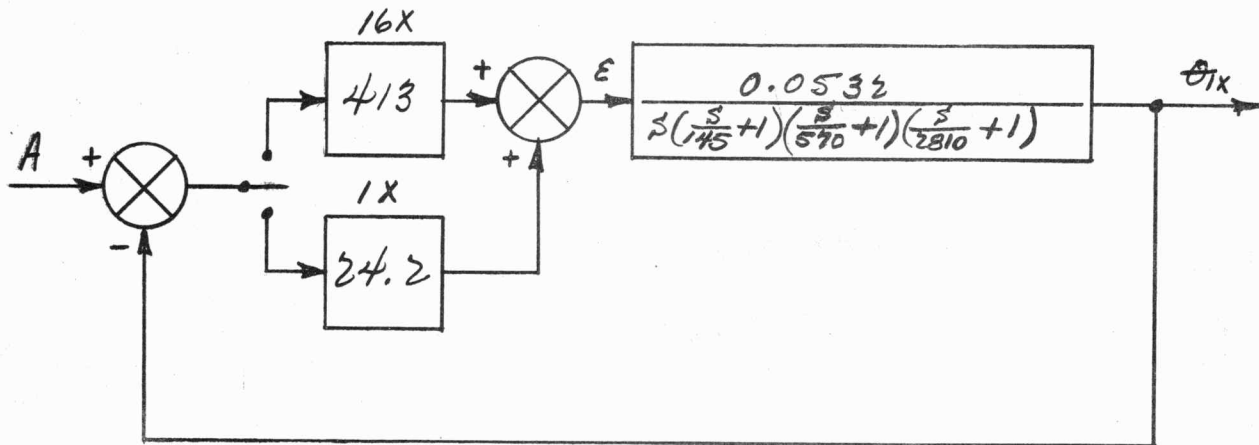


Figure 10

FINE ALIGN

In the steady state, approximately 7 volts at the amplifier summing point will saturate the loop. Initially 30 to 40 mv. will saturate the loop until the tachometer feedback brings the loop back into the linear operating region.



## AC SPARK PLUG DIVISION

General Motors Corporation  
Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
DESIGN INFORMATION  
EXHIBITPRELIMINARY PERFORMANCE SPECIFICATION  
INERTIAL COUPLING DISPLAY UNITBy  
A. LaubensteinDate  
8/15/63

## 6.3.1.3 (Continued)

Neglecting the initial saturation, the one speed shaft in the "zero encode" mode can be offset approximately  $\pm 30$  degrees without causing saturation in the steady state.

For an initial one-speed shaft angle, the CDU response is as follows.

With the one half speed resolver controlling,

$$\theta(t) \approx \theta_0 (1.005e^{-.75t} - 0.005e^{-144t})$$

$$0.0357 \text{ rad.} \leq |\theta_0| \leq 0.525 \text{ rad.}$$

With the limited output of the sixteen speed resolver controlling,

$$\theta(t_1) \approx -0.0266 t_1 + \theta_1 \quad \text{for } \theta_1 \text{ positive}$$

$$\theta(t_1) \approx +0.0266 t_1 + \theta_1 \quad \text{for } \theta_1 \text{ negative}$$

$$1.21 \text{ mr.} \leq |\theta_0| \leq 0.0357 \text{ rad.}$$

With the sixteen speed resolver controlling,

$$\theta(t_2) \approx \theta_2 (1.38e^{-29.4t} - 0.38e^{-107t})$$

$$+ 0.0129\dot{\theta}_2 (e^{-107t} - e^{-29.4t})$$

$$|\theta_0| \leq 1.21 \text{ mv.}$$

From the analog computer simulation, which included resolver nonlinearities, amplifier saturation, and motor deadzone, initial offset angles up to  $+350$  degrees were considered. The CDU responses are shown in Figures 12 and 13. From these plots, it is seen that the maximum time to complete this mode of operation will be from 25 to 30 seconds.

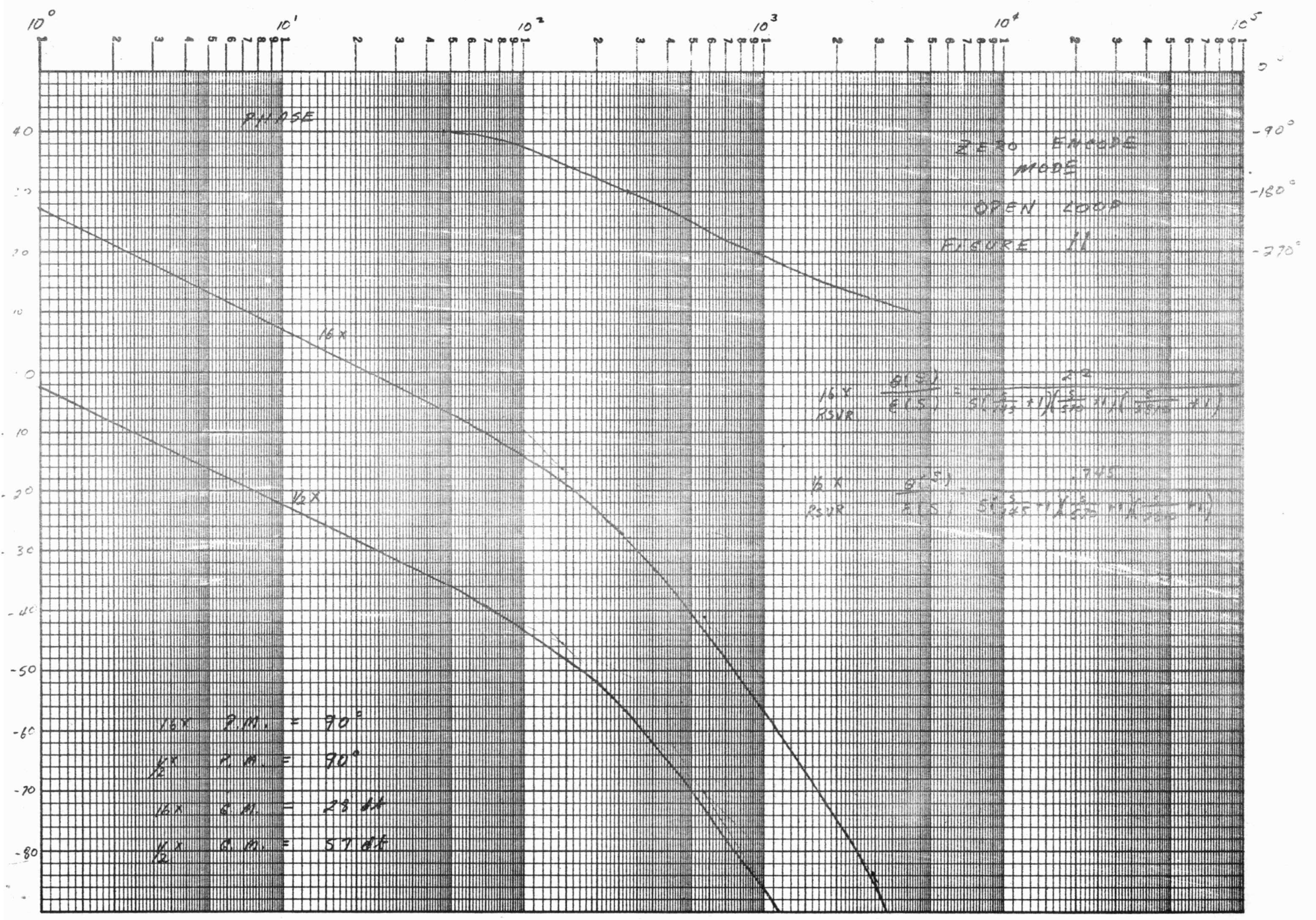
Again neglecting the initial saturation, the one-speed shaft in the "fine align" mode can be approximately 15 degrees away from the gimbal angle without causing saturation in the steady state.

