APOLLO ENGINEERING MEMORANDUM AP-M # 6790

7 May 1965

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FROM: Mr. R. Haigler

SUBJECT: ERROR OF THE ELECTRONIC COUPLING DATA UNIT (Paper XI)

Summary

The error inherent in the present CDU design has been determined to have a maximum range of from +43.25 sec to -66.75 sec. This is an error with a mean of -11.75 sec and a standard deviation of ±24.2 sec.

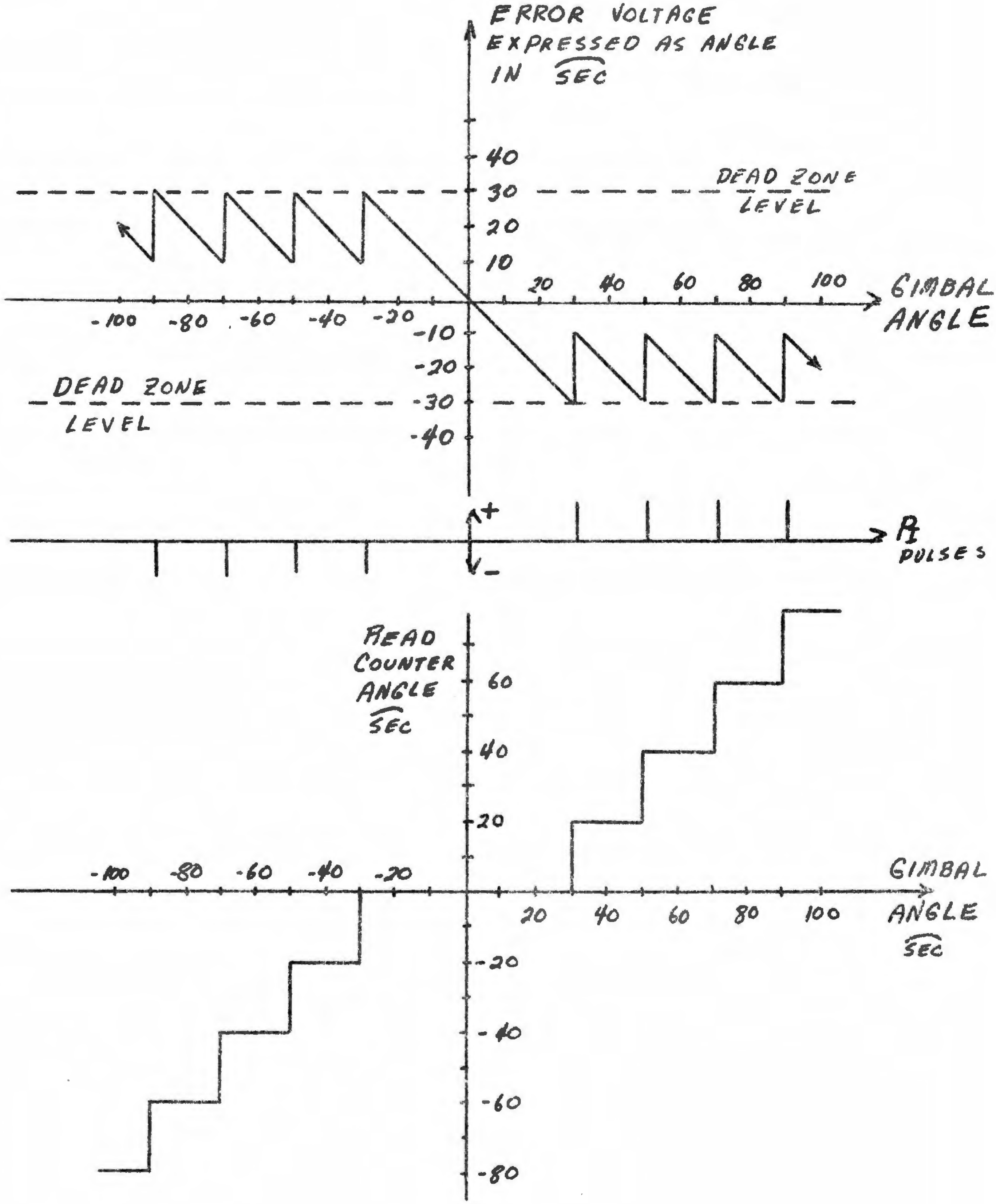
CDU Error Analysis

The error inherent in the CDU can be divided into two categories; the digitation error, and the linearization error.

