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INERTIAL MEASUREMENT UNIT (IMU) ALIGNMENT TESTS

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INERTIAL MEASUREMENT UNIT (IMU) ALIGNMENT TESTS

by

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Prepared by
Washington Engineering Services Co., Inc.
White Flint Science Park
Kensington, Maryland

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CONTENTS

ILLUSTRATIONS

I. GENERAL INFORMATION

A. PURPOSE OF THE IMU ALIGNMENT TESTS.

These tests are for the purpose of establishing the magnitude and direction of certain defined errors so that, when the Inertial Measurement Unit (IMU) is allowed to perform an erection or fine alignment, regardless of orientation, it will be possible to state that a definite relationship does exist between the Navigation Base triad and the actual IMU measurement triad, and further, that this relationship is within some tolerance.

B. GENERAL DESCRIPTION OF THE IMU ALIGNMENT TESTS.

The Alignment Tests are, in general, made only once during the history of an IMU subsystem. They occur at the Subsystem Level, either at MIT or ACSP/Milwaukee. On the other hand, Calibration Tests, which determine scale factors and bias performance of the inertial system, are repeated throughout the history of the system. Calibration Tests are covered in separate documents.

A single, basic principle is involved in the majority of the Alignment Tests. This principle is that the location of an axis of rotation with respect to gravity can be determined by two successive null readings of an accelerometer which is rotated 180° about said axis. The seventeen so-called PIPA Alignment Tests are merely repeated applications of this basic principle in combinations calculated to deduce the desired angular information.

This approach is necessary because the required alignment information must be obtained when the IMU is closed up and provided with what is close to its "operational" environment. Thus, optical or mechanical methods of measurement are ruled out. Of the transducers inside the IMU, the PIPA's are best suited to giving angular information to a few arc-seconds accuracy.

The IRIG Alignment Tests determine the alignment of the IRIG's to the Stable Member triad. The requirements for precision are not as great in this area, relatively speaking. Accordingly, it is the purpose of the IRIG Alignment Tests to determine that the IRIG misalignments are less than ten arc minutes within plus or minus one arc minute. This is accomplished by rotating about an axis orthogonal or nearly orthogonal to the IRIG of interest and by observing the IRIG signal generator preamplifier output for a quantitive measurement of misalignment.

Primarily, the Alignment Tests are to qualify an IMU as stated in the section on PURPOSE. The data taken serves to establish qualification. In the case of measurements of resolver null misalignments, however, the data is immediately used to compensate the 16X resolver nulls electrically to reduce the null misalignments to minimum values. In addition, accelerometer misalignments will be subject to corrective action.

C. DEFINITIONS OF TESTS QUANTITIES.

1. *Axis Systems.*

Earth Fixed Axes (See figure I-1.)
North........Collinear with local horizontal component of earth rate.
Vertical......Collinear with local gravitational attraction (down).
East...........Collinear with $\bar{g}$ x N.*

Trunnion Fixed Axes (See figure I-1.)
Y_{TR}..............Collinear with negative of tilt axis.
Z_{TR}..............Collinear with rotary axis.
X_{TR}..............Collinear with Y_{TR} x Z_{TR}.

Table Fixed Axes (See figure I-1.)
Z_T...............Collinear with Z_{TR}.
X_T...............Collinear with X_{TR} when rotary angle θ as read in optigon screen equals 0.
Y_T...............Collinear with Z_T x X_T.

Fixture Fixed Axes (See figure I-3, I-4, and I-5.)
X_{FXT}...........Parallel to fixture's IMU mounting surface and along X "Pin Line," real or phantom.
Y_{FXT}...........Collinear with Z_{FXT} x X_{FXT}.
Z_{FXT}...........Collinear with the negative normal of the fixture's IMU mounting surface.**

Gimbal Case Fixed Axes (See figure I-3, I-4, and I-5.)
X_{GC}.............Collinear with outer gimbal axis in gimbal case.
Y_{GC}.............Collinear with Z_{GC} x X_{GC}.
Z_{GC}.............Collinear with the normal of the case's mounting flange surface.**

Outer Gimbal Fixed Axes (See figure I-6.)
X_{OG}.............Collinear with X_{GC} and OGA.
Y_{OG}.............Collinear with MGA x OGA.
Z_{OG}.............Collinear with X_{OG} x Y_{OG}.

Middle Gimbal Fixed Axes (See figure I-7.)
Z_{MG}.............Collinear with MGA.
X_{MG}.............Collinear with IGA x MGA.
Y_{MG}.............Collinear with Z_{MG} x X_{MG}.

Stable Member Fixed Axes (See figure I-8.)
Y_{SM}.............Collinear with IGA.
X_{SM}.............Collinear with IGA x Z PIP IRA.
Z_{SM}.............Collinear with X_{SM} x Y_{SM}.

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* On this page, the "X" between two axes refers to a vector crossproduct, which is defined in any standard text on vector mathematics.