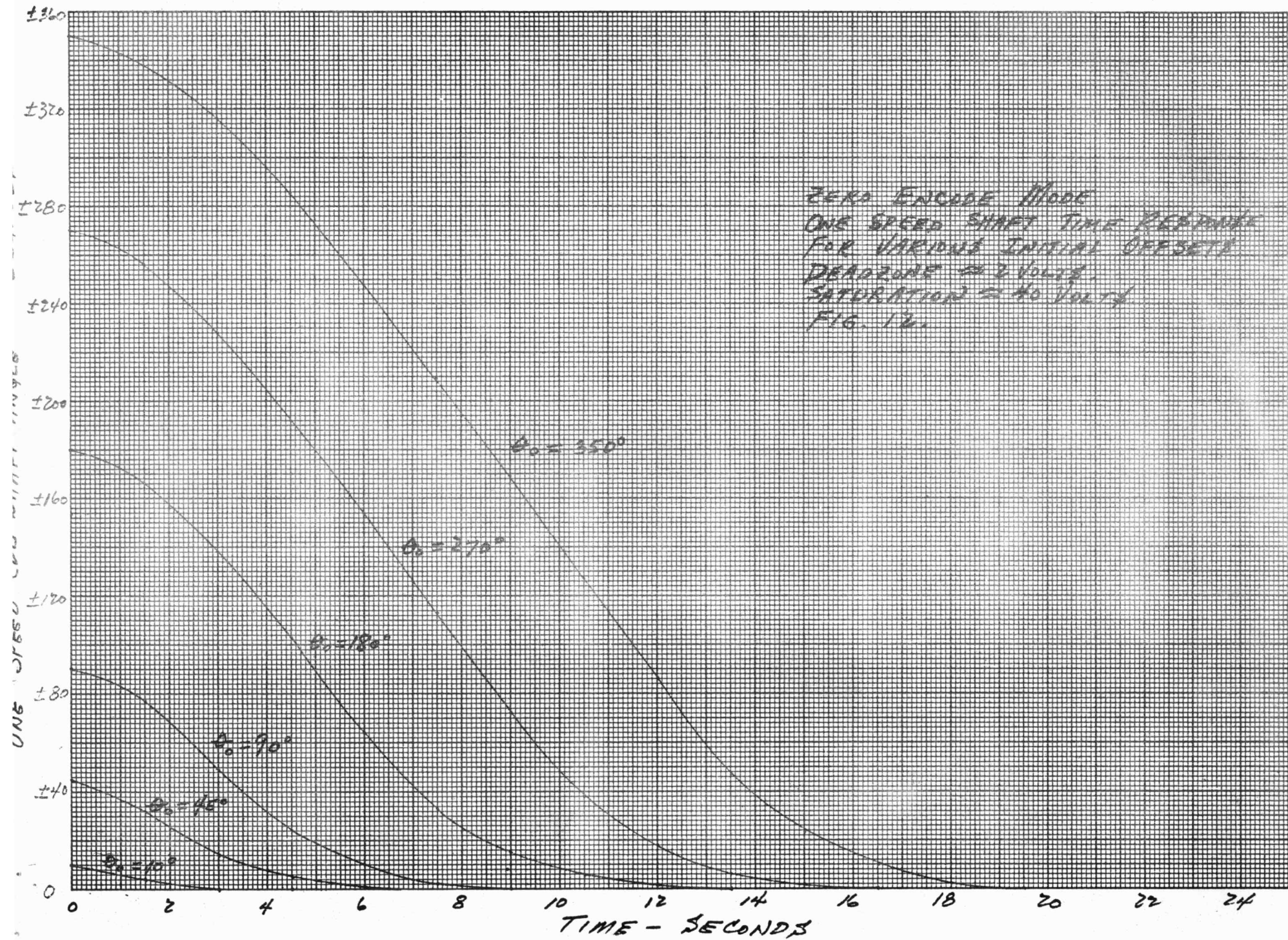
For small angles, the closed loop relations between gimbal angle inputs and one speed CDU shaft outputs are,

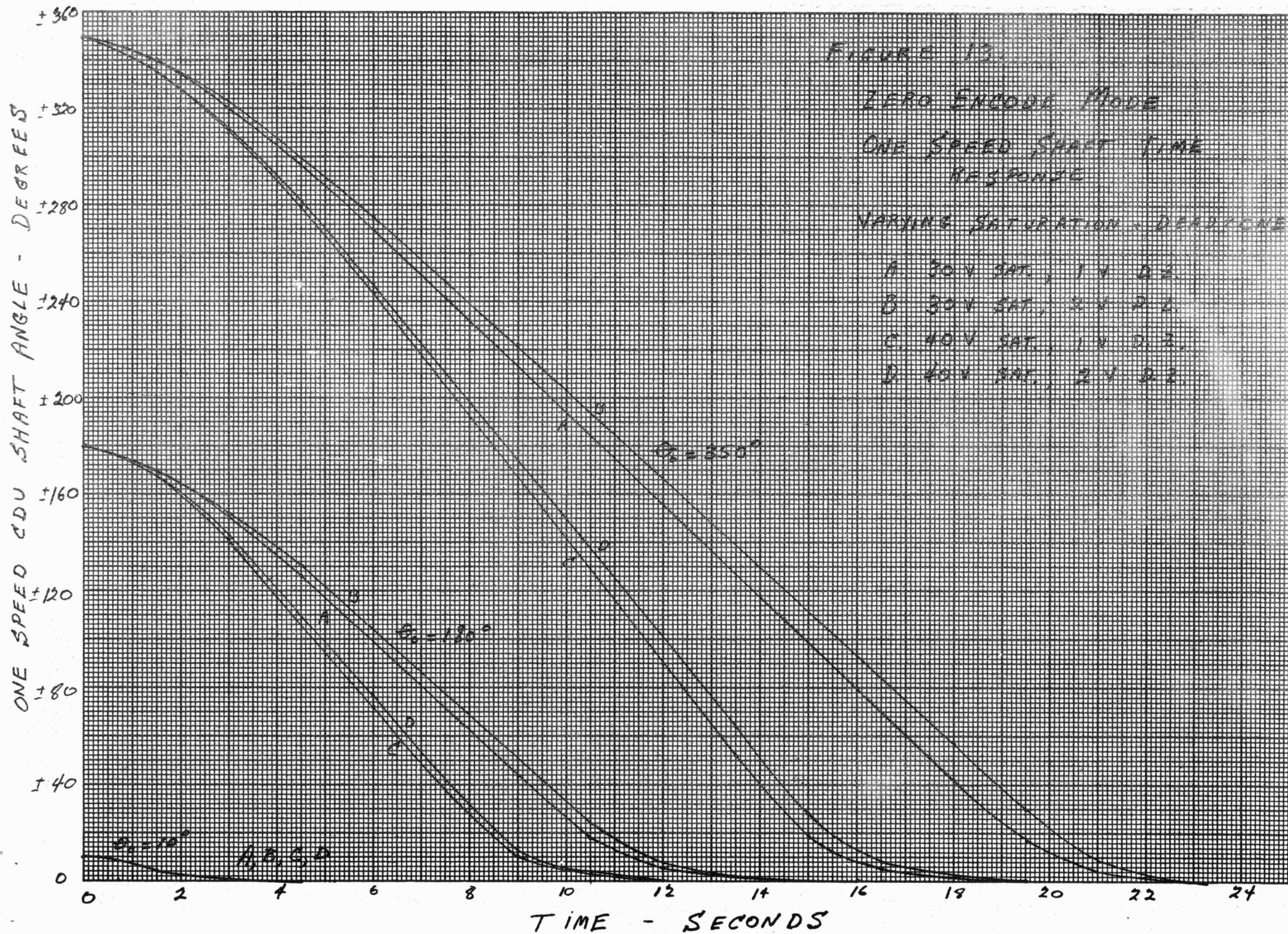
$$\frac{\theta(s)}{A(s)} = \frac{1}{\left(\frac{s}{1.3} + 1\right)\left(\frac{s}{143} + 1\right)\left(\frac{s}{571} + 1\right)\left(\frac{s}{2810} + 1\right)}$$