The digitation error is defined by the CDU read counter dead-zone, the smallest read counter bit size, and the weight of the output pulses to the computer. In the case of an IMU CDU the smallest read counter bit is equivalent to 20 seconds of arc of a 1X shaft, the CDU dead-zone is equivalent to 1 1/2 bits or 30 sec, and the output pulses are weighted at 40 sec (1X shaft). The combination of these errors to produce the digitation error will be derived in the following graphs.

Figure 1 is a plot of error voltage (expressed as an equivalent angle) at the output of the main summing amplifier vs gimbal angle. This figure also shows the 1 1/2 bit dead-zone and the generation of each incrementing pulse to the CDU read counter (P_I pulses).

Figure 1



ERROR VOLTAGE EXPRESSED AS ANGLE IN SEC
40
30
20
10
-10
-20
-30
-40
DEAD ZONE LEVEL
DEAD ZONE LEVEL
-100 -80 -60 -40 -20
20 40 60 80 100
GIMBAL ANGLE
+
-
P_I PULSES
READ COUNTER ANGLE SEC
60
40
20
-20
-40
-60
-80
GIMBAL ANGLE SEC

As can be seen in Figure 1 the maximum error in the read counter angle is ±30 $\widehat{sec}$. This is dependent only on the size of the dead-zone in this case since the quantization (smallest read counter bit size) is smaller than the dead-zone. Figure 1 shows only the case for either + or - rotation of the gimbal starting from zero. If the gimbal were to change direction of rotation at a point other than zero the same error curve (±30 $\widehat{sec}$) would result.

The output of the CDU to the computer is the output of the 2^0 read counter stage ($\Delta 2^0$). Figure 2 shows the CDU output for the same angular rotation as shown in Figure 1. Figure 2 also shows the computer angle (indicated angle) vs actual angle and the error curve vs actual angle. It is important to notice the equation used to define error is:

$$\text{Error} = \text{Indicated Angle} - \text{Actual Angle}.$$

In order to understand more fully the reason for the -10 $\widehat{sec}$ bias in the digitation error, some discussion on the nature of the read counter is necessary. The CDU read counter is a 16 stage binary counter with the output to the computer being an output of the 2^0 bit, therefore, a change in the 2^1 bit. Now, consider the first 3 stages of the binary read counter with a storage of zero as shown below.

Stage →	2^2	2^1	2^0
Value →	0	0	0

Now consider incrementing the counter one bit at a time.

2^2	2^1	2^0
0	0	1

Counter state after receiving the first + pulse

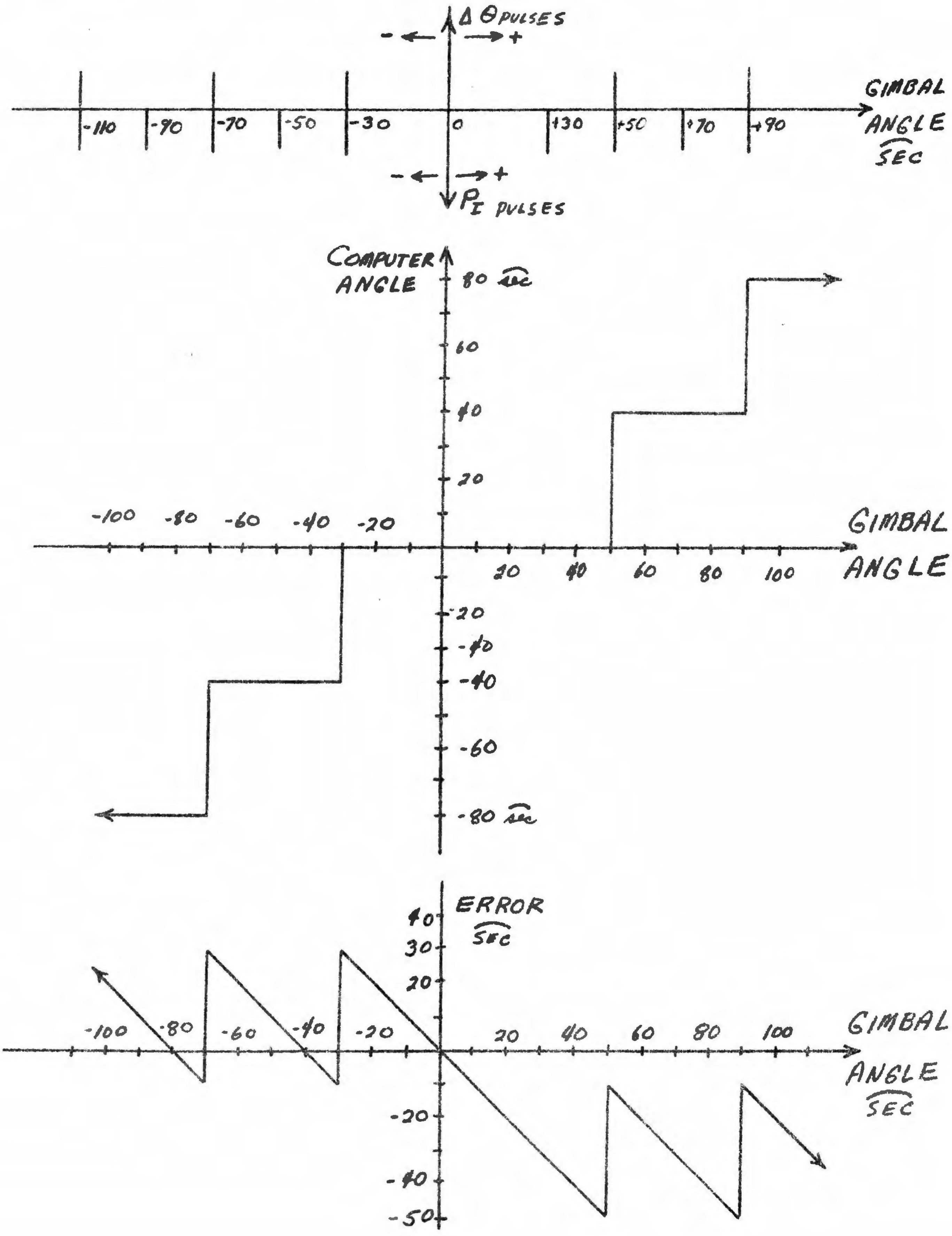
For the first pulse there is no change in the 2^1 bit so no output to the computer.