** The normal to a surface sticks out of that surface.

2. *Table Angle Definitions.*

Φ_j	The jth reading taken from the Tilt Axis Optigon Screen. Positive Φ involves rotation about TA. (See figure I-1.)
θ_i	The ith reading taken from the Rotary Axis Optigon Screen. Note that positive θ involves positive rotation about Z_{TR}. (See figure I-1.)
ϵ_{TR}	Leveling error of the tilt table in the vertical plane containing the Tilt Axis. Positive when TA is rotated about the south vector. (See figure I-2.)
ϵ_{T_T}	Leveling error of the tilt table in the vertical plane normal to the Tilt Axis. Positive when RA at $\Phi = 0$ rotates positively about TA.
$\Phi_{H_{RA}}$	Corrected reading taken from the Tilt Axis Optigon Screen when, with table loaded*, the Rotary Axis is in the horizontal plane. (See JDC 35.0005.)
$\Phi_{H_{MGA}}$	Corrected reading taken from the Tilt Axis Optigon Screen when, with the table loaded*: (a) the Rotary Axis is set at $\theta_{H_{OGA}}$; (b) the Outer Gimbal is positioned at Precision Zero; and (c) the Middle Gimbal Axis is in the horizontal plane. (See JDC 35.0006.)
$\Phi'_{H_{MGA}}$	Corrected reading taken from the Tilt Axis Optigon Screen when, the table loaded*: (a) the Rotary Axis is set at $\theta_{H_{OGA}} + 90°00'00''$; (b) the Outer Gimbal is positioned at Precision Zero; and (c) the Middle Gimbal Axis is in the horizontal plane. (See JDC 35.0008.)
$\theta_{H_{OGA}}$	Corrected reading taken from the Rotary Axis Optigon Screen when: (a) the Rotary Axis is horizontal ($\Phi_{H_{RA}}$), and (b) the Outer Gimbal Axis is also horizontal and East. (See JDC 35.0002.)
$\theta_{H_{IGA}}$	Corrected reading taken from the Rotary Axis Optigon Screen (when: (a) the Tilt Axis is set at $\Phi_{H_{MGA}}$; (b) the Outer and Middle Gimbals are set at Precision Zero; and (c) the Inner Gimbal Axis is pointing down the local vertical) $- 90°00'00''$. (See JDC 35.0010.)

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* Table loading to include IMU, IMU Fixture, and all table-mounted support equipment used during tests.

3. *IMU Flange and Test Fixture Errors.*

(See figures I-3, I-4, and I-5.)

$\epsilon_{F_{X,Y,\text{or } Z}}$	Cumulative Misalignments between Table Fixed Axes and Gimbal Case Fixed Axes using small angle approximations.
$\epsilon_{[FXT]_{X,Y \text{ or } Z}}$	Misalignment between Table Fixed Axes and Fixture Fixed Axes, using small angle approximations.
$\epsilon_{[FLANGE]_{X,Y,\text{or } Z}}$	Misalignment between Fixture Fixed Axes and Gimbal Case Fixed Axes, using small angle approximations.

$$\begin{aligned}\epsilon_{F_X} &= \epsilon_{[FXT]_X} + \epsilon_{[FLANGE]_X} \\ &= \epsilon_{[FXT]_X} \qquad \text{because } \epsilon_{[FLANGE]_X} = 0 \text{ by definition} \\ \epsilon_{F_Y} &= \epsilon_{[FXT]_Y} + \epsilon_{[FLANGE]_Y} \\ \epsilon_{F_Z} &= \epsilon_{[FXT]_Z} + \epsilon_{[FLANGE]_Z}\end{aligned}$$

4. *Gimbal Angle Definitions.*

A_{OG}	Outer Gimbal Angle. Angle from Y_{GC} to Y_{OG}, positive when Outer Gimbal rotates negatively, or by the left hand-rule, about OGA with respect to a fixed Gimbal Case. (See figure I-6.)
A_{MG}	Middle Gimbal Angle. Angle from Y_{OG} to Y_{MG}, positive when Middle Gimbal rotates negatively, or by the left-hand rule, about MGA with respect to a fixed Outer Gimbal. (See figure I-7.)
A_{IG}	Inner Gimbal Angle. Angle from X_{MG} to X_{SM}, positive when stable member rotates negatively, or by the left-hand rule, about IGA with respect to a fixed Middle Gimbal. (See figure I-8.)
ϵ_{OGR}	Outer Gimbal Resolver Error. The misalignment of the 16X resolver null on the OGA, positive when the null misplacement produces a positive Outer Gimbal Angle in the precision zero mode. (See figure I-9.)
ϵ_{IGR}	Inner Gimbal Resolver Error. The misalignment of the 16X resolver null on the IGA, positive when the null misplacement produces a positive Inner Gimbal Angle in the precision zero mode. (See figure I-9.)
ϵ_{MGR}	Middle Gimbal Resolver Error. The misalignment of the 16X resolver null on the MGA, positive when the null misplacement produces a positive Middle Gimbal Angle in the precision zero mode. (See figure I-9.)
ϵ_{MGA}	Middle Gimbal Axis Error. The misalignment of the MGA with respect to the OGA and represented as positive rotation of MGA away from Z_{OG} about Y_{OG}. (See figure I-6.)
ϵ_{IGA}	Inner Gimbal Axis Error. The misalignment of the IGA with respect to the MGA and represented as positive rotation of IGA away from Y_{MG} about X_{MG}. (See figure I-7.)