for the one-speed resolver controlling and

$$\frac{\theta(s)}{A(s)} = \frac{1}{\left(\frac{s}{29.4} + 1\right)\left(\frac{s}{107} + 1\right)\left(\frac{s}{579} + 1\right)\left(\frac{s}{2810} + 1\right)}$$







AC SPARK PLUG DIVISION General Motors Corporation Milwaukee, Wisconsin	<b>XDE</b> 34-S-529	
PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT	ENGINEERING DESIGN INFORMATION EXHIBIT	
	By A. Laubenstein	Date 8/15/63

### 6.3.1.3 (Continued)

for the sixteen speed resolver controlling.

For an initial error angle, the CDU one-speed shaft response is as follows.

With the one-speed resolver controlling,

$$\theta(t) = A_o + 1.01(\theta_o - A_o)e^{-1.3t} - 0.01(\theta_o - A_o)e^{-143t}$$

$$0.0207 \text{ rad.} \leq |\theta_o - A_o| \leq 0.262 \text{ rad.}$$

With the limited sixteen speed resolver output controlling,

$$\theta(t_1) \approx -0.0266t_1 + \theta_1 \quad \theta_1 \text{ positive}$$

$$\theta(t_1) \approx +0.0266t_1 + \theta_1 \quad \theta_1 \text{ negative}$$

$$1.21 \text{ mv.} \leq |\theta_o - A_o| \leq 0.0207 \text{ rad.}$$

With the sixteen speed resolver controlling,

$$\theta(t_2) \approx A_o + 1.38(\theta_2 - A_o)e^{-29.4t} - 0.38(\theta_2 - A_o)e^{-107t}$$

$$+ 0.0129\theta_2 (e^{-107t} - e^{-29.4t})$$

$$|\theta_o - A_o| \leq 1.21 \text{ mv.}$$

From the equations and the computer simulation the followup times for various initial offset errors are as shown in Figure 14.

The open and closed loop frequency plots, Figures 15 and 16 indicate the loop stability and bandwidth.

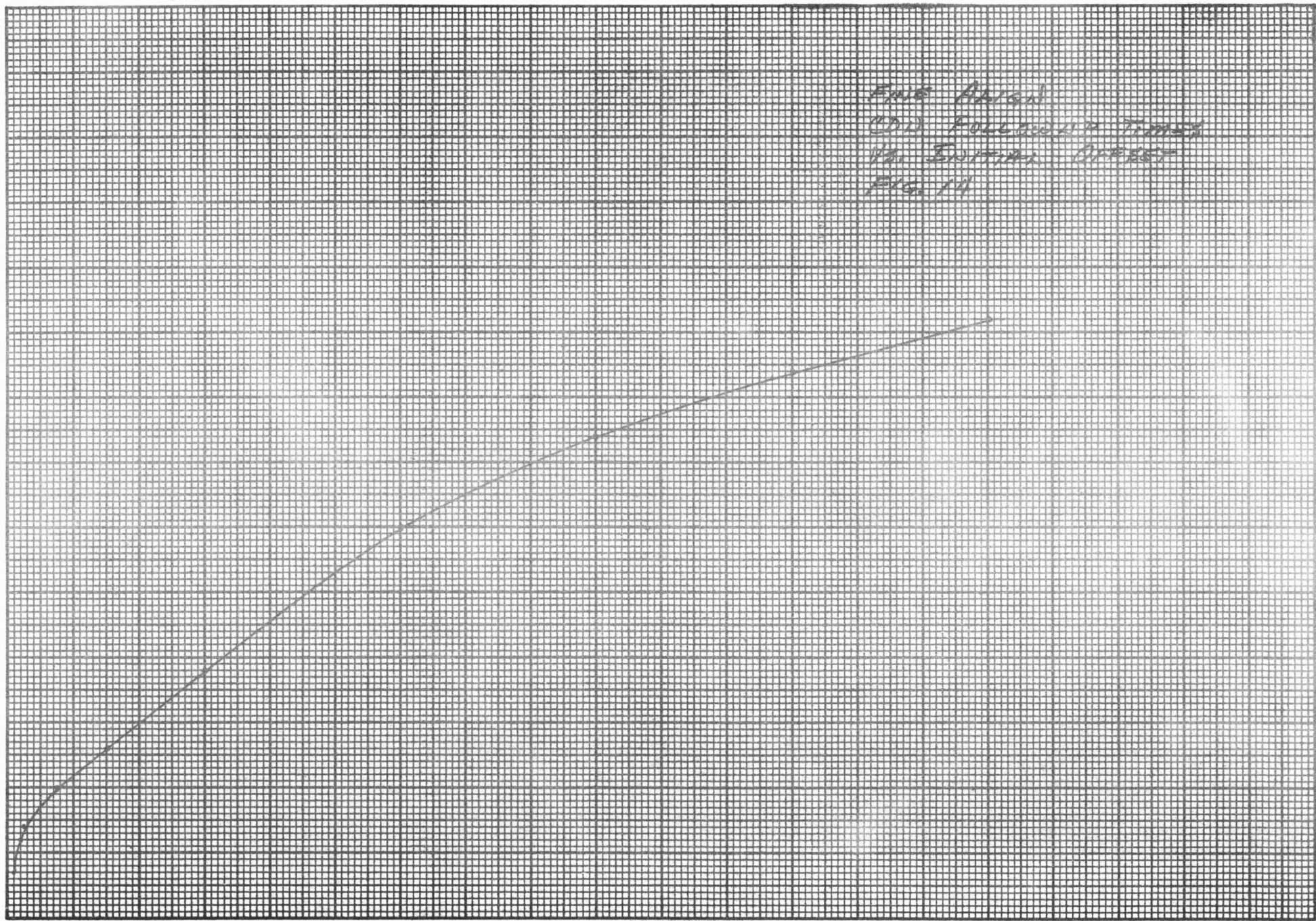
When the CDU is subjected to a velocity input in the "fine align" mode, a steady state "velocity lag" error occurs; that is, the output shaft position lags the commanded position by a constant amount in the steady state with a velocity input. For low rate inputs, the sixteen-speed resolver output controls the loop. However, as the input rate is increased, the loop is controlled by the one-speed resolver and the limited sixteen-speed resolver outputs. The switch between the sixteen and one speed resolver occurs for input rates somewhere between 1.5 and 1.6 deg./sec.

