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OPTICAL RADAR ANGLE TRACKING MOUNT

George J. Thompson, et al

Owens-Illinois, Incorporated

Prepared for:

Rome Air Development Center
Advanced Research Projects Agency

September 1974

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RADC-TR-73-205 ADDENDUM
Final Report
September 1974

OPTICAL RADAR ANGLE TRACKING MOUNT

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D D C
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This is a technical report designated F(4)-864-047-022-2251A, consisting of:

(1) Hydrostatic Bearing Tests, Azimuth and Elevation.
(2) Servo Transfer Functions
(3) Summary of Test Results for the Optical Radar Angle Tracking Mount.

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OPTICAL RADAR ANGLE TRACKING MOUNT

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This Report Was Partially Funded
Under ARPA Order 1279

FOREWORD

This Final Report, covering the period July 1973 to July 1974, was prepared by Owens-Illinois, Incorporated, Fecker Systems Division, Pittsburgh, Pennsylvania, under Contract F30602-72-C-0192, Job Order 65270121, with Rome Air Development Center, Griffiss Air Force Base, New York. The investigation is also partially sponsored by the Defense Advanced Research Project Agency under ARPA Order 1279. Mr. Fred J. Demma (OCTM) was the RADC Project Engineer.

Numbered by Fecker Systems F(4)-864-047-022-2251A, this report is issued as an addendum to the interim technical report, RADC-TR-73-205, dated July 1973, and should be considered a part thereof. Sections III through VI and Appendices F through H constitute this addendum.

This report has been reviewed by the RADC Information Office (OI) and is releasable to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved.

APPROVED:

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Project Engineer

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FOR THE COMMANDER:

JAMES G. McGINNIS, Lt Col, USAF
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ABSTRACT

A Technical Report designated F(4)-864-047-022- 2251A (RADC-TR No. 1279) consisting of:

.. Hydrostatic Bearings Tests, Azimuth and Elevation.

.. Servo Transfer Functions

.. Summary of test results for the Optical Radar Angle Tracking Mount

EVALUATION

This effort was for the design, fabrication, installation, and test of a Coelostat Tracking Mount which permits optical sensor instrumentation to remain stationary while the mount points anywhere within the hemisphere. This particular system allows excursions of approximately five (5) degrees below the horizon with a one (1) meter clear aperture. The mount is a two (2) mirror system. Both mirrors are mounted on a platform that is rotatable to any azimuth position at a maximum velocity of 5°/sec and an acceleration of 3.0°/sec^2.

The tracking mount fabricated by Owens-Illinois under this effort is a unique system built to exacting specifications, with the critical parameter being a 1σ random dynamic tracking error of ≤ 20 μradians. An error budget analysis conducted prior to this fabrication contract demonstrated the feasibility of a 1σ error of ≤ 20 μradians, however, it remained to be experimentally verified. During the final acceptance testing phase of the contract the individual random error contributions such as the base, structure, azimuth axis, and elevation axis were measured and resulted in a 1σ error of 17.7 μradians.

At the conclusion of the final acceptance testing the mount will undergo its calibration phase with additional test data providing a firm basis for definition of the systematic errors in the system. Once this is accomplished a complete characterization of the mount performance will be completed.

The high angular resolution and precise beam control provided by the coelostat will be utilized in precision laser beam pointing experiments in support of laser signature technology efforts contained in RADC Technology Planning Objective Number 5. Specifically, 10.6μ laser backscatter experiments will be conducted to exploit the inherently precise wavelength dependent resolution capabilities of laser sensors.

Fred J. Demma

FRED J. DEMMA
Project Engineer

SECTION III

HYDROSTATIC BEARING TESTS

1.0 INTRODUCTION

Testing was conducted on the system oil bearings and their elements to verify their predicted performances.

Total system oil flow as well as bearing stiffnesses was determined.

Testing was conducted in four steps in accordance with the applicable test procedures.

a. Azimuth axis bearing vertical stiffness IAW FSD document F(8)-864-047-022-2287.

b. Azimuth axis bearing moment stiffness IAW FSD document F(8)-864-047-022-2287.

c. Elevation axis bearing lateral stiffness IAW FSD document F(8)-874-047-022-2292.

d. Total system oil flow.

The measured values were compared with predicted values and found to be more than satisfactory. Any differences between predicted and actual values are discussed in the individual sections. Variations in manufacturing tolerances in both the mechanical parts and the fluid being used contribute mostly to these differences. In addition many of the calculations are based on idealized mathematical models, especially in the case of stiffness calculations. Nevertheless, actual and predicted values agreed very well. Flow predictions were very close to actual flow, probably because of the use of empirical equations rather than purely theoretical equations. Even this is somewhat surprising since such quantities as flow, Q, and capillary tube length, l, vary as the third and fourth power, respectively, with linear dimensions. Allowances were consequently made during the design phase to minimize the affects of critical dimensional variations such as oilgaps and capillary tube lengths. Tight manufacturing tolerances were maintained in the manufacture of the oil bearing elements. In the case of the capillaries they were purposely made long so they could be cut to suitable lengths although this later proved to be unnecessary.

Test procedures for the azimuth and elevation axes bearings are included. The specific data obtained are included in each test procedure. Plots of Load vs. Deflection are made for each stiffness determination. These are also included at the end of each test procedure.

2.0 AZIMUTH AXIS BEARING

The test for azimuth thrust and tipping moment stiffness capacity was conducted in accordance with FSD Test Procedure F(8)-864-047-022-2287 (Appendix F). The test, as performed, gives the overall bearing stiffness, K, rather than just the stiffness of the oil film, K_{of}. The final result is the sum of reciprocals of all the element stiffnesses of the bearing which includes the top plate, K_{tp}, the bottom plate, K_{bp}, the side ring, K_r, and the oil film so that

$$\frac{1}{K} = \frac{1}{K_{tp}} + \frac{1}{K_{bp}} + \frac{1}{K_r} + \frac{1}{K_{of}} .$$

This equation holds true for both the vertical and moment stiffnesses. The vertical stiffness is 22.8×10^6 lb/in. The moment stiffness is 15.3×10^9 in-lb/rad. The predicted (or calculated) moment stiffness for the azimuth thrust bearing was 13.5×10^9 in-lb/rad. The predicted thrust stiffness was 19.2×10^6 lb/in.

The azimuth axis thrust bearing no load pressure ratio, B', with P_s = 240 psi and P_r = 130 psi was

$$B' = \frac{P_r}{P_s} = \frac{130}{240}$$

$$B' = 0.54 \text{ (predicted } B' = 0.50\text{)}$$

The azimuth axis radial bearing pressure ratio, B', with P_s = 240 psi and P_r = 85 psi was

$$B' = \frac{P_r}{P_s} = \frac{85}{240}$$

$$B' = 0.35 \text{ (predicted } B' = 0.30\text{)}$$

No corrections to the capillaries were necessary.

3.0 ELEVATION AXIS BEARING

The test for elevation axis bearing lateral stiffness was conducted in accordance with FSD Test Procedure F(8)-864-047-022-2292 (Appendix G).

The actual lateral stiffness is 12 X 10^6 lb/in. The calculated stiffness is 5.5 X 10^6 lb/in. This represents a stiffness which is greater than double the calculated or required stiffness. Two reasons for this are:

(a) The measured no load oil film gap is 0.0027 inch as compared with the designed gap of 0.003 inch.

(b) The measured capillary pressure ratios are approximately 30% greater than required.

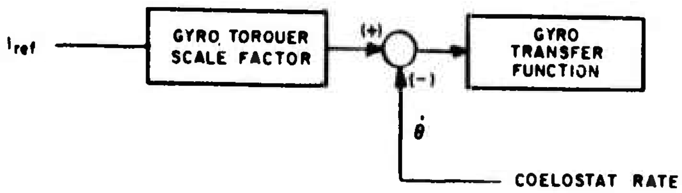
Both of these factors add in the same direction to provide greater stiffness. No changes were made because the bearing operates satisfactorily.

SECTION IV

SERVO TRANSFER FUNCTIONS

1.0 GYRO TRANSFER FUNCTION

The gyro transfer function can be represented as



The gyro torquer scale factor is given as 135.64°/hr/ma or 0.6576×10^{-3} rad/sec/ma.

The gyro reference is supplied from a unity gain op-amp with a maximum output of ±10 volts. This is located on card 704-0004-05. An 11-ohm series resistor is used for scaling and the gyro torquer impedance is 39.62 ohms for a total of 50.62 ohms. The voltage to rate transfer function is

$$K_1 = \text{(Gyro Torquer Scale Factor) (ma/volt)}$$

$$K_1 = 0.6576 \times 10^{-3} \frac{\text{rad/sec}}{\text{ma}} \times \frac{10^3 \text{mv}}{50.62\Omega} = 13.0 \times 10^{-3} \text{ rad/sec/volt}$$

2.0 RATE REFERENCE (COMPUTER MODE)

The analog rate reference signal is provided by a 12-bit D/A and a polarity switch. This is shown on Drawing 007-0089. The output voltage is + or -10 volts with a command signal of 0 1111 1111 1111 for +10 V, and the inverted command for -10 volts. Quantization is 2.4 mv/bit.

The overall rate reference transfer function is, therefore,

$$K_2 = \frac{\text{volts}}{\text{bit}} (K_1)$$

$$K_2 = (2.4\text{x}10^{-3})(1.3\text{x}10^{-2}) = 3.12\text{x}10^{-5} \text{ rad/sec/bit}$$

2.1 Rate Reference (Joystick Mode)

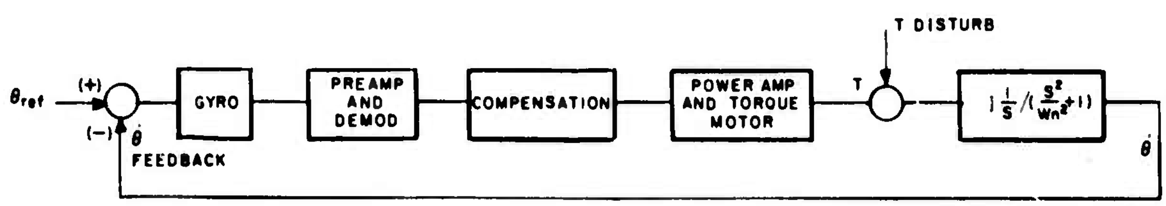
The output from the joystick is fed to card 704-0003-02. The voltage is dipped at 2.4 volts and amplified to 10 volts. This gives maximum slew rate.

The analog signal is then fed to a slew rate limiter circuit on card 007-0083. This prevents the gyro from being torqued at an acceleration which the servo cannot follow. Also, it prevents the gyro rotor from being torqued against the limit stop which is $\pm 3.3°$. The slew rate limit circuit limits the dv/dt to nominally 2.0 v/sec for the azimuth axis and nominally 5.0 v/sec for the elevation axis.

The output from the slew rate limiter is fed to the gyro torquer, via the gyro torquer amplifier (704-0004-05).

3.0 RATE LOOP

The rate loop can be represented as:



Rate Loop

The preamplifier, located on card 007-0076 has a gain of 100 and a time constant of 13 μsec. The time constant will have no effect on the servo bandwidth. The demodulator has unity gain.

The compensation is located on cards 704-0004-06, 704-0004-07, and 704-0004-08. The compensation on these cards was chosen to be compatible with the actual mount and transducer functions.

The networks on card 704-0004-06 are 2-pole Butterworth low pass filters with 200-Hz cutoff frequency and two notch filters. The notch frequencies can be ignored in the transfer function as they are used to cancel the gyro bearing vibration at 255 Hz and vibrations due to rotor unbalance at 400 Hz. The resultant transfer function for this card is:[1]

$$G_1(s) \approx (L_1)\left[\frac{R_9}{2R_8}\left(\frac{1}{1+\frac{R_8 C_{14} s}{2}}\right)\left(\frac{1}{1+R_9 C_{10} s}\right)\left(\frac{R_4}{2R_1}\right)\left(\frac{1}{1+\frac{R_1 C_{13} s}{2}}\right)\left(\frac{1}{1+R_4 C_9 s}\right)\right]$$

$$\text{where } L_1 = \frac{1}{0.64\text{x}10^{-6}s^2+1.1\text{x}10^{-3}s+1}$$

Substituting values yields,

$$G_1(s) \approx \frac{1}{(0.64\text{x}10^{-6}s^2+1.1\text{x}10^{-3}s+1)(0.68\text{x}10^{-3}s+1)(0.34\text{x}10^{-3}s+1)(0.42\text{x}10^{-3}s+1)^2}$$

The transfer function for the azimuth axis compensation card (704-0004-07) is:

$$G_2 \approx \left(\frac{R_4}{R_1}\right)\left[\frac{1+\left(R_{18}+\frac{R_4}{2}\right)C_2 s}{\left(1+\frac{R_1 C_1}{2}s\right)\left(1+\frac{R_{18}+R_4}{2}C_2\right)\left(\frac{2R_{18}}{2R_{18}+R_4}\right)s}\right]\left(\frac{R_{12}}{2R_8}\right)$$

$$\left[\frac{1}{\left(1+\frac{R_8 C_a s}{2}\right)\left(1+R_{12}C_{13}s\right)}\right]\left(\frac{R_{17}}{R_{15}}\right)\left(\frac{1}{1+R_{17}C_9 s}\right)$$

$$\approx \frac{108(0.2s+1)}{(10^{-3}s+1)(0.75\text{x}10^{-3}s+1)(3.6\text{x}10^{-3}s+1)(0.33\text{x}10^{-3}s+1)(6.0\text{x}10^{-3}s+1)}$$

---

[1]Jackson, A.S., "Analog Computation", McGraw-Hill, New York, 1960. Appendix IV, page 621.