2^2	2^1	2^0
0	1	0

After receiving the second + pulse

Upon the receipt of the second + pulse the 2^1 stage changes state and, therefore, one $\Delta\theta$ pulse is generated.

Figure 2


Δ θ PULSES
- +
GIMBAL ANGLE SEC
-110 -90 -70 -50 -30 0 +30 +50 +70 +90
- +
P_I PULSES
COMPUTER ANGLE
80 sec
60
40
20
-100 -80 -60 -40 -20
20 40 60 80 100
GIMBAL ANGLE
-20
-40
-40
-60
-80 sec
ERROR SEC
40
30
20
-100 -80 -60 -40 -20
20 40 60 80 100
GIMBAL ANGLE SEC
-20
-40
-50

Now consider the same counter with a negative input (count down) starting at zero.

2^2	2^1	2^0	
0	0	0	Start at zero
1	1	1	Count down 1 pulse
1	1	0	Count down 1 pulse again
1	0	1	Count down again

It can be seen from this chart that if the $\Delta\theta$ output is a change in the 2^1 stage a $\Delta\theta$ pulse is produced on the 1st, 3rd, 5th, etc. count down pulses. This is the result shown in Figure 2.

From the last curve of Figure 2 it is seen that the maximum error, starting at zero gimbal angle, is +30 or -50 $\widehat{sec}$ depending on which direction the gimbal angle turns. For a realistic value of error it must be assumed that the gimbal angle is random and that we may change direction at any gimbal angle. Figure 3 shows the locus of error vs gimbal angle for both positive and negative angular rotation.