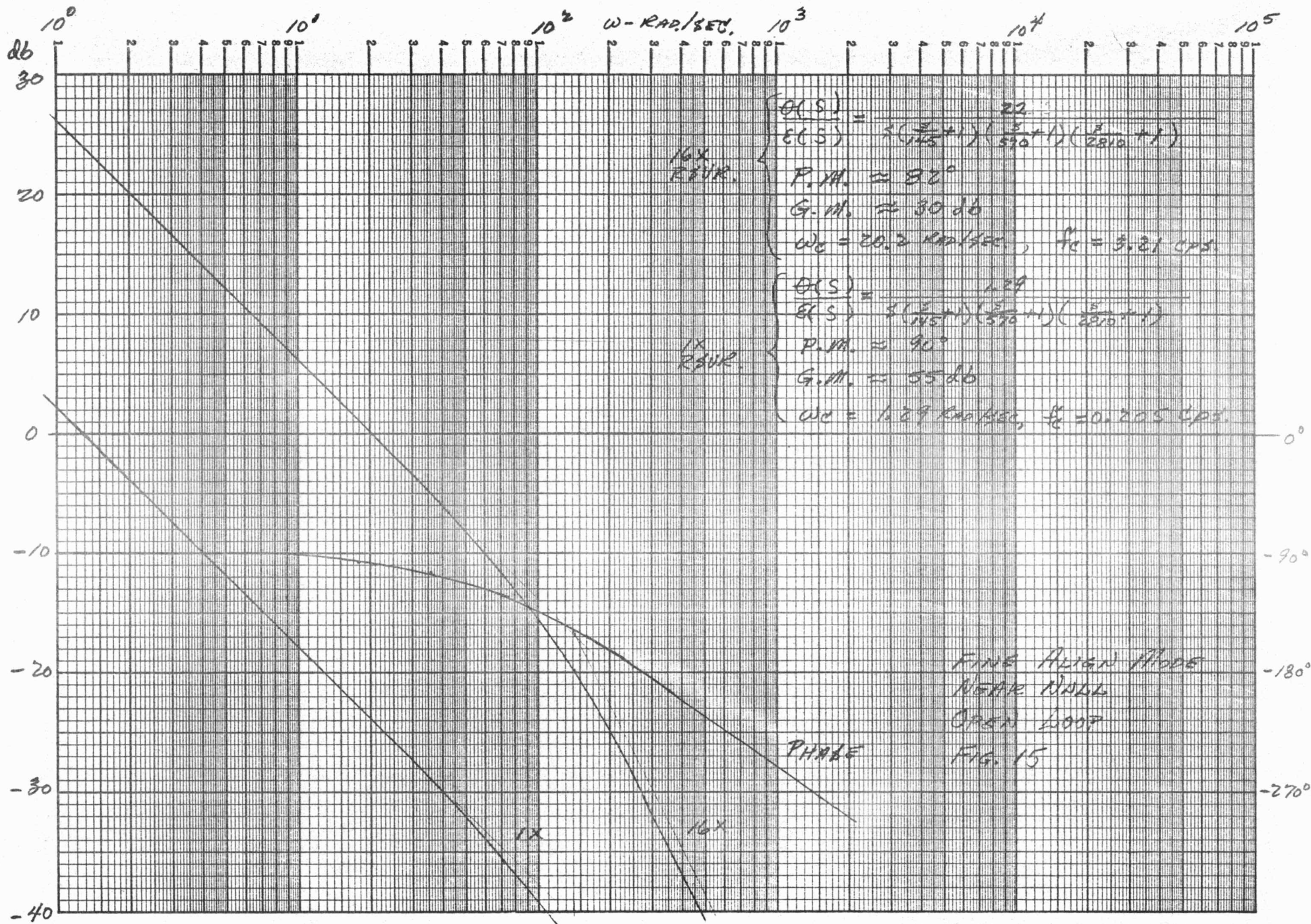
ERIC ARON  
CDI FOLLOWUP TIMES  
VS. INITIAL OFFSET  
FIG. 14

TIME TO ZERO - SECONDS

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300

INITIAL ERROR - ARC MINUTES





16X  
RVR.

$$G(S) = \frac{22}{S \left( \frac{S}{145} + 1 \right) \left( \frac{S}{570} + 1 \right) \left( \frac{S}{2870} + 1 \right)}$$

P.M.  $\approx 80^\circ$   
 G.M.  $\approx 30$  db  
 $\omega_c = 20.2$  RAD/SEC,  $f_c = 3.21$  CPS.

IX  
RVR.

$$G(S) = \frac{1.29}{S \left( \frac{S}{145} + 1 \right) \left( \frac{S}{570} + 1 \right) \left( \frac{S}{2870} + 1 \right)}$$