The notch frequency at 41.5 Hz is not included as it is used to cancel the lowest resonant frequency.

The transfer function for the elevation axis card (704-0004-08) is:

$$G_3 \approx \frac{R_4}{R_1}\left[\frac{1+\left(R_{18}+\frac{R_4}{2}\right)C_2 s}{\left(1+\frac{R_1 C_1}{2}s\right)\left[1+\left(R_{18}+\frac{R_4}{2}\right)\left(\frac{2R_{18}}{2R_{18}+R_4}\right)C_2 s\right]}\right]\left(\frac{R_{12}}{2R_8}\right)$$

$$\left[\frac{1}{\left(1+\frac{R_8 C_6}{2}s\right)\left(1+R_{12}C_{13}s\right)}\right]\left(\frac{R_{17}}{R_{15}}\right)\left(\frac{1}{1+R_{17}C_{14}s}\right)$$

$$G_3 \approx \frac{30.6(0.2s+1)}{(5.2\text{x}10^{-3}s+1)(0.5\text{x}10^{-3}s+1)(3.6\text{x}10^{-3}s+1)(0.33\text{x}10^{-3}s+1)(3.3\text{x}10^{-3}s+1)}$$

For the elevation axis the notch frequency and the lowest structural resonance is at 45 Hz.

The transfer function for the azimuth axis power amplifier and torque motor is:

K_3= (azimuth power amplifier gain) (azimuth torquer scale factor)

$$K_3 = 2.56\ \frac{\text{amp}}{\text{volt}} \times 43\ \frac{\text{ft-lb}}{\text{amp}} = 110\ \frac{\text{ft-lbs}}{\text{volt}}$$

The azimuth inertia is 26,000 slug-ft^2.

For the elevation axis, the power amplifier and torque motor transfer function is:

K_4 = (elevation power amplifier gain) (elevation torquer scale factor)

$$K_4 = 0.77\ \frac{\text{amp}}{\text{volt}} \times 19.5\ \frac{\text{ft-lb}}{\text{amp}} = 15\ \frac{\text{ft-lb}}{\text{volt}}$$

The elevation inertia is 1700 slug-ft^2. The power amplifiers are shown on Drawing 712-0004.

4.0 POSITION LOOP

The binary position reference signal is provided by 23 bits of absolute position information. The command signal is proportional to 0.00004291 degrees (0.16 arc sec) per LSB. This signal is provided by thumbwheel switches or computer.

The position error signal, i.e., reference minus encoder feedback, has the same scale factor. This is fed to a 16-bit plus polarity bit D/A. The D/A consists of paralleled 12-bit and 6-bit D/A's connected to the 18 LSB's, i.e., bits 2^{-6} through 2^{-23}.

The transfer function for the error signal is:

$$K_5 = \left(\frac{\text{D/A full scale voltage}}{2^{18}}\right)\left(\frac{\text{bits}}{\text{degree}}\right)$$

$$= \left(\frac{10}{2^{18}}\right)\left(\frac{1}{42.91 \times 10^{-6}}\right) = 0.89 \text{ volts/degree}$$

or,

$$K_5 = 50.9 \text{ volts/radian.}$$

The compensation depends upon the magnitude of the position error which is sensed by the position error sensor, card 007-0103. For errors above 250 mv, M_1 and M_2 on card 704-0004-03 are shorted out. This results in an overall position loop transfer function of:

$$G_4(s) = (\text{A/D scale factor})\ (K_1)$$

$$= (50.9)(13 \times 10^{-3}) = 0.66 \text{ rad/sec/radian}$$

For error signals below 250 mv, the transfer function includes the compensation of M_1 and M_2 on 704-0004-03, and is:

$$G_5(s) = G_4(s)\left(\frac{R_{14}}{R_{13}}\right)\left(\frac{1 + R_{11} C_2 s}{R_1 C_2 s}\right)$$

$$= 6.14 \left(\frac{1+s}{s}\right)$$

The overall position loop transfer function is:

$$G_6(s) = \frac{6.14\ (s+1)}{s^2} \text{(rate loop transfer function)}$$

The rate limit circuit is in the loop, so the dv/dt to the gyro torquer is limited to nominally 2.0 v/sec for azimuth and nominally 5.0 v/sec for the elevation axis.

The compensation circuit is on card 704-0004-03.

5.0 SERVO BANDPASS TEST DATA

The following graphs illustrate the measured servo bandpass for both Elevation and Azimuth axis servos.

The results shown by the curves include:

a) Servo bandpass frequency response shows the peak responses at 9.5 Hz for azimuth and 11.5 Hz for elevation. The -3db points are approximately 13 Hz for azimuth and 16 Hz for deviation.

b) The phase shift shows the 90° point at 9 Hz for azimuth and 10.5 Hz for elevation.

c) Both bandwidth curves appear to be typically dominant second order systems with some effects of frequency dependent terms beyond the bandwidth. A plot of a second order system approximately the same damping ratio[1] is plotted for comparative purposes in each case and presented in Figure 1.

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[1] Savant, C.J., "Basic Feedback Control System Design", McGraw-Hill, New York, 1958. Figure 5-3a, page 128.

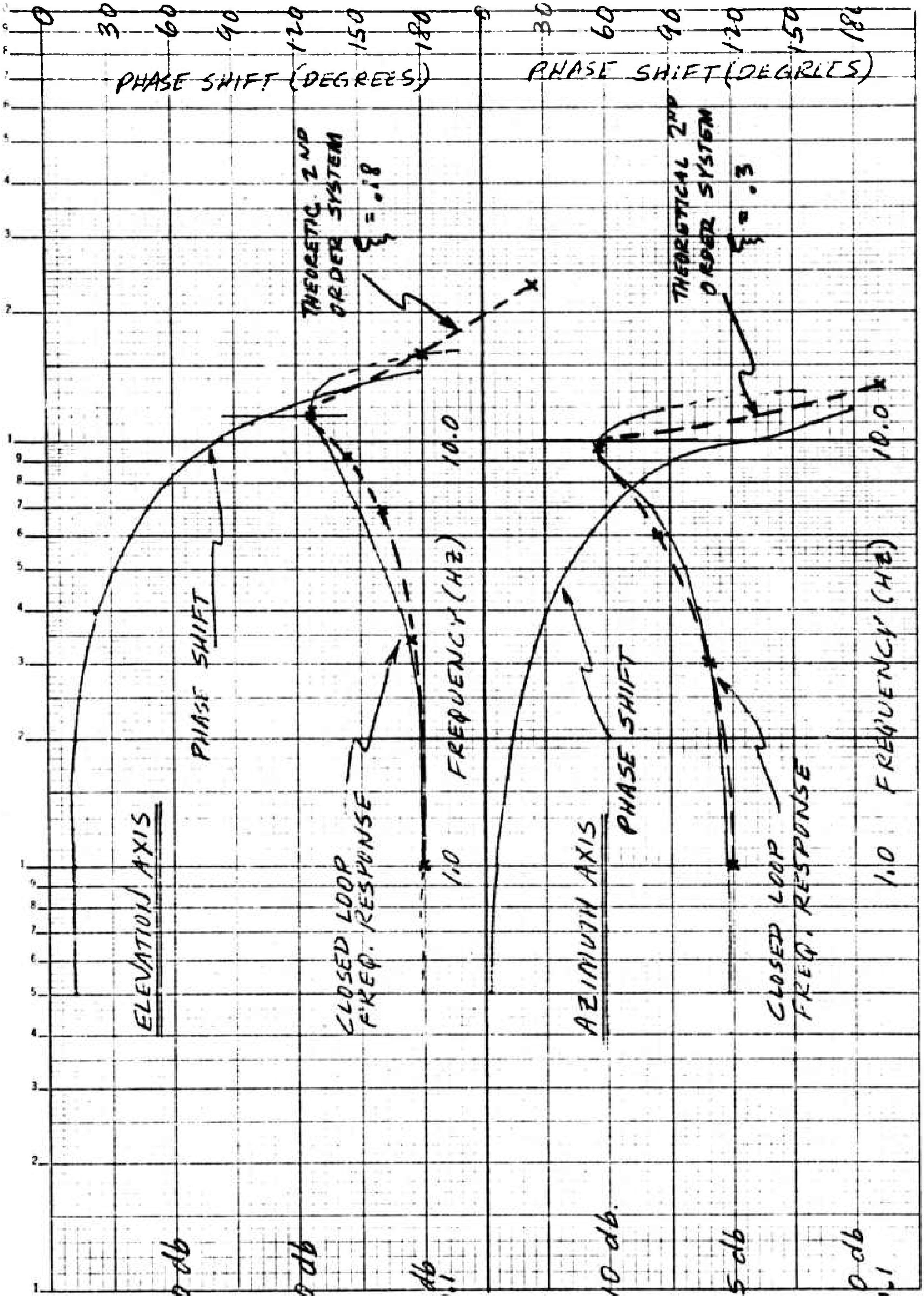
PHASE SHIFT (DEGREES)
PHASE SHIFT (DEGREES)
THEORETIC. 2ND ORDER SYSTEM
ξ = .18
THEORETICAL 2ND ORDER SYSTEM
ξ = .3
ELEVATION AXIS
AZIMUTH AXIS
PHASE SHIFT
PHASE SHIFT
CLOSED LOOP FREQ. RESPONSE
CLOSED LOOP FREQ. RESPONSE
FREQUENCY (HZ)
FREQUENCY (HZ)
1.0
10.0
1.0
10.0
20 db
10 db
0 db
10 db
5 db
0 db
0.1
0.1

Figure 1.

SECTION V

COMPUTER INTERFACE SUBSYSTEM

1.0 GENERAL DESCRIPTION

During the term of the referenced contract, an additional operational mode was added to the contract specification, that being an External Digital or Computer Controlled mode. In this mode the positioning or the rate of rotation of the azimuth and elevation axes is exclusively controlled by commands and signals fed to the coelostat control system via a computer interface unit from a specially configured Datacraft 6024 computer. A Slave mode (slaved to a microwave radar unit at the site) is accommodated through the use of the computer which translates the "following errors" into absolute position or rate commands to the coelostat. To implement this new mode, a Computer Interface Subsystem (CIS) was added whose function is to provide two-axis position and rate data to the coelostat and provide the computer with data and status from the coelostat. This function is accomplished via command/data combinations supplied by the computer and status/data combinations supplied by the coelostat for input to the computer. The action is for the computer to supply a command word to the CIS which will define the next operation to be performed on subsequent data sent to the CIS from the computer. Likewise, in the reverse direction, the status of the current operation and data is available to the computer via status word and encoder data input. It should be pointed out that commands and data are double buffered to eliminate latency between time slices.

1.1 Modes

The CIS operates in one of three modes that are defined by the computer and output to the CIS via the command word. These modes are:

TRACK MODE: Encoder input is transferred to the forward register at every new update of the encoders.

	Transfer to the computer is accomplished under ABC control.
HOLD MODE:	Encoder input is transferred to the forward register at every external time reference mark (or every 10th). Transfer to the computer is accomplished under interrupt control.
RANDOM MODE:	Encoder input is transferred to the forward register when the interface detects a command word bit being set. Transfer to the computer is done at a later time under program control.

1.2 Words

The next two tables define the format of the command word and the status words.

COMMAND WORD

BIT #	
0	Interrupt Bits
1	
2	
3	Select 1 = AZ, 0 = EL
4	Mode 1 = Rate, 0 = Position
5	If RATE then SIGN 1 = CW, 0 = CCW
6	Mode, 1 = Track, 0 = Hold
7	Hold Mode Option
8	Zero
9	CPU Power Fail 1 = Power Fail
10	0 = Status Word 1, 1 = Status Word 2

STATUS WORDS

BIT #		
0	(LSB)	"ZERO" Status Word #1 = 0
1		System On Line = 1, $\overline{\text{Off-Line}}$ = 0
2		AZ CW Zone = 0, $\overline{\text{AZ CW Zone}}$ = 1
3		AZ CCW Zone= 0, $\overline{\text{AZ CCW Zone}}$ = 1
4		AZ Sign 1 = CW, 0 = CCW
5		EL Sign 1 = CW, 0 = CCW
6		AZ Slew 1 = SLEW, 0 = Linear
7		EL Slew 1 = SLEW, 0 = Linear

0	(LSB)	"ONE" Status Word #2 = 1
1		Encoder Input Buffer Full = 1
2		Interface Power Fail = 0, $\overline{\text{Fail}}$ = 1
3		Hold Mode Option Actuated
4		SS Actuated AZ = 1, EL = 0
5		Spare
6		Position (0), Rate (1) Actuated
7		Spare

2.0 THEORY OF OPERATION

The block diagram of Figure 2, illustrates the main data flow and control blocks of the CIS.