5. *Accelerometer (PIPA) Misalignments and Biases.*

If n = X, Y, or Z, and m = X, Y, or Z:

α_{n_m} .... Misalignment Rotation of the n PIPA case-fixed triad, [consisting of the Input Reference Axis (IRA), the Pendulous Reference Axis (PRA), and the Output Axis (OA)] about the stable member "m" axis.

Examples:

JDC 35.0010: α_{X_Z} JDC 35.0015: α_{Y_Z} JDC 35.0017: α_{X_Y}
JDC 35.0012: α_{Z_X} JDC 35.0016: α_{Y_X}

α_{B_n} .... A fictitious rotation of the n PIPA Case [either about its Output Axis (OA) or its Pendulous Reference Axis (PRA)] which will produce a moment due to gravity equal in sign and magnitude to the actual bias moment.

Examples:

JDC 35.0001: α_{B_X} JDC 35.0003: α_{B_Y} JDC 35.0004: α_{B_Z}

On the PIPA theory diagrams, figures II-1 through II-14, IRA′; PRA′; OA′ depict the fictitious orientation of the PIPA case as rotated by α_B.

6. *Intermediate Misalignments Useful During Tests.*

$$\alpha'_{X_Z} = \alpha_{X_Z} - \epsilon_{MGR}$$
$$\alpha''_{X_Z} = \alpha_{X_Z} - \epsilon_{IGA} + \epsilon_{OGR}$$
$$\alpha'_{Z_X} = \alpha_{Z_X} - \epsilon_{MGR}$$
$$\alpha''_{Z_X} = \alpha_{Z_X} + \epsilon_{IGA}$$
$$\alpha'_{Y_Z} = \alpha_{Y_Z} - \epsilon_{MGR}$$
$$\alpha'_{Z_Y} = \alpha_{Z_Y} - \epsilon_{IGR}$$

7. *IRIG Alignment Definitions.*

$n = X, Y, \text{or } Z$

E_n	Voltage Output of the n IRIG Preamplifier. Units: volts.
A_{I_n}	Angle of Rotation of n IRIG about its own Input Reference Axis with respect to inertial space. Units: radians.
A_{F_n}	Angle of Rotation of n IRIG Float about its own output axis with respect to the case. Units: radians.
A_P	Angle by which the Driven Gimbal in IRIG Alignment Tests is not collinear with the earth rate vector. Units: radians.
A_D	Angle by which the Stable Member is rotated about the Driven Gimbal in IRIG Alignment Tests. Units: radians.
T	Duration of a single IRIG Alignment Test from nulling the IRIG Float to final reading of phase sensitive voltmeter. Units: seconds.
$\frac{H}{C}$	IRIG Gain Constant relating Angle Float, A_F, to the Input Angle, A_I. Units: dimensionless.
W_{IE}	Angular velocity of the earth about its own axis with respect to inertial space. Units: radians/second.
W_{BD_n}	Apparent drift rate of the n IRIG due to combined uncertainty and acceleration-sensitive terms of drift. Units: radians/second.
S_n	The n IRIG gain from A_{I_n} to E_n. Units: millivolts/milliradian.
S'_n	Signal Generator gain of the n IRIG from A_{F_n} to E_n. Units: millivolts/milliradian.
U_m	Uncertainty in quantity "m", used in IRIG alignment tests. Units: identical to quantity "m".
λ	Local latitude. Units: degrees, minutes, seconds.

8. *Gyro (IRIG) Misalignments.*

If $n = X, Y, \text{or } Z$, and $m = X, Y, \text{or } Z$, then:

γ_{n_m}	Misalignment rotation of the n IRIG case-fixed triad [consisting of the Input Reference Axis (IRA), the Spin Reference Axis (SRA), and the Output Axis (OA)] about the Stable Member "m" axis.