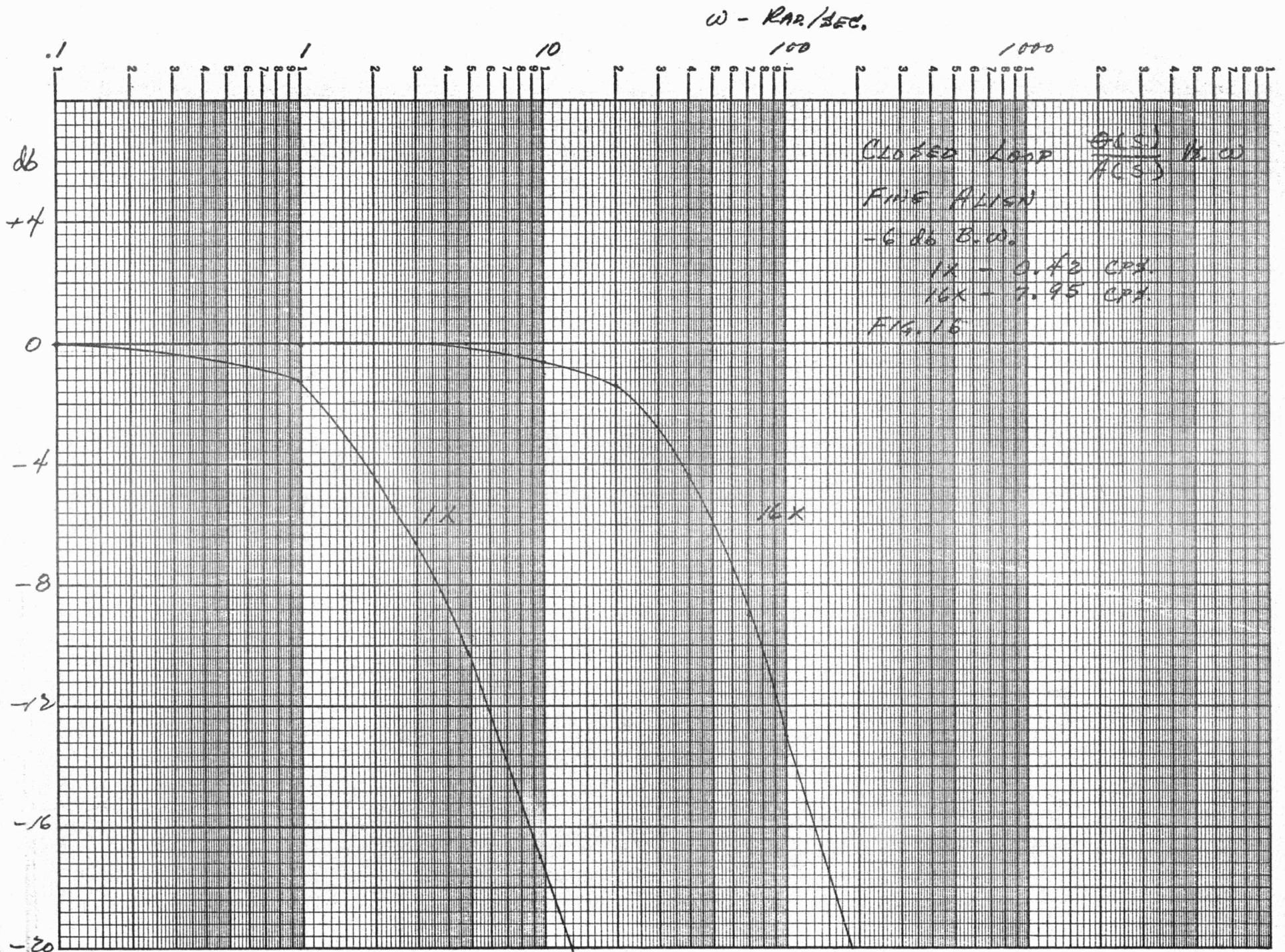
P.M.  $\approx 90^\circ$   
 G.M.  $\approx 55$  db  
 $\omega_c = 1.29$  RAD/SEC,  $f_c = 0.205$  CPS.

FINE ALIGN MODE  
 NEAR NULL  
 OPEN LOOP  
 FIG. 15

PHASE

IX

16X





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	ENGINEERING DESIGN INFORMATION EXHIBIT	
PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT	By	Date
	A. Laubenstein	8/15/63

## 6.3.1.3 (Continued)

Using approximate transfer functions for the "fine align" mode, the "velocity lag" can be obtained as follows,

$$\frac{\theta(S)}{A(S)} = \frac{1}{\frac{S}{1.3} + 1} \quad \text{one speed control}$$

$$\frac{\theta(S)}{A(S)} = \frac{1}{\frac{S}{29.4} + 1} \quad \text{sixteen speed control}$$

for the velocity input  $A(S) = \frac{A}{S^2}$ ,

$$\theta_{1X}(t) = At - \frac{A}{1.3} + \frac{A}{1.3} e^{-1.3t} \quad \text{one speed control}$$

$$\theta_{1X}(t) = At - \frac{A}{29.4} + \frac{A}{29.4} e^{-29.4t} \quad \text{sixteen speed control}$$

The constant terms,  $-\frac{A}{1.3}$  and  $-\frac{A}{29.4}$ , are the amount that the output position lags the commanded position and are called the "velocity lags".

These constants can be shown in another form independent of the input command rate. These would be the output time lags due to a velocity input. From above,

$$\tau = \frac{1}{1.3} = 0.77 \text{ sec.} \quad \text{one speed control}$$

$$\tau = \frac{1}{29.4} = 0.034 \text{ sec.} \quad \text{sixteen speed control}$$

From the computer simulation,

$$\tau = 0.9 \text{ sec.} \quad \text{one speed control}$$

$$\tau = 0.05 \text{ sec.} \quad \text{sixteen speed control}$$

The position lag for any rate input can now be calculated from these time lags.

The CDU input rates that could occur in the "fine align" mode are a result of pulsing the gyros (1.1 deg./sec.) and spacecraft attitude rates (0.25 deg./sec.). It appears that the sixteen speed resolver will retain

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ENGINEERING  
 DESIGN INFORMATION  
 EXHIBIT

PRELIMINARY PERFORMANCE SPECIFICATION  
 INERTIAL COUPLING DISPLAY UNIT

By  
 A. Laubenstein

Date  
 8/15/63

6.3.1.3 (Continued)

control for typical velocity inputs.

6.3.1.4 COMPUTER DRIVEN MODE -- In the "coarse align", "attitude control", and "entry" modes of operation, the CDU one speed shaft is driven by the AGC to some desired angle. The computer pulse information is converted in the DAC to an analog signal which positions the CDU. CDU shaft position information is then quantized and compared to the commanded position in the DAC and in the AGC.