2.1 Data

The twenty-four (24) data lines coming from the computer I/O channel are received via differential line receivers and terminated with 100 ohms. These lines (DTU00-DTU23) are compared against a two-volt reference voltage in order to increase noise immunity of the I/O bus. The output of the receiver provides both true and inverted signals which are then distributed throughout the chassis.

There are also 24 data lines that drive back to the computer I/O channel. These drivers are high current emitter followers with a characteristic impedance of 100 ohms. The inputs of these 24 drivers originate from a 2 to 1 multiplexer. The inputs to the multiplexer, in turn, come from the forward registers of the double buffered encoder inputs. The azimuth inputs to the multiplexer are gated by AZEN and the elevation by ELEN.

The data from the encoders (AZ00-AZ22,EL00-EL22) are received in a fashion similar to that of channel's. The storage register is strobed by $\overline{\text{AZTRK/ELTRK}}$ and the forward register by $\overline{\text{AENFS/EENFS}}$. AZENRDY AND ELENRDY are the data ready signals from the encoders. They in turn generate $\overline{\text{AZTRK}}$ and $\overline{\text{ELTRK}}$ which cause the encoder data to be strobed into the storage register whenever there is an update of new data. If the axis is in Track mode (AZ MODE or EL MODE = 1) then $\overline{\text{AENFS}}$ and $\overline{\text{EENFS}}$, respectively cause the new data to also be strobed into the forward register. If the axis is in Hold mode, then D10S will cause the strobe into the forward register.

D10S is the divide by ten strobe generated after the Hewlett Packard Time Standard (HMPTIM) is divided by ten. If a 10K Hz standard is used, the divide by ten can be bypassed.

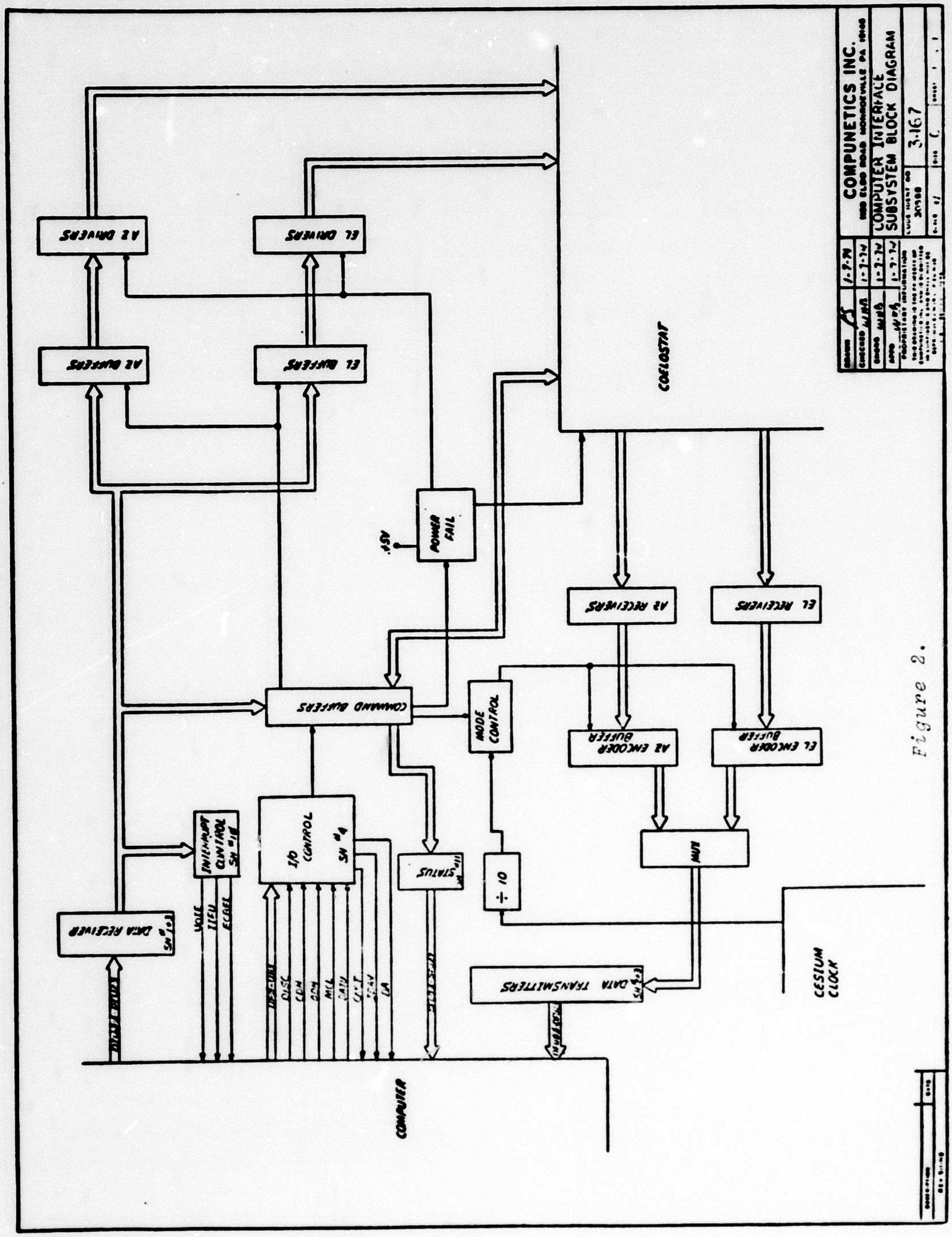
COMPUNETICS INC.
COMPUTER INTERFACE SUBSYSTEM BLOCK DIAGRAM
3.167
COELOSTAT
COMPUTER
CESIUM CLOCK
AZ DRIVERS
EL DRIVERS
AZ BUFFERS
EL BUFFERS
POWER FAIL
COMMAND BUFFERS
MODE CONTROL
AZ RECEIVERS
EL RECEIVERS
AZ ENCODER BUFFER
EL ENCODER BUFFER
MUX
÷ 10
DATA TRANSMITTERS
STATUS
I/O CONTROL
INTERRUPT CONTROL
DATA RECEIVER

Figure 2.

Transition errors on encoder input will not occur because the bandwidth of the HMPTIM to register strobe exceeds the bandwidth of the coelostat by at least a factor of thirty.

2.2 Power Failure

If a power failure in the CPU occurs, a command word must be sent to the CIS with bit number nine set. If the bit is reset to zero within 10 ms no power fail action will be taken by the CIS, otherwise all outputs to the coelostat will be clamped to zero. In the event of CIS power up, or a master clear sent from the computer, signal MCE ensures that the outputs to the coelostat are clamped to zero until legitimate data are strobed into the forward register of the double buffer.

2.3 Main Control Logic for I/O Channel

Signal UR0-UR3 are the unit number lines. These lines in conjunction with DISC are decoded and generate TUS (This Unit Selected). TUS is then returned to the channel as CNCT to indicate that the unit (CIS) is not busy and may accept data. TUS is also used to enable other portions of the control logic. The CDH line from the channel indicates that command data are present on the 24 data lines and may be strobed into the CIS. CDH set the CDA flip-flop. CDH also generated GCMD which fires two one shots. The first strobe loads the command register and interrupts flip-flops and the second strobe resets the CDA flip-flop and generates DA (Data Accepted) which indicates to the channel that the command data output operation is complete. The output of data is handled in an identical manner (ref. ODA flip-flop).

The IDAV signal to the channel indicates that data are available for input. This is generated from the ALWREQ (Allow Request) flip-flop which is set if data are ready for input. This will occur any time new data are available from the encoders as a function of the mode of the axis. After the channel has accepted the data it responds with a DATU signal which indicates that the data was accepted by the channel.

A master clear may originate either from the CPU via the MCL line or from an Auto Master Clear generated during power up of the CPU (MC-1). These two are ORed together and puts the CIS into an initial start up state.

2.4 Interrupt Logic

The interrupt logic is controlled by bits 0, 1, and 2 of the command word. The eight possible interrupt conditions are as follows:

Bit No. 0	1	2	Action
0	0	0	No Action
1	0	0	No Action
0	1	0	Disable Input Interrupt
1	1	0	Enable Input Interrupt
0	0	1	Disable Output Interrupt
1	0	1	Enable Output Interrupt
0	1	1	Disable Both Interrupts
1	1	1	Enable Both Interrupts

The IIENB and OIENB flip-flops hold the interrupt state. IIFU is returned to the computer to indicate that an input interrupt will occur when data are available. The UOIE Signal indicates that the interface is indeed ready for an output interrupt.

2.5 Status

Eight parallel status bit lines SFU00-SFU07 provide status information to the channel. Due to the fact that there are more than eight bits of status information, command word bit 10 indicates which of the two 8-bit status words to be put onto SFU00-SFU07. The STATO flip-flop controls this with signals STATO and STAT1 as enables to the status word MUX.

3.0 EXTERNAL DIGITAL MODE CIRCUITS

3.1 Signals from Coelostat to Interface

1. System-ON-Line

   This signal consists of three parts;

   a. Elevation Servo ON

   b. Azimuth Servo ON

   c. External Digital Mode selected.

   When all three of these are logic "0" inputs, the output to Interface is logic "1". If any one of the three is not logic "0" (System NOT-ON-LINE), then the output to Interface will not be logic "1".

2. Azimuth Axis Zone Indicators

   This information consists of two signals:

   a. AZ CW Zone

   b. AZ CCW Zone

   When the azimuth axis is in the position range of ±180° from zero, a logic "1" signal will exist as a CW Zone signal and a CCW Zone signal. When the azimuth axis rotates beyond CW or CCW 180°, that particular zone signal will change to a logic "0".

3. Sign (Direction) in Position Mode

   This information consists of two signals:

   a. Azimuth CW/CCW

   b. Elevation CW/CCW

   The MSB of digital error as computed by the subtractor represents the "shortest path" direction that the mount will travel (always less than 180°). This MSB or sign signal is as follows:

   AZ (CW logic "1")
   (CCW logic "0")
   EL (CW logic "0")
   (CCW logic "1")

4. Slew Range

This information consists of two signals each consisting of two component parts:

a. AZ Slew/Linear Range

b. EL Slew/Linear Range

The Slew or Linear differentiation is determined by the number of computed position error bits (18) required to saturate the position D/A converters. This 18-bit saturation logic "0" signal is inverted and AND gated with an inverted logic "0" External Position Mode signal (from computer) to provide a logic "1" Slew Range signal. When not in External Position mode or not in Slew Range (Linear) the output to the Interface is a logic "0".

5. Encoder Data

Encoder data (23-bits) and an encoder data ready signal are supplied directly from the Azimuth and Elevation Encoder chassis. These data are outputted from the encoder storage register which is continuously being internally strobed or updated by the up and down pulse. "True" data are a logic "1" and "False" data are a logic "0". The data ready signals are simultaneous with the STROBE pulses generated in the subtractor to shift the position error data from storage to the DAC. Data ready is a logic "1", not ready is a logic "0".

3.2 Signals from Interface to Coelostat

1. Sign (Direction) in Rate Mode

This external signal reverses the polarity of the analog rate error signal in order to accomplish CW or CCW rotation of either azimuth or elevation axis.

a. For azimuth, a logic "1" (for CW) signal changes the state of an Analog Switch which in turn reverses the output 0 to (+) or (-) 10V. A logic "0" causes CCW rate operation.

b. For elevation, a logic "1" (for CW) signal changes the state of an Analog Switch which in turn reverses the output 0 to (+) to (-) 10V. A logic "0" causes CCW rate operation.

2. Command Data

Twenty-three (23) bits of command data per axis are fed into the Position Designate chassis. In the External Position mode, all 23 bits (per axis) are the digital command inputs to the respective subtractor wherein its comparison with the angle encoder data (23 bits) determines the digital position error angle and sign (direction). From this point, Ext. Digital Position is identical to Manual Digital Position.

In the External Rate mode, the 12 LSB of these data are the digital command inputs to the respective rate DAC whereby the analog voltage output (0 to +10V) determines the rate at which the respective coelostat axis will rotate.

3. External Digital Mode Selection

For each axis, a logic "0" for Ext. Digital Position selection, or a logic "1" for Ext. Digital Rate selction, accomplishes three (3) distinct functions:

a. In Position the logic "0" enables the slew range logic "1" signal to be outputted.

b. In Rate, the logic "1" enables the rate DAC to be strobed by the internal STROBE pulse generated via the Angle Encoder U + D pulse train.

c. In Rate, the logic "1" switches the servo inner loop command input from an internal analog signal to the External Rate Command analog signal.

4. External Rate Inputs (Analog)

Following the D/A conversion and direction switching of the Digital Rate Command signals, the analog voltage is fed to a compensation amplifier in the Servo Control chassis. The outputs of these amplifiers when selected are fed directly into the respective Gyro Torquer amplifiers where the mount operation functions in a manner identical to other modes.

When operating either Azimuth or Elevation axes in the Ext. Digital Rate mode, a step change in rate command must be limited to a maximum of 1.25 deg/sec. This applies to increase or decrease of rate and includes starting and stopping .