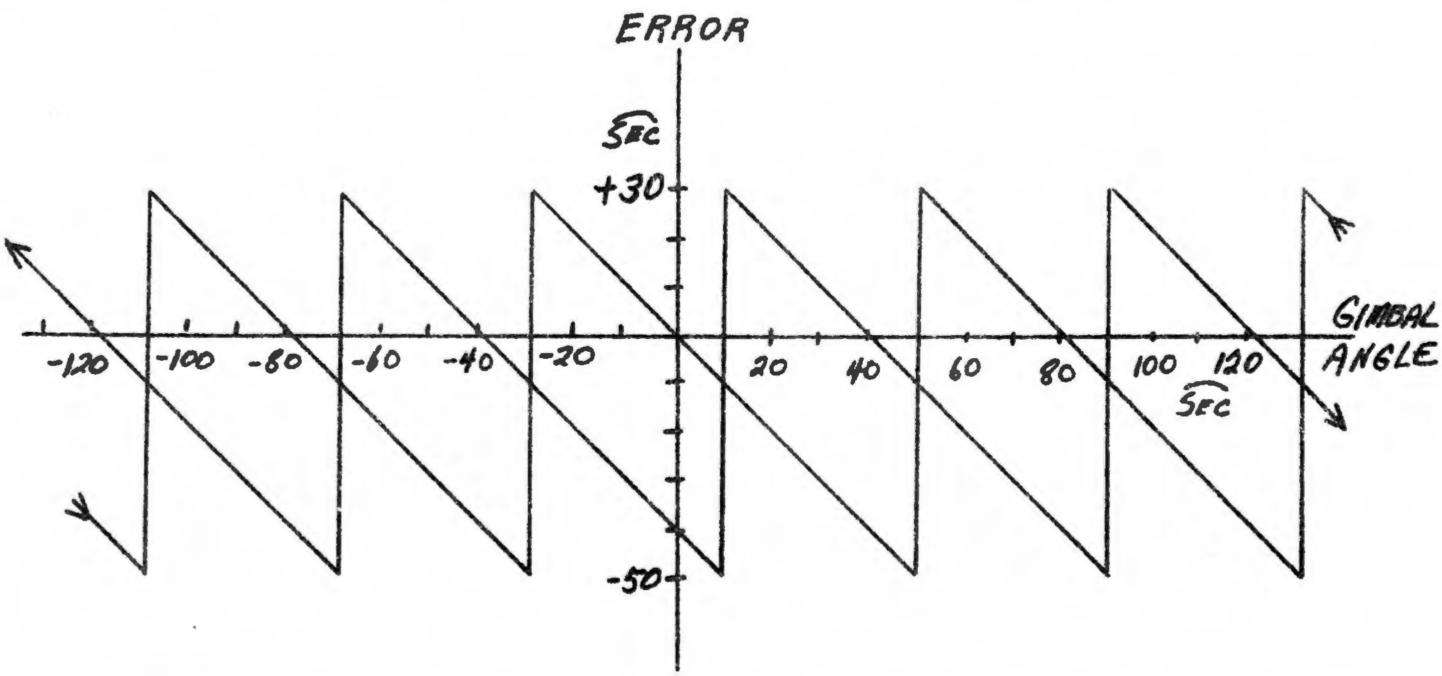
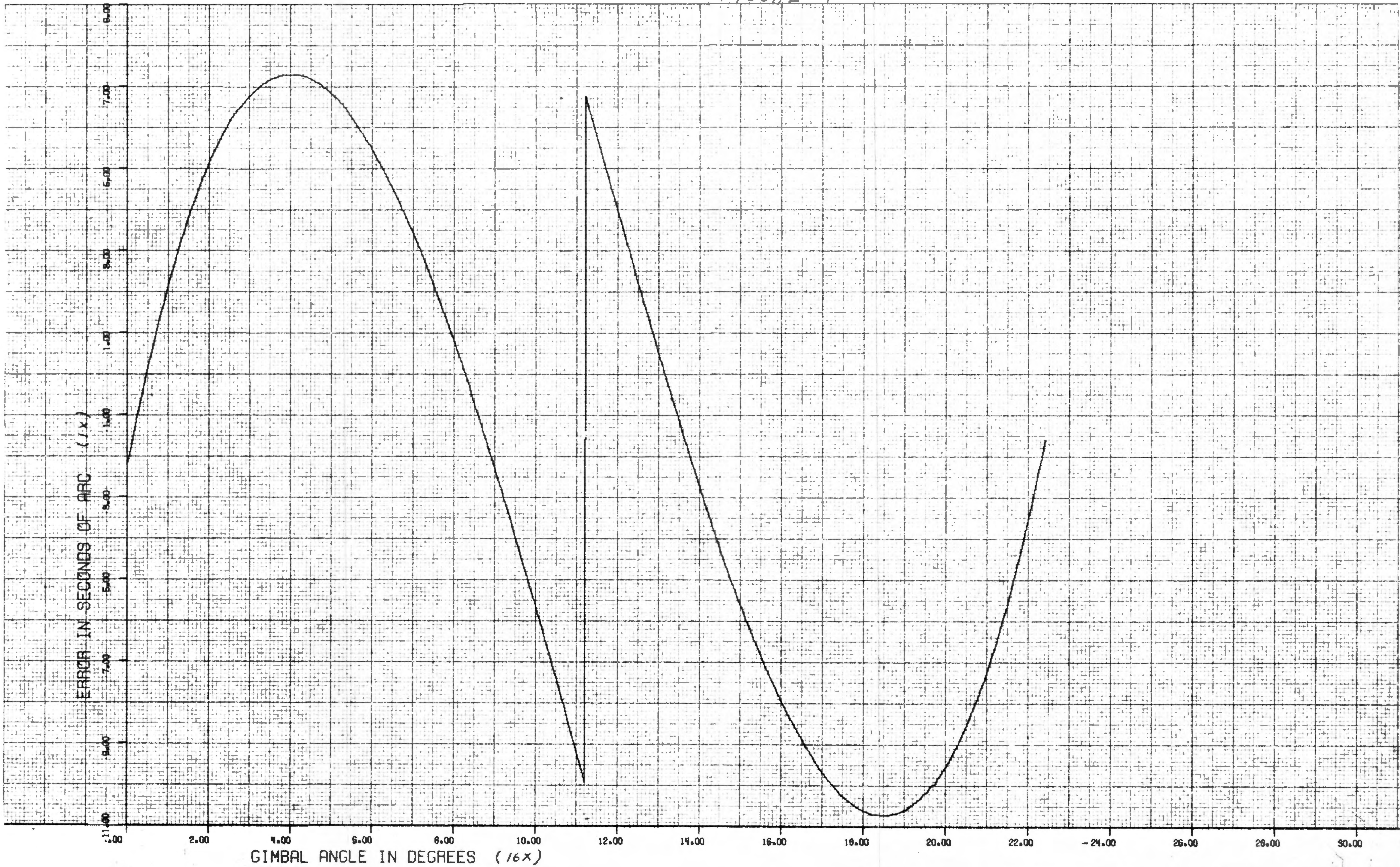