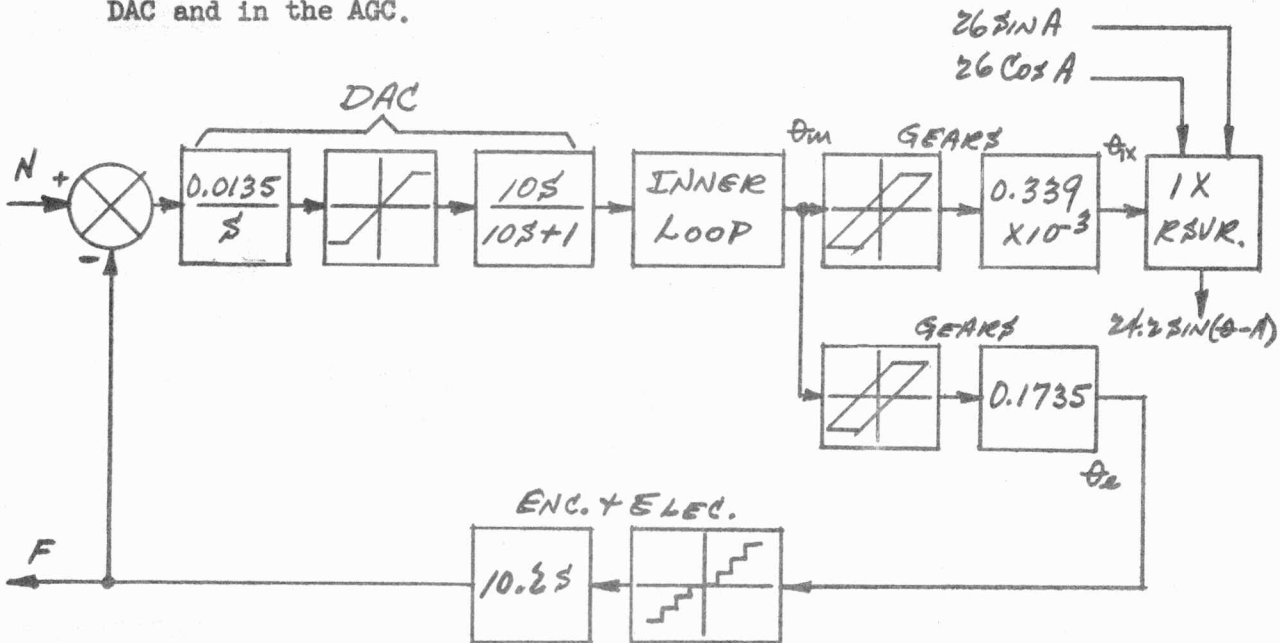
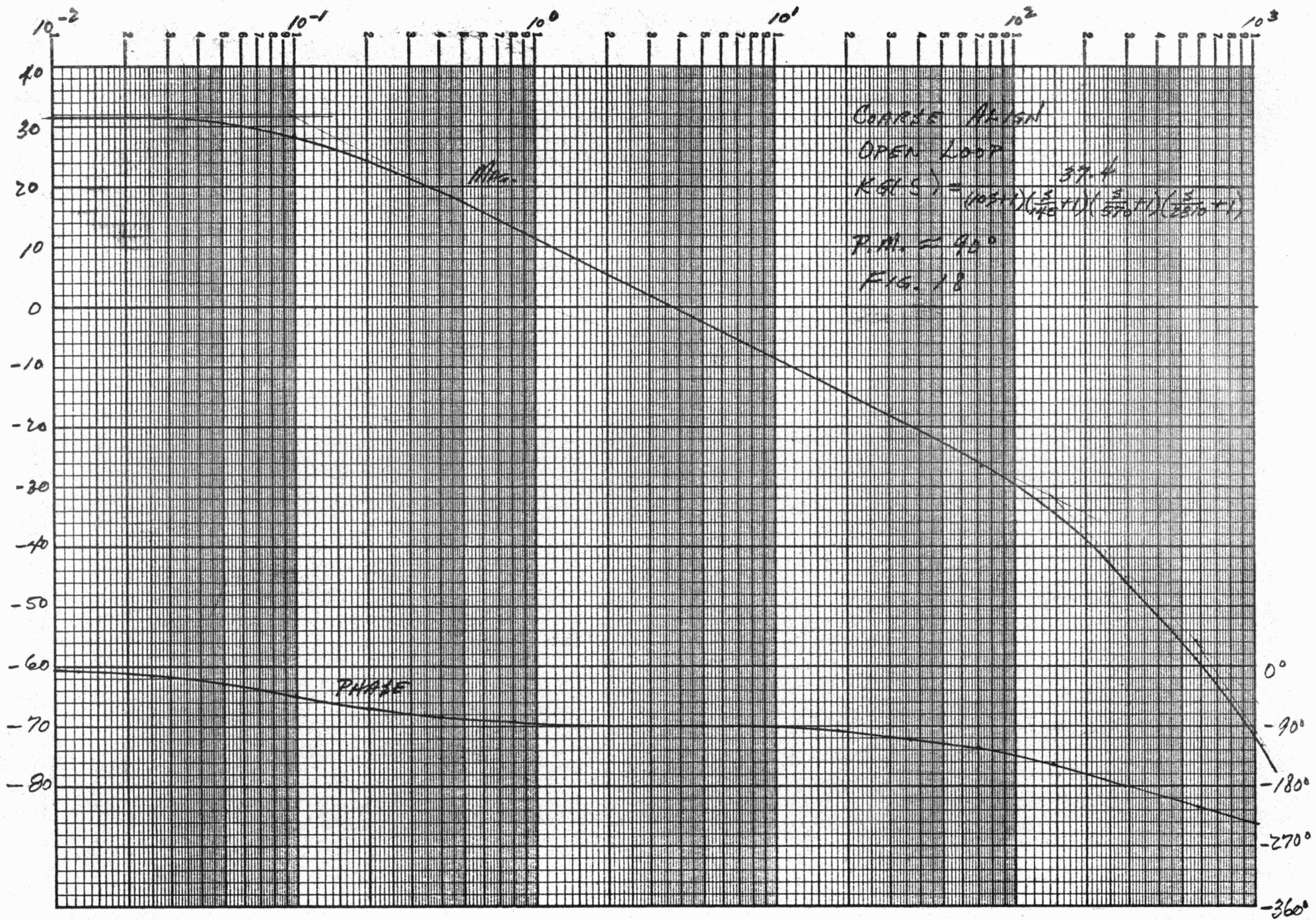


Figure 17

COMPUTER DRIVEN MODE -- CDU LOOP

Since the bandwidth of the CDU loop in this mode is very small compared to the 3200 pps pulse rate from the AGC, the steps of voltage that are placed on the DAC capacitor appear as a continuous signal to the rest of the CDU loop. Likewise, the feedback pulses from the encoder electronics arrive at a very fast rate except just as the CDU shaft is stopping.



AC SPARK PLUG DIVISION

General Motors Corporation  
Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
DESIGN INFORMATION  
EXHIBIT

PRELIMINARY PERFORMANCE SPECIFICATION  
INERTIAL COUPLING DISPLAY UNIT

By  
A. Laubenstein

Date  
8/15/63

6.3.1.4 (Continued)

Neglecting the nonlinearities, i.e., saturation, deadzone, backlash, and quantizing, the loop could be represented as,

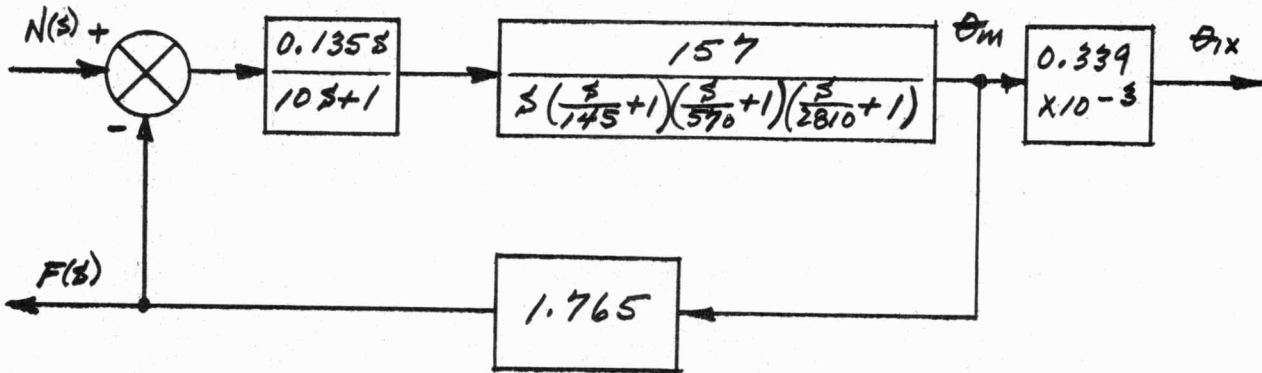


Figure 19

where  $N(S)$  is a step input of a magnitude equal to the summation of the strengths of a train of impulses.