5. Power Failure

This signal can originate in either of two places, either at the CPU (Computer) or at the Interface Unit. As long as both are OK (logic "1" signal), the servo interlocks will be closed. If either fails, the logic becomes "0", the servo interlocks open, and both elevation and azimuth servoes go OFF.

When the system is not in Digital Command mode and/or not in Ext. Digital mode, the K1 or CPU failure interlock is bypassed.

6. External Preset

For External Position Command mode it is necessary (same as Manual Position Command mode) to PRESET or shift from storage the position command data into the U + D counters on the digital subtractor.

This Preset is a pulse which originates at the Interface Unit and is negative going about 1 μsec duration. It occurs when (at the interface chassis) new data have been strobed into the forward registers. Between Preset pulses, new external position command data can be entered into the Interface storage registers without affecting the previous command.

3.3 Signals from Computer to Interface

1. 23 bits of Elevation Axis Command Data
   - Position Mode - All 23 bits
   - Rate Mode - Least significant 12 bits
2. 23 bits of Azimuth Axis Command Data
   - Position Mode - All 23 bits
   - Rate Mode - Least significant 12 bits
3. Command Mode Selection
   Rate or Position
4. CPU Power Failure Monitor
5. Sign (Direction) Command - Elevation
   (Rate Mode Only)
6. Sign (Direction) Command - Azimuth
   (Rate Mode Only)
7. Command Rate Mode Buffers Initialize
8. Mode Select - Track or Hold
9. Hold Mode Option - Computer
   Interrupt or HP5061A Timer
10. Computer Controlled Interrupt Select/Enable

3.4 Signals from Interface to Computer

Signals Originating at the Coelostat:

1. 23 bits of Elevation Encoder Position Data
2. 23 bits of Azimuth Encoder Position Data
3. System-On-Line
4. Azimuth CCW Zone
5. Azimuth CCW Zone
6. Azimuth Sign (Direction) Position Mode Only
7. Elevation Sign (Direction) Position Mode Only
8. Ext. Digital Command Mode Selected

9. Elevation Position Slew Range Indicator
10. Azimuth Position Slew Range Indicator

Signals Originating at the Interface (Controller):

11. Elevation Encoder Input Buffers Full
12. Azimuth Encoder Input Buffers Full
13. Elevation Position Encoder Input Data Flag
    LSB (Of 24 bits) = "1" Data Incoming
    LSB (Of 24 bits) = "0" Data Not Incoming
14. Azimuth Position Encoder Input Data Flag
    LSB (Of 24 bits) = "0" Data Incoming
    LSB (Of 24 bits) = "1" Data Not Incoming
15. Interface (Controller) Power Failure
16. Elevation Data Subsystem Actuated
17. Azimuth Data Subsystem Actuated
18. Position or Rate Mode Actuated
19. Hold Mode Option Actuated

4.0 HARDWARE DESCRIPTION

The chassis is organized into card rows and card slots. Each card row contains 30 card slots and are designated A, B, C, etc., from front to back respectively. Each card slot is in turn numbered in ascending order (2-31) from left to right. Each card position contains a connector with 62 pins for back plane interconnections. Power supplies and connectors are located to the rear of the chassis.

The following is a list of the major characteristics of the CIS.

1. Compunetics Part #00-3467
2. Physical Dimensions - 6 1/4" High x 19" Wide x 24" Long, 0.8 cubic feet.
3. Approximate Weight - 25 lbs.
4. Power Requirements - 115 VAC, 60 Hz.

(BLANK)

SECTION VI

SUMMARY OF ACCEPTANCE TEST DATA

1.0 TEST RESULTS

The following tabulation of test results was obtained by testing in accordance with the approved Acceptance Test Procedure, F(8)-864-047-022-2345A, dated November 19, 1973 and revised July 3, 1974. In addition, RADC comments to this Final Data Report and the Fecker Systems reply to those comments have been reproduced verbatim in Appendix H.

a)	Azimuth Bearing Wobble	0.356 arc sec
b)	Elevation Bearing Wobble	0.628 arc sec
c)	Leveling (Verticality)	±0.35 arc sec
d)	Orthogonality of Mech. Axes	-13.35 arc sec
e)	Freedom of Rotation	EL 200.8° AZ 721.26°
f)	Mirror Surface	
	Elevation	<1/10 λ at 6328Å
	Azimuth	<1/10 λ at 6328Å
g)	Azimuth Mirror	
	Operation Attitude	0.17 λ at 6328Å
h)	Elevation Mirror	
	Operational Attitude	0.39 λ at 6328Å
i)	Static Pointing Accuracy	3.469 arc sec
j)	Mirror Parallax	51.07 inches
k)	Elevation Encoder	0.599 arc sec
l)	Azimuth Encoder	0.576 arc sec
m)	Azimuth Servo Jitter (position)	
	±4 bits =	±0.6 arc sec
n)	Elevation Servo Jitter (position)	
	±3 bits =	±0.45 arc sec
o)	Azimuth Servo Bandwidth	
	90° phase shift point	10 Hz
	-3 db point	13 Hz
	Elevation Servo Bandwidth	
	90° phase shift point	11.5 Hz
	-3 db point	16 Hz

p)	Azimuth Servo Smoothness (rate)	0.2144°/hr
	Elevation Servo Smoothness (rate)	0.536°/hr
q)	Acceleration	
	(Includes Slew Rate Limiting)	
	Azimuth	$1.63°/sec^2$
	Elevation	$4.38°/sec^2$

2.0 RANDOM ERROR ANALYSIS

Error Contributor	Peak	σ (RMS)	σ^2
I. Base			
Alignment	1.0 *	---	---
Foundation	0.5 *	---	---
Thermal Drift	1.0 *	0.1	0.01
II. Structure			
Leveling (Verticality)	0.35	---	0.12
Static Pointing Accuracy	---	3.469	12.03
Azimuth Mirror Misalignment			
Azimuth Bearing Random Wobble			
Elevation Mirror Misalignment			
Elevation Bearing Random Wobble			
Orthogonality of Axes			
III. Azimuth Axis			
System Jitter	0.6	---	0.36
Encoder Noise Gyro Noise			
Encoder Accuracy	---	0.576	0.33
Dynamic Tracking	0.15	---	0.02
IV. Elevation Axis			
System Jitter	0.45	---	0.20
Encoder Noise Gyro Noise			
Encoder Accuracy	---	0.599	0.36
Dynamic Tracking	0.18	---	0.03

*Estimates assumed to be correctable $\Sigma\sigma^2 = 13.46$

$$1\sigma = \sqrt{\Sigma\sigma^2} = 3.67 \text{ arc seconds}$$

Specification requirement of 20 μrad = 4.12 arc sec.

3.1 SYSTEMATIC ERROR CALIBRATION CURVES

3.1 In addition to the errors contained in the foregoing random error analysis, there are two systematic error correction curves which can be used to compensate for their inherent error components.

a) The first curve (Figure 3) shows the OPTO-MECHANICAL Systematic Error Curve and includes as systematic error contributors:

Azimuth Bearing
Elevation Bearing
Azimuth Mirror Alignment
Elevation Mirror Alignment
Orthogonality of Mech. Axes

b) The second curve (Figure 4) shows the ELEVATION ENCODER Systematic Error Curve and is unique to this elevation encoding subsystem.

3.2 Since both curves represent arc seconds of error as a function of Elevation angle, they could be combined into a single systematic error curve or used separately. In either case the correction is accomplished by subtracting the arc second value established by the curve(s) for each position of the Elevation axis.

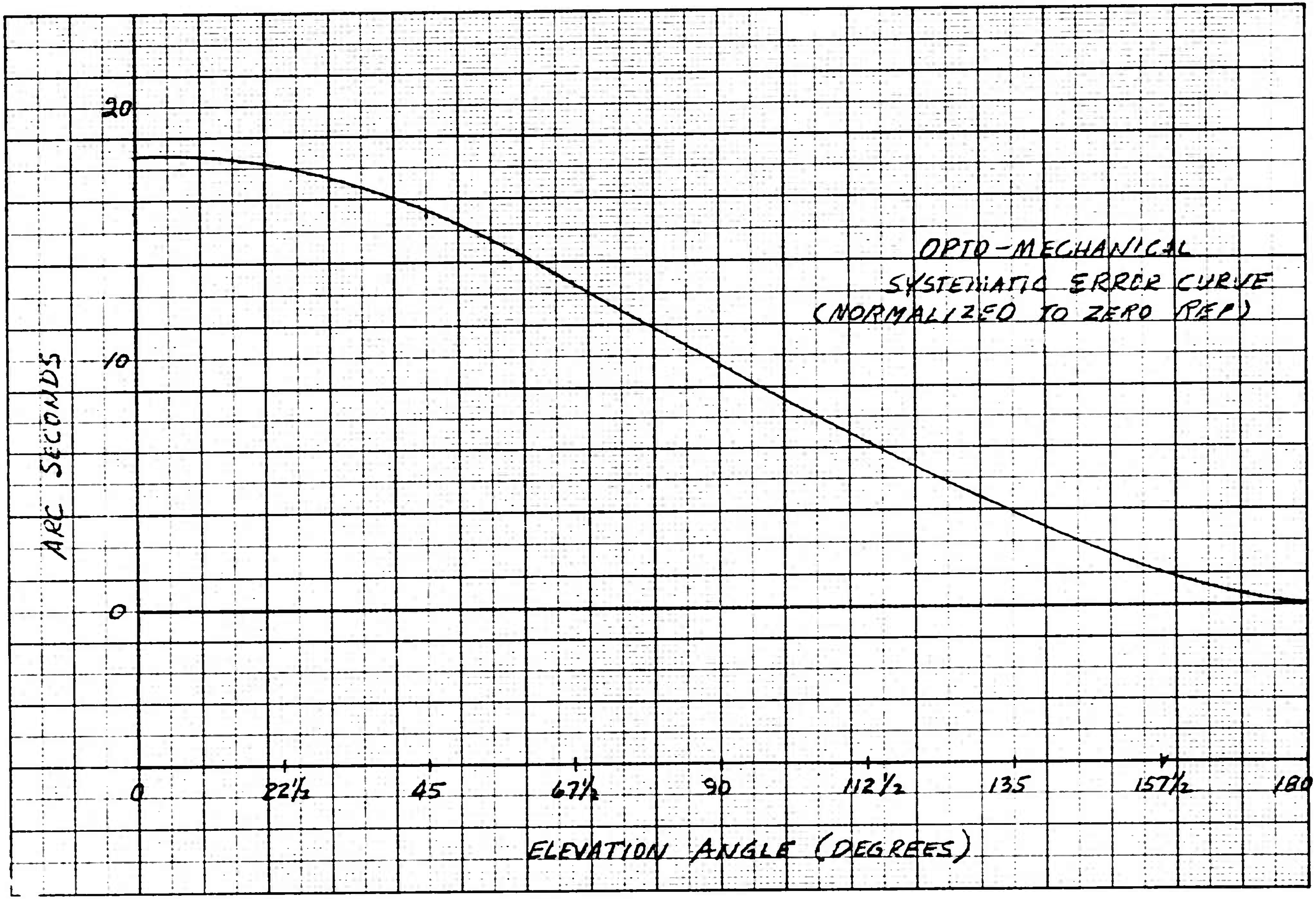
OPTO-MECHANICAL
SYSTEMATIC ERROR CURVE
(NORMALIZED TO ZERO REF)
ARC SECONDS
20
10
0
0
22½
45
67½
90
112½
135
157½
180
ELEVATION ANGLE (DEGREES)

Figure 3.