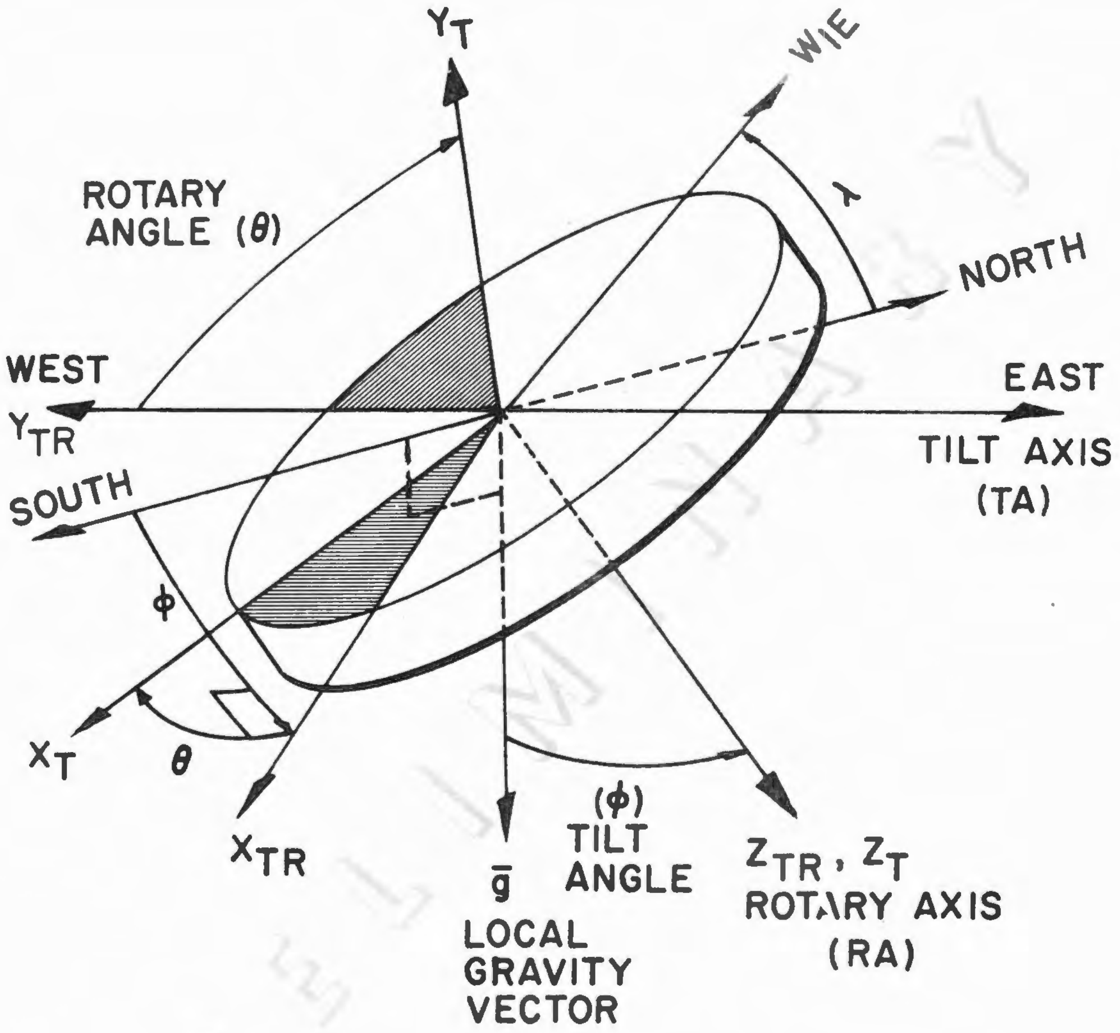
Intermediate Misalignments useful during the test:

$\gamma'_{X_Y} = \gamma_{X_Y} - \epsilon_{IGR}$

$\gamma'_{Y_X} = \gamma_{Y_X} + \epsilon_{IGA}$

$\gamma'_{Y_Z} = \gamma_{Y_Z} - \epsilon_{MGR}$

$\gamma'_{Z_Y} = \gamma_{Z_Y} - \epsilon_{IGR} + \epsilon_{MGA}$



Earth Fixed Axes: NORTH, EAST, $\bar{g}$

Trunnion Fixed Axes: X_{TR}, Y_{TR}, Z_{TR}

Table Fixed Axes: X_T, Y_T, Z_T

Figure I-1. Ideal Tilt Table Orientation.