The assumption of a step input is valid for a limited number of pulses coming at a very fast rate in a small finite time compared to the time constants of the loop.

$$\frac{\theta_{1X}(S)}{N(S)} = \frac{0.185 \times 10^{-3}}{\left(\frac{S}{4} + 1\right)\left(\frac{S}{139} + 1\right)} \quad \frac{\text{rad.}}{\text{pulse}}$$

$$\frac{\theta_{1X}(S)}{N(S)} = \frac{38.1}{\left(\frac{S}{4} + 1\right)\left(\frac{S}{139} + 1\right)} \quad \frac{\text{sec.}}{\text{pulse}}$$

$$\theta_{1X}(t) = N \times 10^{-4} (1.85 - 1.9e^{-4t} + .0547e^{-139t}) \quad \text{rad.}$$

$$\frac{F(S)}{N(S)} = \frac{0.961}{\left(\frac{S}{4} + 1\right)\left(\frac{S}{139} + 1\right)} \quad \frac{\text{pulse}}{\text{pulse}}$$

Approximately 4% of the pulse information is lost in the DAC due to the charge leaking off the capacitor since ideally one pulse would produce  $\frac{\pi}{(2)14}$  radians or 39.6 sec. of one-speed shaft rotation.

## AC SPARK PLUG DIVISION

General Motors Corporation  
Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
DESIGN INFORMATION  
EXHIBITPRELIMINARY PERFORMANCE SPECIFICATION  
INERTIAL COUPLING DISPLAY UNITBy  
A. LaubensteinDate  
8/15/63

## 6.3.1.4 (Continued)

The above expressions neglect the important consideration that the voltage on the DAC capacitor is limited to 10 volts maximum. In addition, each succeeding input pulse carries less weight than the preceding pulse because the voltage on the capacitor bucks the charging voltage source. Another consideration is the fact that the weight of the feedback pulses increases with the charge existing upon the DAC capacitor, because any existing voltage on the capacitor adds to the charging voltage. Each of these effects results in information being lost in the DAC in addition to that lost due to DAC decay.

An analog computer simulation of the CDU in the AGC driven mode was performed using a constant weight for input or feedback pulses, but including the DAC saturation, the amplifier saturation, and the motor deadzone, as well as, the one-speed resolver nonlinearity.

The results from this simulation indicate that due to the DAC output limit and the decay of the DAC capacitor, approximately 4.5% of the pulse information in one standard burst of 0.0833 seconds or approximately 7.5% of the pulse information in an "entry" burst of 0.32 seconds is lost.

In the actual system, considerably more information than this will be lost due to the varying weight of the input and feedback pulses as explained above, and also, the more pulse bursts in succession the more information that will be lost because the DAC output does not go to zero between bursts of pulses.

Analog Computer Results

AGC Command	$\theta_{IX}$ Output	Time Constant	Time for $\pm 2\%$ Final	DAC Error	$\dot{\theta}_{IX}$ Max.
One Burst = 267 Pulses	2.8 deg.	0.58 sec.	1.4 sec.	4.5%	5.2 deg./sec.
Entry = 1025 Pulses	10.4 deg.	1.15 sec.	2.45 sec.	7.5%	10.9 deg./sec.
Continuous Train	134 deg. in 10 sec.	---	---	Increas- ing	15.2 deg./sec.

TABLE 2

<p align="center"><b>AC SPARK PLUG DIVISION</b> General Motors Corporation Milwaukee, Wisconsin</p>	<p><b>XDE</b> 34-8-529</p>	
<p><b>PRELIMINARY PERFORMANCE SPECIFICATION</b> <b>INERTIAL COUPLING DISPLAY UNIT</b></p>	<p align="center"><b>ENGINEERING DESIGN INFORMATION EXHIBIT</b></p>	
	<p>By A. Laubenstein</p>	<p>Date 8/15/63</p>

6.3.2 **STATIC PERFORMANCE** -- The static errors of the CDU are dependent upon the system function and will be discussed separately for each. The individual errors that contribute to any of the total output errors will be discussed and likely distributions will be assumed. These will then be combined to yield an indication of the total output errors. All errors will be given as deviations from some imaginary one-speed ideal shaft position. The zero reference is defined as the sixteen-speed CDU resolver electrical in-phase zero.

6.3.2.1 **FOLLOW-UP FUNCTION STATIC ERRORS** -- While performing the follow-up function, the CDU shaft repeats the gimbal angle. The pertinent outputs are the encoder output pulses and the dial readings.

6.3.2.1.1 **ENCODER OUTPUT ERROR** -- The encoder output error is the error between the encoder electronics pulse output and the actual gimbal angle.

<u>Contributing Errors</u>	<u>Max. Values</u>	<u>Assumed Distribution</u>	<u>Standard Deviation</u>
Encoder Pulse Centering	± 3.6 sec	uniform	± 2.04 sec
Encoder Quantizing	± 19.775 sec	uniform	± 11.4 sec
Rsvr. and Tach Nulls	± 2 sec	uniform	± 1.15 sec
Motor Deadzone	± .75 sec	uniform	± .433 sec
16X to Encoder Backlash	± 2 sec	uniform	± 1.15 sec
16X Gimbal Rsvr. Ang. Error	± 20 sec	sinusoidal	± 14.14 sec
16X Gimbal Rsvr. Null	± .334 sec	uniform	± .193 sec
16X CDU Rsvr. Ang. Error	± 3.75 sec	sinusoidal	± 2.65 sec
Total Standard Deviation = normal			± 18.5 sec

This normally distributed error has a mean of either + 10 or -10 sec. This miscentering is an additional error in this output.

**AC SPARK PLUG DIVISION**  
 General Motors Corporation  
 Milwaukee, Wisconsin

**XDE** 34-5-529

**ENGINEERING  
 DESIGN INFORMATION  
 EXHIBIT**

**PRELIMINARY PERFORMANCE SPECIFICATION  
 INERTIAL COUPLING DISPLAY UNIT**

By  
**A. Laubenstein**

Date  
**8/15/63**

**6.3.2.1.2 DIAL READING ERROR --** The dial reading error is the difference between what the dial reads and the actual gimbal shaft angle.