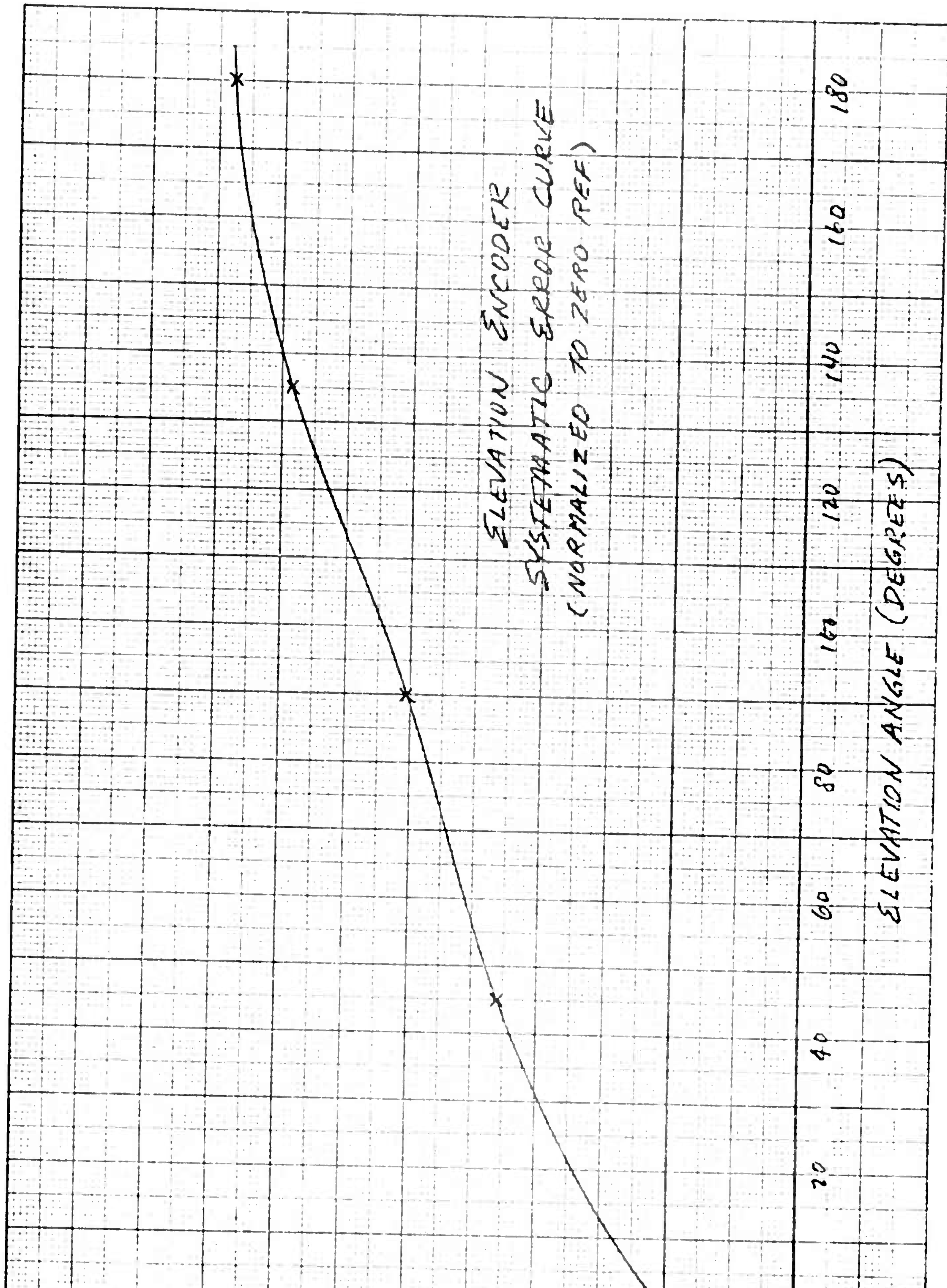
ELEVATION ENCODER
SYSTEMATIC ERROR CURVE
(NORMALIZED TO ZERO REF)
ARC SECONDS
0
2
4
6
8
0
20
40
60
80
100
120
140
160
180
ELEVATION ANGLE (DEGREES)

Figure 4

APPENDIX F

TEST PROCEDURE FOR THE
AZIMUTH AXIS HYDROSTATIC BEARING
FOR THE 864 COELOSTAT INSTRUMENT

F(8)-864-047-022-2287

Test Data

TEST PROCEDURE FOR THE AZIMUTH AXIS HYDROSTATIC BEARING FOR THE 864 COELOSTAT INSTRUMENT

F(8)-864-047-022-2287

June 26, 1973

Prepared For:

Rome Air Development Center
Griffiss Air Force Base
New York

OWENS-ILLINOIS
FECKER SYSTEMS DIVISION
4700 BAUM BOULEVARD PITTSBURGH, PA. 15213

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TEST PROCEDURE FOR THE AZIMUTH AXIS HYDROSTATIC BEARING FOR THE 864 COELOSTAT INSTRUMENT

The azimuth bearing is a combination radial and thrust bearing. The radial portion of the bearing serves only to center the bearing and will not be tested for load; however, the capillary will be adjusted to the correct length to provide the specified pressure drop and corresponding stiffness. The azimuth thrust bearing restrains both the thrust load and tipping moment and must be tested to determine both. The capillaries must also be adjusted for the thrust bearing before testing can begin.

The procedure will be in two sections. The first section will outline the method of adjusting the capillaries. The second section will outline the method of determining the thrust bearing stiffnesses.

1.0 ADJUSTMENT OF CAPILLARIES

Because capillary lengths vary so greatly with changes in film thickness and capillary diameter, an exact determination of length cannot be made until the bearings and capillaries are actually fabricated and in operation. The capillary is, therefore, made larger than required and cut to the proper length during the final testing of the bearing.

1.1 Test Equipment Required

FSD 254-0048 - Capillary testing fixture (with two 0-400 psi pressure gauges).

Hydraulic oil supply for bearing.

1.2 Test Preparation

1. The azimuth bearing should be fully assembled on to the base with the platform mounting flange (254-0042, Item 3) in place in accordance with 254-0042.
2. Cap off all oil pressure lines intended for the elevation bearing.
3. Remove capillary tube to be tested from desired bearing pad and insert into capillary testing fixture.
4. Insert testing fixture with capillary into bearing pad from which capillary was removed.
5. Turn on hydraulic supply to 230 psi.

1.3 Test Procedure

Measure the pressure drop across the capillary to be adjusted by recording the two gauge readings on the capillary testing fixture. The upstream gauge will indicate the supply pressure, P_s, and the downstream gauge will indicate the recess pressure, P_r. P_s must always be greater than P_r or the hydraulic circuitry is in error. A pressure ratio β', exists between the two pressures, P_s and P_r such that

$$\beta' = \frac{P_r}{P_s}$$

Adjust the capillary lengths to obtain the ratio β'.

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1.3.1 Azimuth Radial Bearing Pressure Ratio

The required pressure ratio for the azimuth radial bearing is

$$\beta' = 0.3$$

Adjust all the azimuth radial bearing capillary lengths (12 capillaries) to obtain a pressure ratio of

$$\beta' = 0.3$$

This may be done by machining off the excess length of the capillary. However, if the capillary length is too short, engineering should be contacted. Care must be taken not to remove an excessive amount from the capillary length otherwise the capillary must be replaced.

1.3.2 Azimuth Thrust Bearing Pressure Ratio

The required pressure ratio for the azimuth thrust bearing is

$$\beta' = 0.5$$

Adjust all the azimuth thrust bearing capillary lengths (24 capillaries) to obtain a pressure ratio of

$$\beta' = 0.5$$

This may be done by machining off the excess length. However, if the capillary length is initially too short, engineering should be contacted. Care must be taken not to remove an excessive amount from the capillary length otherwise the capillary must be replaced.

2.0 AZIMUTH BEARING STIFFNESS MEASUREMENT

These tests will determine the vertical stiffness of the azimuth bearing and the moment stiffness of the azimuth bearing about an axis normal to the plane of rotation (tipping moment stiffness). The two tests will be conducted separately. However, the moment stiffness test will serve as a cross check for the vertical stiffness test.

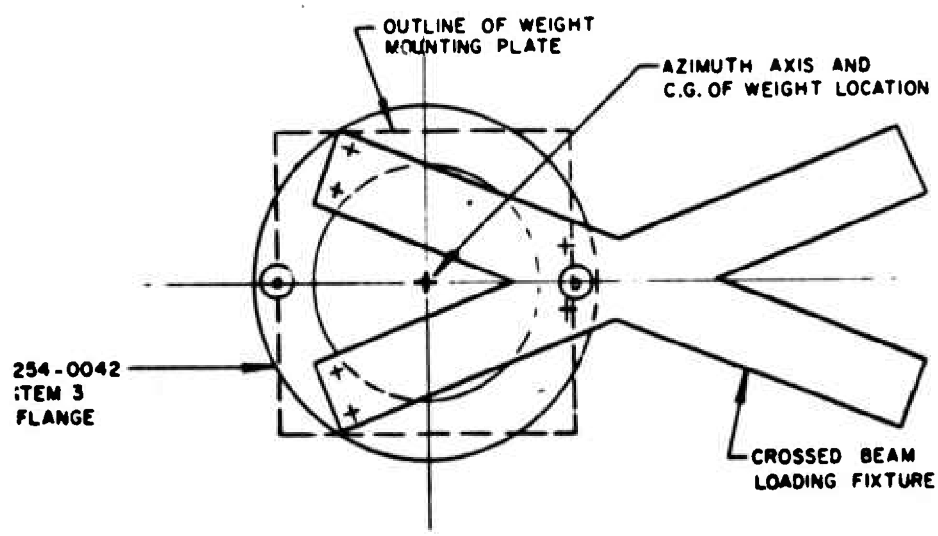
2.1 Vertical Stiffness Test

2.1.1 Test Equipment Required

1. Cleveland Gauge, Model OH215, with 2 pick-ups
2. Mounting brackets for Cleveland Gauge pick-ups
3. Crossed-beam loading fixture
4. Weights for calibration (approximately 10,000 lbs. - total)
5. 1" thick flat plate for mounting weights.

2.1.2 Test Preparation

1. The azimuth bearing should be fully assembled onto the base with the platform mounting flange (254-0042, Item 3) in place in accordance with 254-0042.
2. Cap off all oil pressure lines intended for the elevation bearing.
3. Bolt crossed beam loading fixture into position atop the platform mounting flange as illustrated on the following page.



4. Lay the 1" thick flat plate atop the crossed beam loading fixture and center about azimuth axis as closely as possible.

5. Mount the Cleveland Gauge pick-ups into position at locations (a) and (b) on the above sketch to measure vertical deflection changes of the rotor relative to the stator of the azimuth bearing, for the corresponding applied calibration weights. The pick-ups must be located so that they are equidistant from the azimuth axis and diametrically opposed from each other.

6. Record the weight of each test weight accurately.

2.1.3 Test Procedure

1. Place the weights, gently, on the 1" thick flat plate at the axis of rotation and record the corresponding deflection of each weight, as read on the Cleveland Gauge, in Table 1.

2. Remove the weights, one at a time, and record deflections again. Check to see that the Cleveland Gauge returns to its "zero" position when the last weight is removed.

2.2 Moment Stiffness Test

2.2.1 Test Equipment Required

a. Cleveland micrometer gauge Model OH215, with 2 pick-ups

b. Mounting brackets for Cleveland Gauge pick-up.

c. Crossed-beam loading fixture

d. Weights for calibration (approximately 10,000 lbs.)

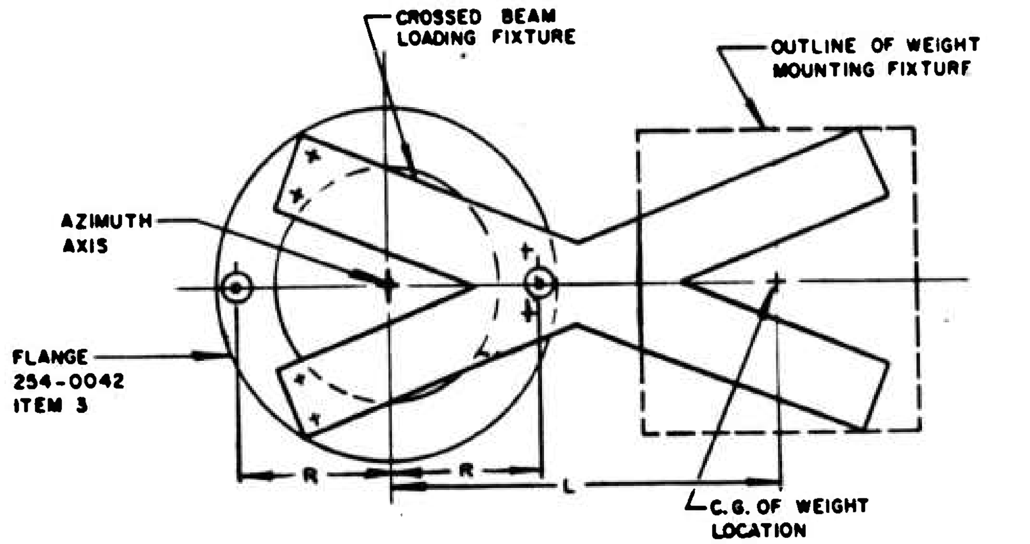
e. 1" thick flat plate for mounting weights

2.2.2 Test Preparation

1. The azimuth bearing should be fully assembled onto the base with the platform mounting flange (254-0042, Item 3) in place in accordance with 254-0042.

2. Cap off all oil pressure lines intended for the elevation bearing.

3. Bolt the crossed-beam loading fixture into position atop the platform mounting flange as shown on the following page, Figure 2.



L≃50 IN.

4. Lay the 1" thick flat plate atop the crossed-beam loading fixture a distance "L" from the azimuth axis, as shown in Figure 2.

5. Mount the Cleveland Gauge pick-ups at locations (a) and (b), on above sketch, to measure vertical deflection changes of the rotor relative to the stator of the azimuth bearing, for the corresponding applied calibration weights. Locate the pick-ups so that they are equidistant from the azimuth axis and diametrically opposed.

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6. Record the weight of each test weight accurately.

2.2.3 Test Procedure

1. Place the weights, gently, on the 1" thick flat plate at the location indicated in Figure 2 and record the corresponding deflection of each weight from the Cleveland Gauge in Table 2. The center of gravity of the weights must be in line with the line intersecting the two Cleveland pick-ups, (a) and (b).