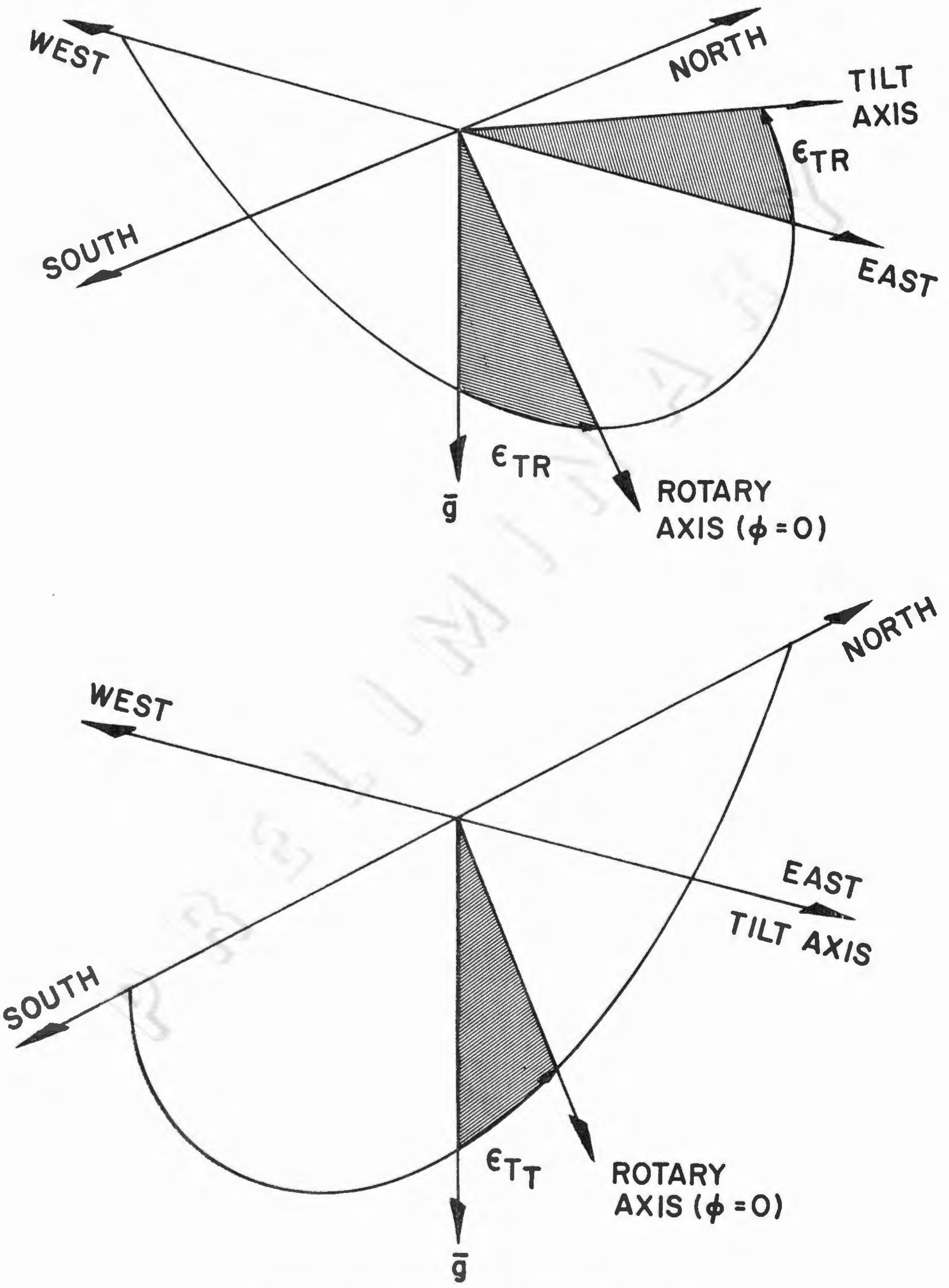


Figure I-2. Tilt Table Leveling Errors.