<u>Contributing Errors</u>	<u>Max. Values</u>	<u>Assumed Distribution</u>	<u>Standard Deviation</u>
Dial Zero Align	± 60 sec	normal	± 20 sec
16X to Dial Backlash	± 2 sec	uniform	± 1.15 sec
Resolver and Tach. Nulls	± 2 sec	uniform	± 1.15 sec
Motor Deadzone	± .75 sec	uniform	± .433 sec
Dial Resolution	± 7.2 sec	normal	± 2.4 sec
16X gimbal Rsvr. Ang. Error	± 20 sec	sinusoidal	± 14.14 sec
16X Gimbal Rsvr. Null	± .334 sec	uniform	± .193 sec
16X CDU Rsvr. Ang. Error	± 3.75 sec	sinusoidal	± 2.65 sec
Total Standard Deviation = normal			± 24.8 sec

**6.3.2.2 COMPUTER DRIVEN FUNCTION --** When considering the CDU alone and not considering the position feedback and comparison in the AGC, the CDU one-speed shaft may be in error by as much as 50%. This static error is very dependent upon the number of input pulse bursts, the number of pulses per burst and the DAC nonlinearities. Since in actual system operation, there is a comparison in the AGC of input and feedback pulses, the encoder output, in the steady state, is always within one pulse of the computer desired angle. Therefore, including the position feedback to the computer and taking the computer desired angle as the reference, the output errors are as follows.

AC SPARK PLUG DIVISION  
General Motors Corporation  
Milwaukee, Wisconsin

XDE 34-8-529

ENGINEERING  
DESIGN INFORMATION  
EXHIBIT

PRELIMINARY PERFORMANCE SPECIFICATION  
INERTIAL COUPLING DISPLAY UNIT

By  
A. Laubenstein

Date  
8/15/63

#### 6.3.2.2.1 ONE-SPEED RESOLVER OUTPUT ERROR - NORMAL

<u>Contributing Errors</u>	<u>Max. Values</u>	<u>Assumed Distribution</u>	<u>Standard Deviation</u>
Encoder Quantizing	$\pm 19.775 \text{ sec}$	uniform	$\pm 11.4 \text{ sec}$
Encoder Pulse Centering	$\pm 3.6 \text{ sec}$	uniform	$\pm 2.04 \text{ sec}$
Encoder to 1X Backlash	$\pm 270 \text{ sec}$	uniform	$\pm 156 \text{ sec}$
1X CDU Rsvr. Ang. Error	$\pm 180 \text{ sec}$	sinusoidal	$\pm 127 \text{ sec}$
1X Gimbal Rsvr. Ang. Error	$\pm 300 \text{ sec}$	sinusoidal	$\pm 212.0 \text{ sec}$
1X CDU Rsvr. Align	$\pm 60 \text{ sec}$	normal	$\pm 20 \text{ sec}$
Total Standard Deviation = normal			$\pm 300 \text{ sec}$

This normally distributed error has a mean of either  $+10$  or  $-10 \text{ sec}$ . This miscentering is an additional error in the output.

#### 6.3.2.2.2 16X RESOLVER OUTPUT ERROR - ENTRY

<u>Contributing Errors</u>	<u>Max. Values</u>	<u>Assumed Distribution</u>	<u>Standard Deviation</u>
Encoder Quantizing	$\pm 316 \text{ sec}$	uniform	$\pm 182.5 \text{ sec}$
Encoder Pulse Centering	$\pm 57.6 \text{ sec}$	uniform	$\pm 33.1 \text{ sec}$
1X Gimbal Rsvr. Ang. Error	$\pm 300 \text{ sec}$	sinusoidal	$\pm 212 \text{ sec}$
16X CDU Rsvr. Ang. Error	$\pm 60 \text{ sec}$	sinusoidal	$\pm 42.4 \text{ sec}$
Encoder to 16X Backlash	$\pm 32 \text{ sec}$	uniform	$\pm 18.5 \text{ sec}$
Total Standard Deviation = normal			$\pm 285 \text{ sec}$

This normally distributed error has a mean of either  $+160$  or  $-160 \text{ sec}$ . This miscentering is an additional error in this output.



AC SPARK PLUG DIVISION General Motors Corporation Milwaukee, Wisconsin	XDE 34-S-529	
	ENGINEERING DESIGN INFORMATION EXHIBIT	
PRELIMINARY PERFORMANCE SPECIFICATION INERTIAL COUPLING DISPLAY UNIT	By	Date
	A. Laubenstein	8/15/63

6.3.2.3 MANUAL OPERATION -- In manual operation, the output of interest is the one-speed CDU resolver output. The CDU gear train is positioned using the dial readout. The one-speed CDU resolver output error is as follows.

<u>Contributing Errors</u>	<u>Max. Values</u>	<u>Assumed Distribution</u>	<u>Standard Deviation</u>
Dial Resolution	$\pm 7.2 \text{ sec}$	normal	$\pm 2.4 \text{ sec}$
Dial Zero Alignment	$\pm 60 \text{ sec}$	normal	$\pm 20 \text{ sec}$
Dials to LX Backlash	$\pm 270 \text{ sec}$	uniform	$\pm 156 \text{ sec}$
LX CDU Rsvr. Align	$\pm 60 \text{ sec}$	uniform	$\pm 34.6 \text{ sec}$
LX Gimbal Rsvr. Ang. Error	$\pm 300 \text{ sec}$	sinusoidal	$\pm 212 \text{ sec}$
LX CDU Rsvr. Ang. Error	$\pm 180 \text{ sec}$	sinusoidal	$\pm 127 \text{ sec}$
Total Standard Deviation = normal			$\pm 295 \text{ sec}$

#### 6.4 PRACTICAL CONSIDERATIONS

During the analog computer simulations, the loop nonlinearities were varied to indicate their effects on the loop responses. Figure 13 shows the effects of varying the amplifier saturation level and the motor deadzone on the loop response during the "zero encode" mode. The general effects noted here hold for the other modes of operation as well; that is, the lower the saturation level and the larger the deadzone, the slower the loop response. All other recorded data was taken using a 2 volt deadzone and a 30 volt saturation level.

In order to reduce the complexity of the simulation, gear backlash was not included. However, its effects on loop static and dynamic performance can be predicted.

Dynamically, the gearing backlash will inject a slight amount of phase lag into the loops causing them to be a little less stable. However, this is not important since the CDU is very stable in all modes of operation.

AC SPARK PLUG DIVISION  
 General Motors Corporation  
 Milwaukee, Wisconsin

XDE 34-S-529

ENGINEERING  
 DESIGN INFORMATION  
 EXHIBIT

PRELIMINARY PERFORMANCE SPECIFICATION  
 INERTIAL COUPLING DISPLAY UNIT

By  
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 8/15/63

Statically, the gearing backlash will add to the static errors of the loops and has been considered in Section 6.3.2.

6.5 TEST TOLERANCE CORRELATION

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