2. Remove the weights, one at a time, and record deflections again. Check to see that the Cleveland Gauge returns to its "zero" position when the last weight is removed.

3. Record the distance of the pick-ups from the azimuth axis as "r".

r = 21 in.

4. Record the distance of the weight C.G. from the azimuth axis as "L".

L = 48 in.

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TABLE I

VERTICAL STIFFNESS

Load (lbs.)	Deflection (in.) Pick-up (a)	Deflection (in.) Pick-up (b)	Net Deflection $\frac{(a)+(b)}{2}$	Stiffness (k) lbs/inch $\frac{2\,[\text{Load}]}{(a)+(b)}$
2800	110×10^{-6}	150×10^{-6}	130×10^{-6}	21.5×10^{6}
5600	250×10^{-6}	250×10^{-6}	250×10^{-6}	22.0×10^{6}
8400	370×10^{-6}	370×10^{-6}	370×10^{-6}	22.7×10^{6}
11200	490×10^{-6}	490×10^{-6}	490×10^{-6}	22.9×10^{6}

Capillaries length = 5.00"

$B' = 0.54$

$P_s = 240$ psi

$P_r' = 130$ psi (Average top and bottom)

TABLE II
MOMENT STIFFNESS

① Load W (lbs.)	② Deflection (in.) Pick-up (a)	Pick-up (b)	③ Net Deflection (in.) $\frac{(b) - (a)}{2}$	④ Stiffness K in-lb/rad $K = \frac{Z ①}{③}$
2800	$+320 \times 10^{-6}$	-20×10^{-6}	170×10^{-6}	16.7×10^{9}
5600	$+700 \times 10^{-6}$	-40×10^{-6}	370×10^{-6}	15.4×10^{9}
8400	$+1050 \times 10^{-6}$	-70×10^{-6}	560×10^{-6}	15.2×10^{9}
5600	$+700 \times 10^{-6}$	-40×10^{-6}	370×10^{-6}	15.4×10^{9}
2800	$+320 \times 10^{-6}$	-20×10^{-6}	170×10^{-6}	16.7×10^{9}

r = 21 in. (Distance of indicators (a) and (b) from azimuth axis)

L = 48 in. (Moment arm of applied load, W, from azimuth axis)

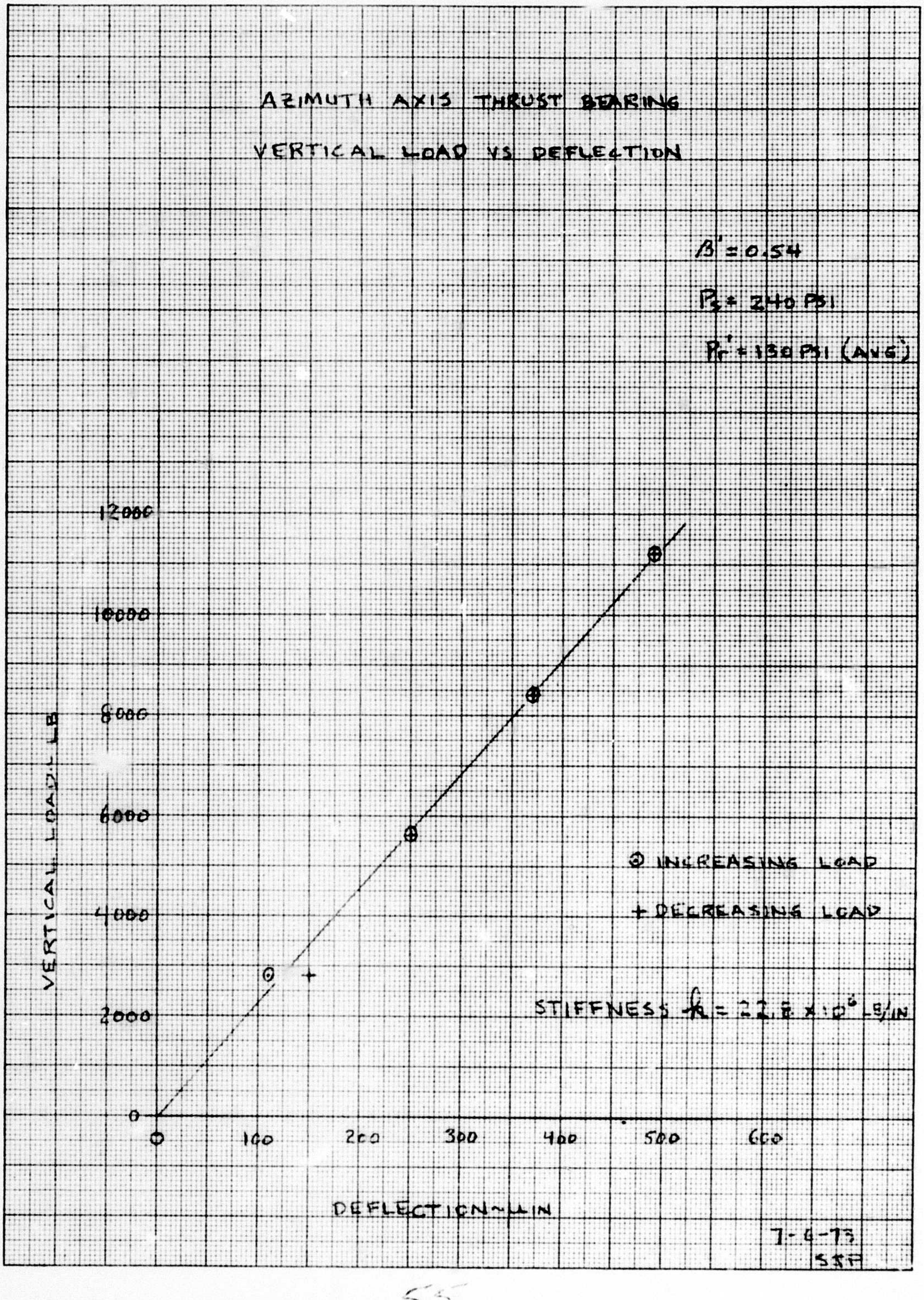
Z = Lr = 1010 in^2.

$$K = \frac{WLr}{\frac{(b) - (a)}{2}}$$

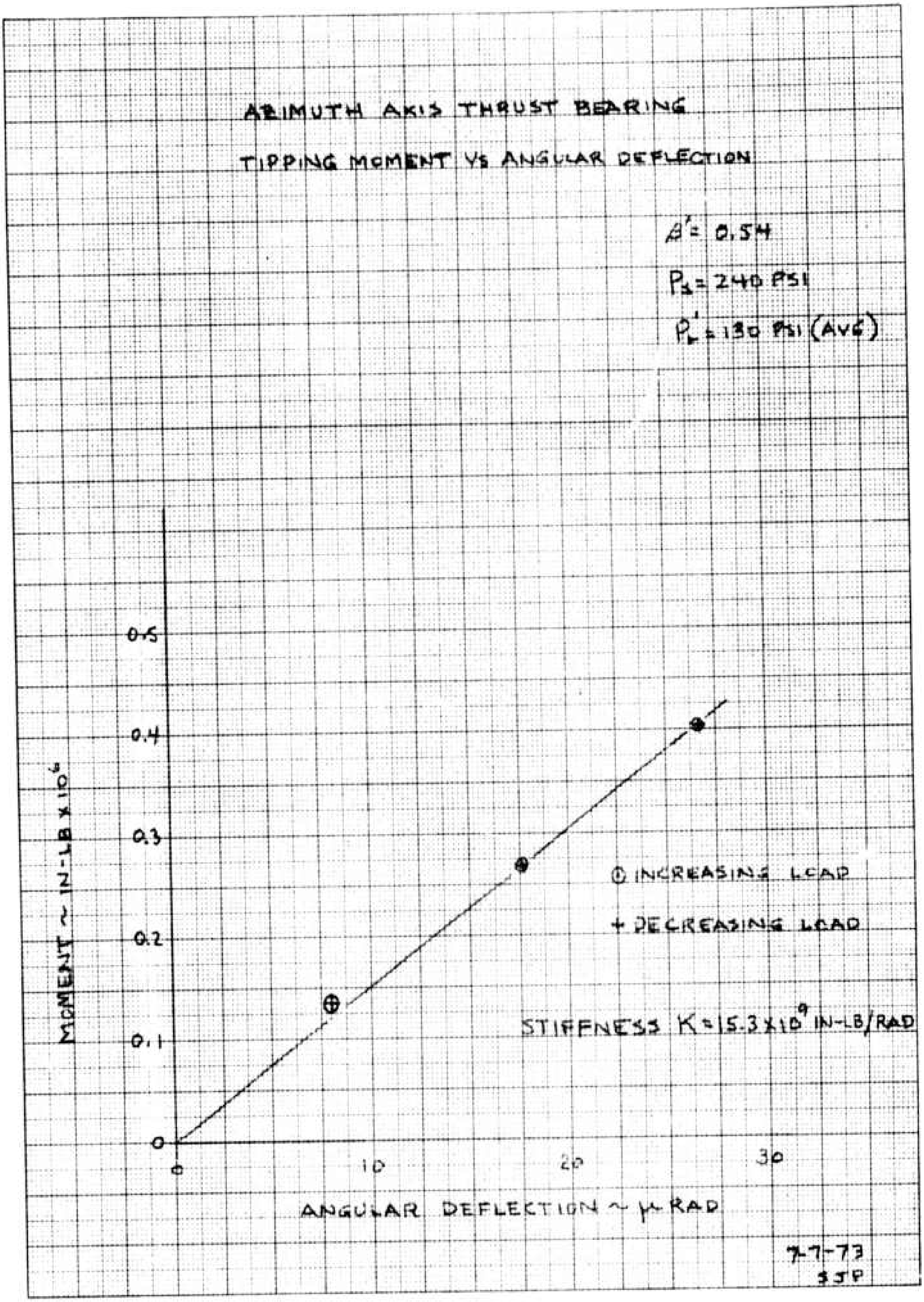
$B' = 0.54$

$P_s = 240$ psi

$P_r = 130$ psi (Avg)



K&E 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A.



K&E 10 X 10 TO THE CENTIMETER 46 1513
KEUFFEL & ESSER CO.

APPENDIX G

TEST PROCEDURE FOR THE ELEVATION AXIS HYDROSTATIC BEARING STIFFNESS FOR THE COELOSTAT TRACKING MOUNT (CORAL)

F(8)-864-047-022-2292

Test Data

TEST PROCEDURE FOR THE ELEVATION AXIS HYDROSTATIC BEARING STIFFNESS FOR THE COELOSTAT TRACKING MOUNT (CORAL)

F(8)-864-047-022-2292

July 10, 1973

OWENS-ILLINOIS

FECKER SYSTEMS DIVISION

4700 BAUM BOULEVARD PITTSBURGH, PA. 15213

TEST PROCEDURE FOR THE ELEVATION AXIS HYDROSTATIC BEARING STIFFNESS FOR THE COELOSTAT TRACKING MOUNT (CORAL)

1.0 GENERAL

The elevation axis hydrostatic oil bearing is mounted in a vertical plane with its axis horizontal. It restrains only radial motion of the elevation axis at the inboard end of the elevation axis and allows the axis to float axially at the inboard side.

This test procedure outlines the method of determining the radial stiffness of the bearing. The capillaries are preadjusted from theoretical calculations and will only be monitored to verify the predicted compensation values. The eccentric load of the radial bearing causes each capillary around the bearing to have a different pressure ratio so that the no load pressure ratios are inconvenient to measure and adjust. However, since the end objective is to attain a minimum required stiffness for the bearing, adjustment of the capillaries will only be made if the minimum stiffness requirement is not met.

2.0 TEST EQUIPMENT REQUIRED

(1) Cleveland Gage, Model OH215 with pick-up
(2) Mounting brackets for Cleveland gage pick-up
(3) Weights for loading bearing (1500-2500 lb)
(4) Capillary testing fixture, 254-0048 (with two 0-400 psi pressure gages)
(5) Hydraulic oil supply for bearing

3.0 TEST PREPARATION

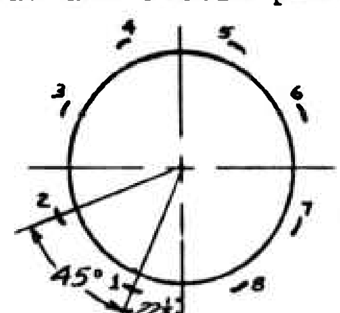
In order to successfully perform the radial stiffness test the elevation axis housing along with the azimuth axis housing should be fully assembled and secured in place atop the support platform with the elevation axis mirror removed.

(1) Remove the elevation axis mirror with cell.

(2) Rotate the elevation axis to the zenith position (full vertical) and apply the elevation axis brake.

(3) Mount the Cleveland gage pick-ups into position to measure the differential displacement between the rotor and the stator. The pick-up may be mounted at the top (or bottom) of the bearing rings.

(4) Insert the capillary testing fixture (254-0048) into any selected pad and record pad number.



Bearing Pad Locations

(5) Turn on hydraulic pressure to approximately 230 psi.

(6) Record the weight of each test weight, accurately.