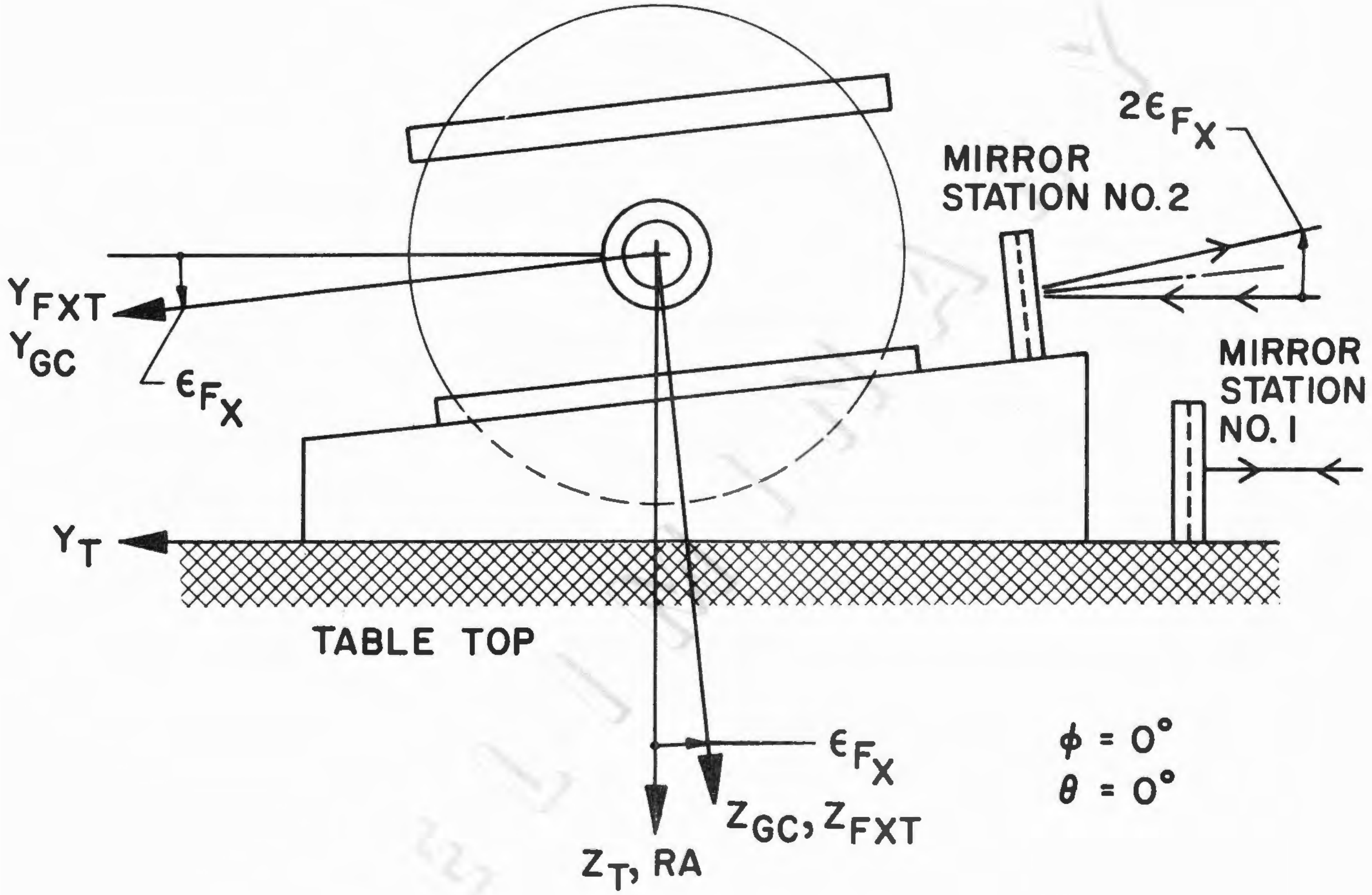


Table Fixed Axes: X_T, Y_T, Z_T

Fixture Fixed Axes: X_{FXT}, Y_{FXT}, Z_{FXT}

Gimbal Case Fixed Axes: X_{GC}, Y_{GC}, Z_{GC}

Figure I-3. IMU Flange and Test Fixture Errors About the X Axis.