Figure 3

CDU LINEARIZATION ERROR

FIGURE 4



From Figure 3 it can be seen that at each value of gimbal angle there are two possible values of error except at the points where $\Delta\theta$ pulses are generated where there are three possible values of error. From Figure 3 the CDU digitation error is -10 sec ±40 sec. It should be recognized that there are two additional errors associated with the digitation error. These are the uncertainity of the dead-zone and the scale factor uncertainity. The uncertainity of the dead-zone is the tolerance of the Schmidt trigger firing level which is used to produce the dead-zone. This error is ±10% of the nominal value (30 $\widehat{sec}$) or ±3 $\widehat{sec}$. The scale factor uncertainity is a result of the error amplifier gain variation. The error AMP gain is 7.5 V/V ±10%. This 10% variation will correspond to an additional ±3 $\widehat{sec}$ of error.

The linearization error is a result of approximating a portion of a sine function with a straight line. In the mechanization of the read counter (Ref. AP-M #4850 and AP-M #4927) the following equation is solved:

$$0 = \sin(\theta - \psi) - \phi \cos(\theta - \psi) + K_2 \sin 11.25^\circ + K_3 \text{ Bias}$$

In this equation ψ is restricted to steps of 11.25 degrees and ϕ is restricted to steps of .088 degrees (16X shaft). K_2 and K_3 are either 1 or 0 depending on the value of θ. For $0 < \theta < 11.25^\circ$ then $K_2 = 1$ and $K_3 = 0$, if $11.25^\circ < \theta < 22.5^\circ$ then $K_2 = 0$ and $K_3 = 1$. Since the error is periodic on 22.5° (16X shaft) intervals, only the first interval is considered. The error curve shown in Figure 4 was computed on the digital computer using a program derived from the actual resistor values used in the CDU. The discontinuity at 11.25° is caused by the removal of the -11.25° bit and the insertion of the bias bit. For more detail on the switching system see AP-M #4850 and AP-M #4927.

Table 1 is a list of the CDU errors previously developed along with their means and standard deviations.

Table 1

Error	Assumed Distribution	Mean	Error	1σ
Digitation Error	Uniform	-10 $\widehat{sec}$	±40 $\widehat{sec}$	±23.3 $\widehat{sec}$
Dead-Zone Uncertainity	Normal	0	± 3 $\widehat{sec}$	± 1 $\widehat{sec}$
Scale Factor Uncertainity	Normal	0	± 3 $\widehat{sec}$	± 1 $\widehat{sec}$
Linearization Error	Sinusodial	- 1.75 $\widehat{sec}$	± 9 $\widehat{sec}$	± 6.36 $\widehat{sec}$
Total	Normal	-11.75 $\widehat{sec}$		±24.2 $\widehat{sec}$

The 1 σ values have been added using a root of the sum of the squares method to determine the 1 σ value of the CDU Error. The worst case CDU error is -66.75 sec +43.25 sec. This analysis has assumed an ideal input to the CDU and, therefore, in any system application the error of the input must be included in the overall error of the CDU indicated angle (Ref. XDE 34-S-11 for the IMU-CDU combined error).

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