4.0 TEST PROCEDURE

(1) Lower the weights gently into position so that they rest inside the elevation housing as close to the elevation oil bearing as possible.

(2) Record the corresponding deflections as "δ" and list them in Table I.

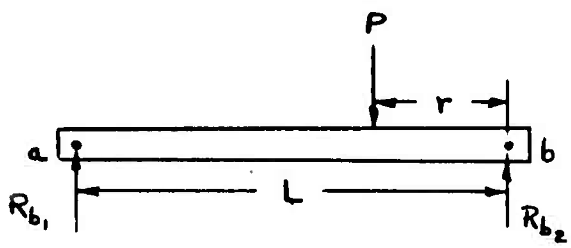
(3) Record the distance of the weight C.G. from the elevation oil bearing as "r".

r = __________ in.

(4) Remove the weights, one at a time, and record the deflections again. Check to see that the Cleveland gage returns to its initial "zero" position when the test weights are removed.

(5) Record the distance between the two elevation bearings as "L".

L = __________ in.



$$\Sigma M_a = R_{b_2} L - (L-r)\, P = 0$$

$$R_{b_2} = \frac{L-r}{L} P$$

(6) At this point, with the weight removed the capillary testing fixture can be used to check the pressure ratios of all the capillaries and recorded in Table II. The bearing load will be known, since it is to be determined prior to assembly of the elevation axis.

TABLE I

LOAD P (lbs)	DEFLECTION δ (in.)	STIFFNESS k (lb/in) $k = Z \frac{P}{\delta}$
0	0	-
2000	0.00015	12×10^6
0	0	-

r = 7 in.

L = 70 in.

$Z = \frac{L-r}{L} = .$ 0.9

Stiffness $k = Z \frac{P}{\delta} = 0.9 \times \frac{2000}{0.00015} = 12 \times 10^6$ lb/in

Design specification stiffness ≈ 5.5×10^6 lb/in

1 { Design specification gap - 0.003"
  Actual gap - 0.0027"

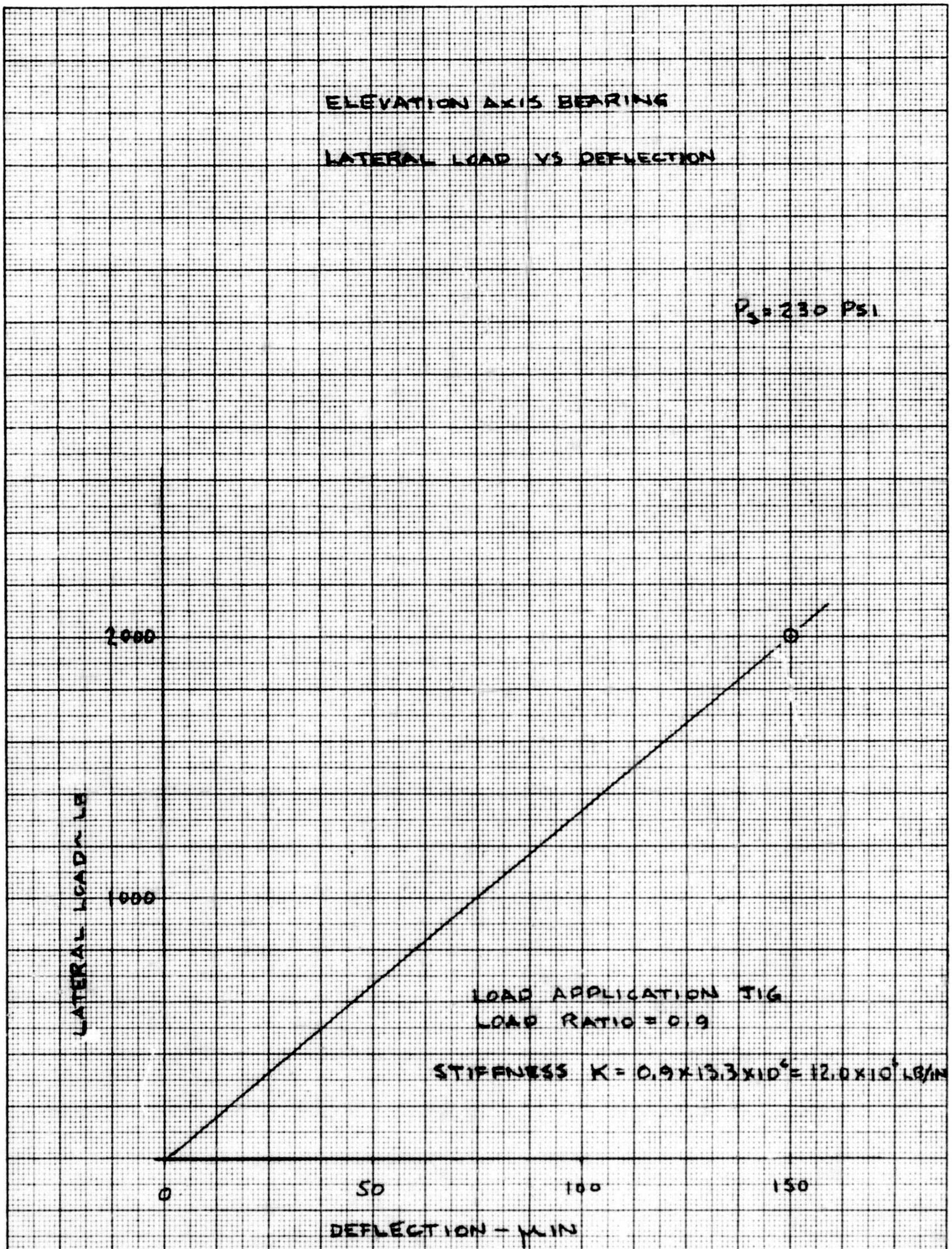
2 { β across capillary #3 design spec - 0.15
  β across capillary #3 actual - 0.20
  This indicates capillary length shorter than that required to obtain design ΔP

Both 1 and 2 contribute to extra stiff bearing

TABLE II

Bearing Pad Location	Pressure Ratio β
1	
2	
3	0.20
4	
5	
6	
7	
8	

Supply Pressure P_s = 230 psi



K+E 10 X 10 TO THE CENTIMETER 46 1513
18 X 25 CM. MADE IN U.S.A.
KEUFFEL & ESSER CO.

APPENDIX H

RADC COMMENTS AND FECKER SYSTEMS REPLY
ON
FINAL REPORT

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS ROME AIR DEVELOPMENT CENTER (AFSC)
GRIFFISS AIR FORCE BASE, NEW YORK XXXX 13441

REPLY TO ATTN OF: PMRZ (AC 315, 330-3204)

8 Aug 1974

SUBJECT: Contract F30602-72-C-0192, Acceptance Test Data Report (Ref your ltrs, 18 and 19 Jul 1974)

TO: Owens-Illinois
Fecker Systems Division
ATTN: Mr. G. E. Miller
4709 Baum Boulevard
Pittsburgh PA 15213

1. Review of the Acceptance Test Data Report submitted has been completed.

2. There are two main technical areas in the Test Data Report which require clarification; namely, the random error analysis in Section 1.3 and the servo and interface testing in Section 1.2.

3. Specific questions concerning these areas are addressed in Attachment 1 to this letter.

4. The technical areas described have been discussed with your personnel and it has been mutually agreed that the desired clarifications would best be handled by written correspondence.

Lawrence L D'Angelo
LAWRENCE L. D'ANGELO
Contracting Officer

1 Atch
Areas Requiring Clarification

AREAS REQUIRING CLARIFICATION WITH REGARD TO OWENS-ILLINOIS, FECKER SYSTEMS DIV (FSD) TEST REPORT DATED 3 JUL 1974

1. The inclusion of base systematic (correctable) errors in a random error analysis is questioned as to being a valid procedure.

The base errors of alignment, foundation and thermal drifts are identified by FSD as correctable errors. As such, they should not be included in a random error budget analysis Further, the 1.0 sec peak thermal drift cited is inconsistent with the coelostat design study results (RADC-TR-70-25, P.111 cited 0.5 sec for expected random peak error for thermal drift). This error source is identified as having a random error component of 0.1 sec (10% of systematic peak). This fractional random part needs to be clarified by FSD.

The original design study cited 0.5 sec for thermal drift random rms. The referenced test report has arbitrarily used 10% of a drift value of 1 sec. Clarification must be given for the selection of this magnitude and the corresponding 10% for random error. If thermal drift is referenced as having a random 10% fraction of its correctable 1 sec drift, should the same error percentages be applied to foundation and alignment correctable errors. This would give an error analysis contribution of 0.05 sec and 0.1 sec for these factors, respectively.

2. The use of the static pointing test results for structure random error analysis:

Earlier discussions between RADC and FSD led to the agreement that individual error contributions would be used as opposed to the final averaged results of the static pointing test. That is, the measured random error associated with AZ wobble (1.3 II), EL wobble 1.3 II) and orthogonality (1.3 II) would replace the static pointing test results. However, this was not done by FSD. Consequently, the reason why it was not done should be furnished to RADC.

3. The significance of bit error in the servo jitter test:

Servo jitter tests on page 111 indicates a jitter range of nominally 6 bits for both Az and El servo positional controls. This indicates the bit range which are random and unrepeatable for the purposes of positional control. Each bit however, has a differing resolution magnitude. FSD

Atch 1

treats each bit as having the same resolution magnitude (0.15 sec $= 360°/2^{23}$) and simply multiplies one-half of the 6 bit random range by 0.15 sec per bit. The correct procedure would be to realize that an error range of 6 bits would really mean that the last 6 bits of the servo position control were random, giving realized control of 23 bits-6 bits = 17 bit of repeatable position setting. Random error for servo positional control is then specified by the random bit range of 6 bits (or $\pm$ the 18 bit location or $\pm 360°/2^{18} = \pm 4.944$ sec $= \sigma_{servo\ position}$). A careful review on FSD's part would clarify that each bit has a different resolution (weight) and cannot be all assigned an error contribution of 0.15 sec.

4. Servo bandwidth response does not show a classical trend with increasing frequency:

The servo gain plots for both Az and El servos do not indicate the classical downward trend with increasing frequency. The steady increase in gain up to the mount resonance implies that this data was taken while not monitoring the proper test point for servo response. The data trend more accurately follows the expected response of a servo compensation network which corrects for gain rolloff with increasing frequency. The data trend for the servo gain needs to be explained by FSD as to this steady increase up to the mount resonance points, and, why the unusual peaking at 0.5 Hz as displayed in the data on page 117 for El axis was not entered in the plots on page 116. Characterization of the servo is critically important for transfer function definition and position-rate control via computer drive as applied to precision tracking efforts which will be occurring during a later date at CORAL.

5. Interface status verification was unsatisfactory:

The status word displayed on pages 147 and 148 do not verify the required CW or CCW zone entry as the test required. This function is critically important for software/programming knowledge of mount position to prevent driving the mount into the limit stops.

OWENS-ILLINOIS
FECKER SYSTEMS DIVISION
4709 BAUM BOULEVARD PITTSBURGH, PA 15213

PHONE (412) 621-3200
CABLE: FECKER-PITTSBURGH

August 23, 1974

Department of the Air Force
Hdqrs. Rome Air Development Center (AFSC)
Griffiss Air Force Base, New York 13441

Attention: Lawrence L. D'Angelo, Contracting Officer

Subject: Contract F30602-72-C-0192

Gentlemen:

Enclosed are three (3) copies of the clarifications to RADC's critique of the Acceptance Test Report submitted under the subject contract. It is anticipated that this item may be now considered complete.

Two (2) copies of the final technical report, Seq No. A008, were forwarded for review under my letter dated 31 July. As requested in the above letter, please return one copy of the report and one copy of the foreward sheet. Also indicate the RADC-TR number and distribution on the copy of the report to be returned.

If you will expedite the above request, then upon distribution by Fecker of the final report, this contract can be considered complete and final payment can be made.

Very truly yours,

G. E. Miller
G. E. Miller
Contracts Manager

m

Enc: Noted above

cc: G. J. Thompson
R. P. LaFleche

CLARIFICATIONS AND EXPLANATIONS
IN REPLY TO RADC'S CRITIQUE
OF AUGUST 8, 1974 ON THE
FECKER SYSTEMS DATA REPORT F-2345A

1. Base Systematic (Correctable) Errors

The errors of alignment, foundation, and thermal drift are tower errors as indicated in the Coelostat Tracking Mount Study (RADC-TR-70-25). This is further indicated in the error analysis and only a small fraction of the thermal drift is included as a component affecting the coelostat accuracy.

The philosophy of this judgement deals with the time period over which these errors occur. The identified errors may usually take as long as a year to manifest themselves and certainly would not be discernible over a 24-hour period. However, there is an obvious short term thermal effect due at least to the changing position of the sun.

It is not expected that the systematic corrections to the instrument line of sight will be so sophisticated as to include this error. Thus, if it is present, it will have an influence on the coelostat line-of-sight. Omission of this "random" error, regardless of the source, would jeopardize the validity of the "error analysis".