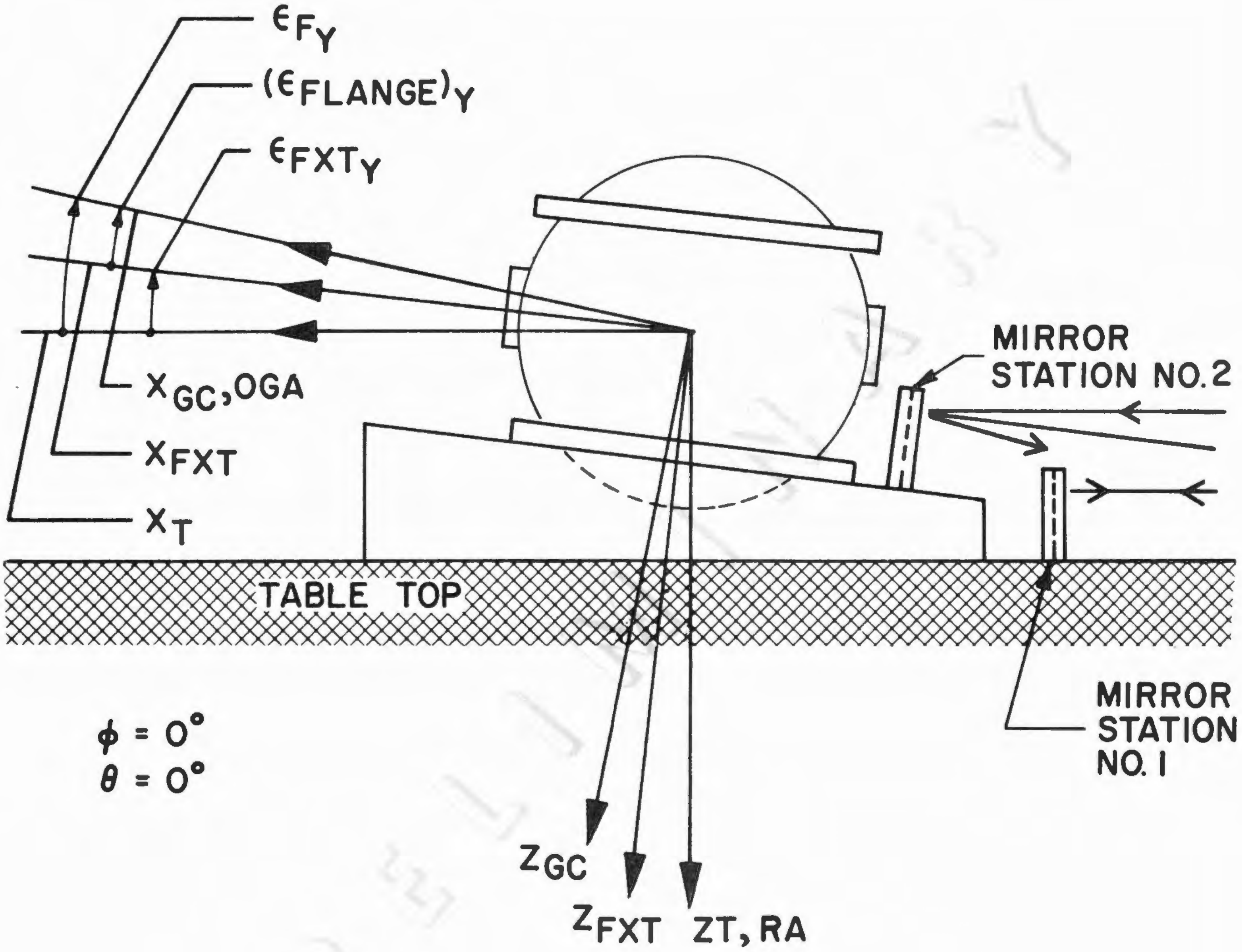


Table Fixed Axes: X_T, Y_T, Z_T

Fixture Fixed Axes: X_{FXT}, Y_{FXT}, Z_{FXT}

Gimbal Case Fixed Axes: X_{GC}, Y_{GC}, Z_{GC}

Figure I-4. IMU Flange and Test Fixture Errors About the Y Axis.