Since the thermal drift is a base parameter, the fabrication contract for the coelostat (F30602-72-C-0192) did not concern itself with precise parametric values. Thus, the validity of 10% of the one arc second as the RMS short term value is optimistic from the coelostat builder's viewpoint. Ten percent of one-half an arc second is even more optimistic. RADC, the seller of the data from the coelostat, obviously has a differing philosophy, and thus, must make their own judgement as to how these base errors will be incorporated in the data reduction or random error analysis, and indeed if the values are as stated.

2. "The use of static pointing test results for structure random error analysis."

During the meeting of May 21, 1974 at RADC, the test data reduction was discussed and our A. Bouvier's understanding was documented on an internal trip report (a copy of this report is included).

The reason for overall data approach lies in the difficulty of the error component separation. Azimuth and elevation wobble data and orthogonality of the mirrors are individually measured and documented. The mirror misalignment and structural deformation cannot be separated, only the combined result is measureable. The test setup utilized in the definition of the systematic error was devised to be an all inclusive measurement to include all error from the input beam of the azimuth axis to the output beam of the LOS. The argument for this approach was:

1. Some of the error components would have to be arbitrarily separated.
2. The accuracy to be demonstrated is extremely precise (errors are in sub arc second range) and each individual test set up would be masked with an additional set up and autocollimator error.

3. Servo Jitter

Contrary to the RADC statement, each bit of jitter does have an equal angle of resolution amounting to $\frac{360^\circ}{2^{23}}$ (or 0.15 arc second). Referring to page 121 (previously page 111) of the Data Report where an average of 6 bits of jitter is designated for each Az and El, each of the 6 bits is also a single LSB with an angular resolution of 0.15 arc second.

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Example No. 1, Az 224^{0}, Local, Page 121

	Reading	Change
Max. reading	47645006	
		1 LSB change
	47645004	
		1 LSB change
	47645002	
		1 LSB change
	47645000	
		1 LSB change
	47644776	
		1 LSB change
	47644774	
		1 LSB change
Min. reading	47644772	
	Total	6 LSB change

Observe that only 6 LSB (0.9 arc sec) caused a one-digit change in the 4th least significant OCTAL digit. This does not mean that an angular variation of 2^{15} (39.5 arc seconds) has taken place. Such is the nature of the OCTAL format.

Since the 6 LSB jitter average is peak-to-peak, (min. to max.), the term can be expressed as ±3 LSB or ±0.45 arc second.

Example No. 2, Az 113^{0}, Local, Page 121

	Reading	Change
Max. reading	24055426	
		1 LSB change
	24055424	
		1 LSB change
	24055422	
		1 LSB change
	24055420	
		1 LSB change
	24055416	
		1 LSB change
	24055414	
		1 LSB change
Min. reading	24055412	
	Total	6 LSB change

Example No. 3, El 39^{0}, Local, Page 121

	Reading	Change
Max. reading	06735676	
		1 LSB change
	06735674	
		1 LSB change
	06735672	
		1 LSB change
	06735670	
		1 LSB change
	06735666	
		1 LSB change
	06735664	
		1 LSB change
Min. reading	06735662	
	Total	6 LSB change

4. Servo Bandwidth

RADC's interpretation of the rate loop servo response curves is somewhat incorrect. The plot shown is the solution to the classic servo transfer function:

$$\frac{\text{Output}}{\text{Input}} = \frac{G(s)}{1+G(s)H(s)}$$

where G(s) is the transfer function of the forward path and H(s) is the feedback transfer function and shows only indirectly the mechanical resonance characteristics. This test was accomplished using a second gyro, operated in the caged mode as a rate transducer and comparing its output with the commanded input to the mount. The actual mechanical resonances of the axes were measured during system checkout and are above 30 Hz for each axis. Thus, since these occur near the start of migration of the transfer function G(s) H(s) (i.e., where $G(s)\ H(s)<1$) the above equation reduces to approximately G(s) and they will appear at the measured resonant frequency. The response is then that of a dominant second order system (i.e., one where the lowest frequency poles of the characteristic equation are complex) with of course some deviation due to the effect of higher order poles and zeroes of the closed loop transfer function including the mechanical resonance.

As for the unusual peak at 0.5 Hz of elevation axis data, we can only rationalize it as a bad data point which is substantiated by the fact that the phase shift remained unchanged and normal at the same frequency.

5. Interface Status Verification

To aid the following explanation of how to readout a Status Word #1, a copy of the Compunetics Status Word description has been included as Figure 1 and has been improved by the addition of details.

STATUS WORDS

BIT #		
0	(LSB)	"ZERO" Status Word #1 = 0
1		System On Line = 1, Off-Line = 0
2		AZ CW Zone = 0, $\overline{\text{AZ CW Zone}}$ = 1
3		AZ CCW Zone= 0, $\overline{\text{AZ CCW Zone}}$ = 1
4		AZ Sign 1 = CW, 0 = CCW
5		EL Sign 1 = CW, 0 = CCW
6		AZ Slew 1 = SLEW, 0 = Linear
7		EL Slew 1 = SLEW, 0 = Linear
0	(LSB)	"ONE" Status Word #2 = 1
1		Encoder Input Buffer Full = 1
2		Interface Power Fail = 0, $\overline{\text{Fail}}$ = 1
3		Hold Mode Option Actuated
4		SS Actuated AZ = 1, EL = 0
5		Spare
6		Position (0), Rate (1) Actuated
7		Spare

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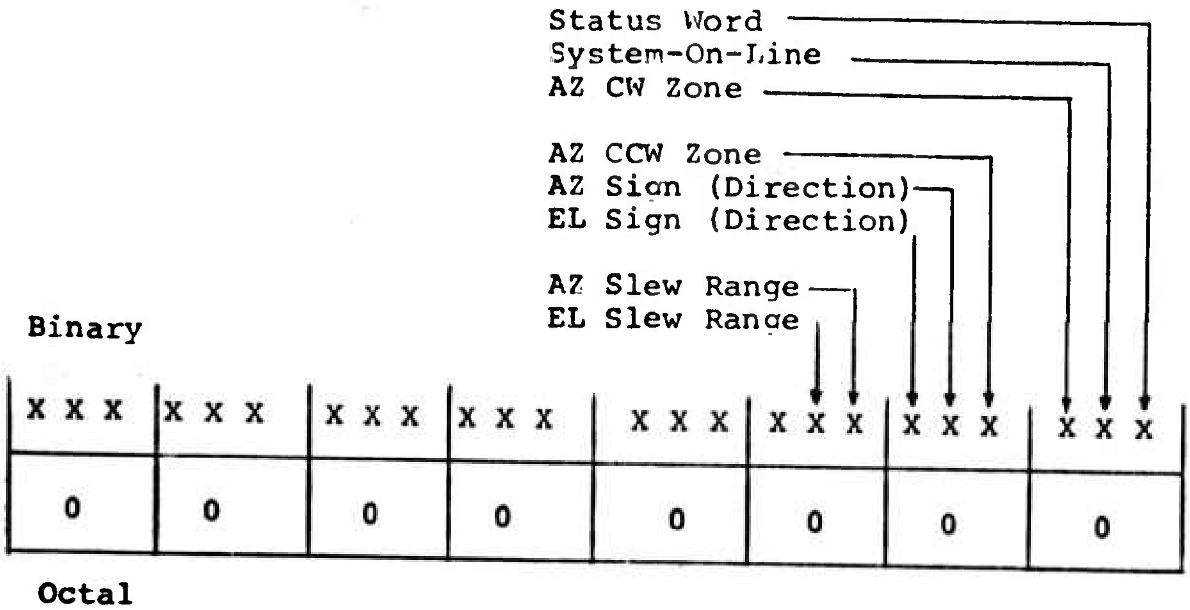
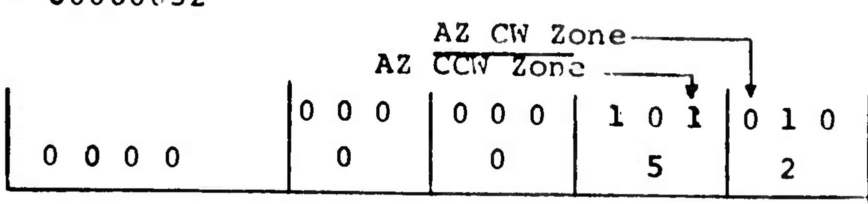
a. General

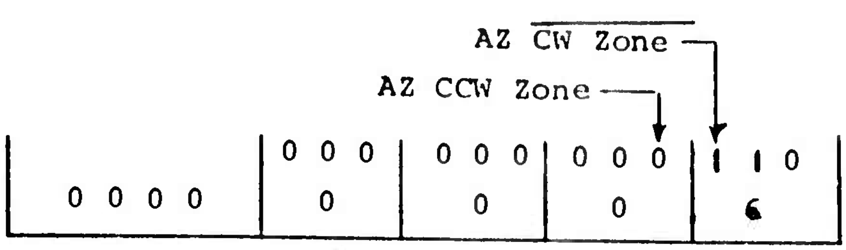


Using the above aids, a review of the Status Word #1 readouts as displayed by printouts D, E, F, H, and K on pages 157 and 158 (previously pages 147 and 148) shows them to be correct with regard to AZ CW and CCW zone entry. Each is illustrated below:

b. Paragraph 18.1.4, "D", AZ CW 185°. Status Word #1 = 00000052



c. Paragraph 18.1.5, "E", AZ CCW 185°. Status word #1 = 00000006



d. Paragraph 18.2, "F", AZ Zero position
Status Word #1 = 00000056

AZ $\overline{\text{CW}}$ Zone
AZ $\overline{\text{CCW}}$ Zone

	0 0 0	0 0 0	1 0 1	1 1 0
0 0 0 0	0	0	5	6

e. Paragraph 18.2.1-a, "H", AZ CW motion toward 94°
Status Word #1 = 00000176

AZ $\overline{\text{CW}}$ Zone
AZ $\overline{\text{CCW}}$ Zone

	0 0 0	0 0 1	1 1 1	1 1 0
0 0 0 0	0	1	7	6

f. Paragraph 18.2.1-b, "K", AZ CW motion toward 151°
Status Word #1 = 00000136

AZ $\overline{\text{CW}}$ Zone
AZ $\overline{\text{CCW}}$ Zone

	0 0 0	0 0 1	0 1 1	1 1 0
0 0 0 0	0	1	3	6

6. Additional Data Report F-2345A Corrections

a. The systematic error curves shown on Pages 51 and 114 are resubmitted as corrected by their normalization to reference zero arc seconds rather than the actual autocollimator readings as previously shown. Three copies of each are attached.

To make use of these two correction curves, they could be added algebraically to form a single error curve in arc seconds as a function of EL angle. The compensating correction to be programmed would be a value equal and opposite to that shown on this resultant error curve.

b. All of the pages following page 119 are numbered in error from 111 to 159. They should be numbered from 120 to 169. Page numbers referenced in this document are corrected numbers.

INTRA-COMPANY CORRESPONDENCE

22 May 1974

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FECKER SYSTEMS DIVISION
PITTSBURGH, PENNSYLVANIA

Subject Trip Report to RADC (Shop Order 864)

RADC Personnel: Larry DiAngelo
Fred Demma
Bill Wolfe
Bob Ogradnik

1. The mechanical acceptance test data, wobble, orthogonality, mirror alignment, etc., are accepted provided the random components are within the 20 microradians. The data, particularly the tests run during last week needs to be reduced to reflect an error curve as a function of the elevation angle. A calibration curve for the elevation encoder will be accepted.

The data reduction for the overall tests which include azimuth and elevation wobble, orthogonality, mislevel and mirror misalignment was agreed to be presented as follows.

-- Average all elevation and azimuth coordinate reading for the Run 5 (mount elevation angle ϵ = const. for varying azimuth mount positions, vary ϵ by $\Delta\epsilon$ = 11-1/4°). Determine systematic error as a function of mount elevation angle and Random component.

-- Repeat the procedure for a second run to assure repeatability of data.

2. The programming to test the interface chassis is considered as a cost sharing item by RADC. They want information:

a. acceptance test procedure for Compunetics task.

b. Is the original installation task by Compunetics reduced due to the availability of the program?

3. Ogradnik expressed unsatisfactory "lock-in" of the position designate mode (offset and change of offset). Also claims the switching from coarse range to lock on appears "out of adjustment". (Range 1 brings it close, when switching occurs an acceleration pulse brings it to an "extreme" overshoot.) Submit information about the corrections which were installed since shipped.

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22 May 1974

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PITTSBURGH, PENNSYLVANIA

Subject Trip Report to RADC - con't.

4. Schedule of remaining tasks.

Week of 5/28 - Complete all servo test (contingent on the availability of the Op. AMP under repair!)

Week of 6/7 - Complete interface installation

Week of 6/21 - Complete interface checkout and line item 0002.
Complete item 0006. (Manual and Final Report, Acceptance Test Data)
The Final Report shall include the error budget (total random <20 microradians!)

Note: 3 weeks of Compunetic effort is maximum anticipated effort.

A. Bouvier

Distribution:

J. Thompson
R. Strane
S. ~~Snyder~~
R. Startari
S. Pappas
G. Miller
J. Ullom
R. LaFleche

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Source AFSCR 23-50, 11 May 70

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