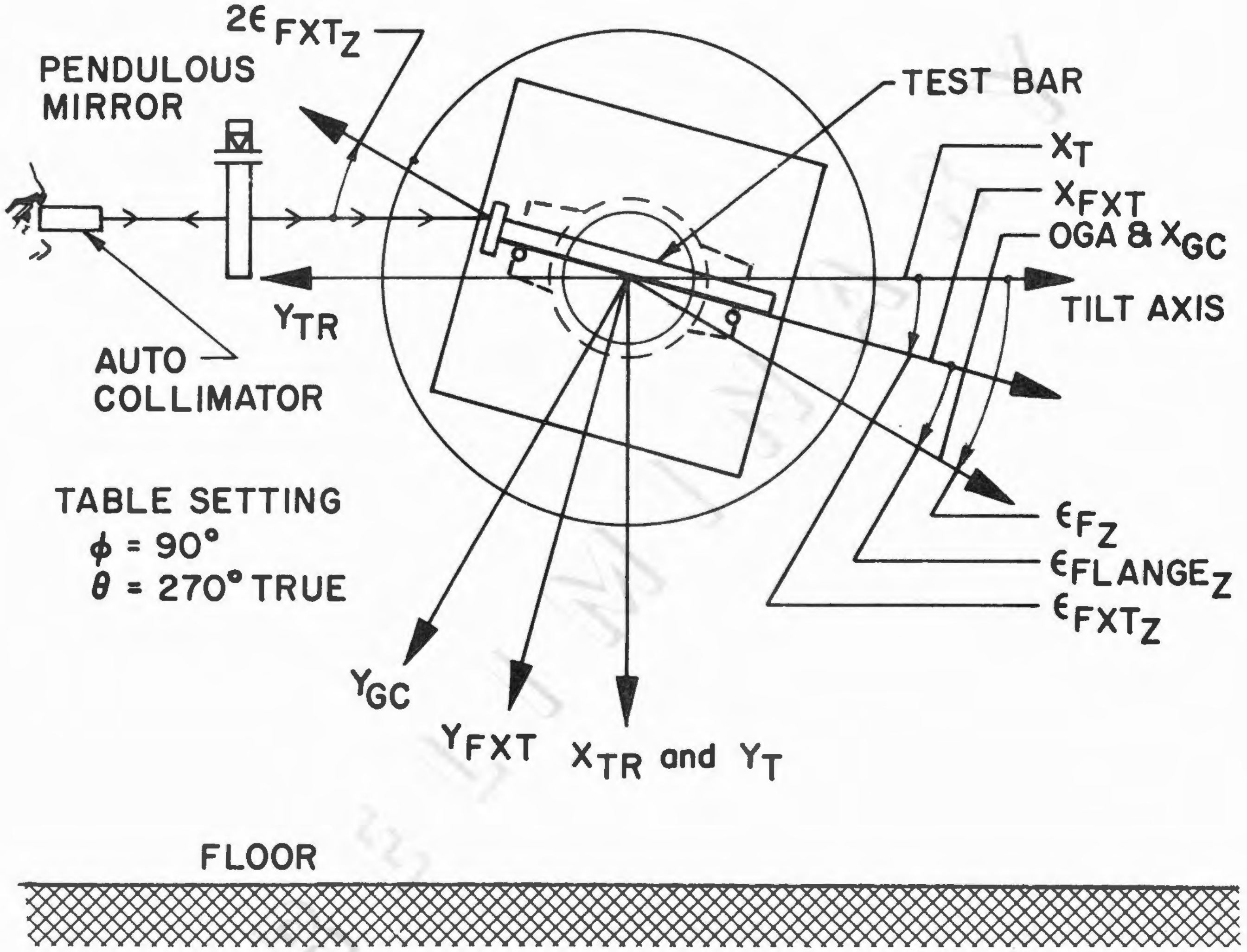
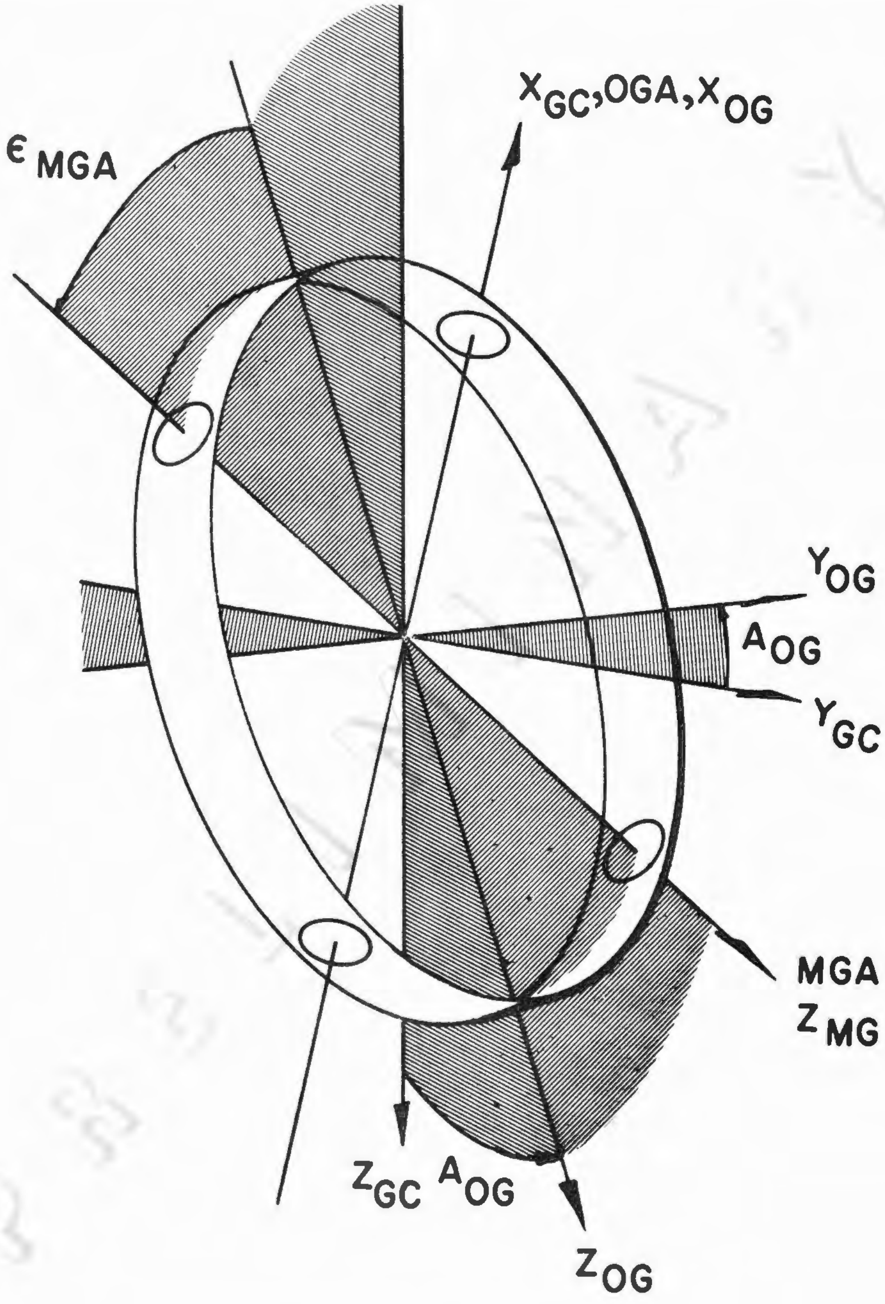


Table Fixed Axes: X_T, Y_T, Z_T

Fixture Fixed Axes: X_{FXT}, Y_{FXT}, Z_{FXT}

Gimbal Case Fixed Axes: X_{GC}, Y_{GC}, Z_{GC}

Figure I-5. IMU Flange and Test Fixture Errors About the Z Axis.

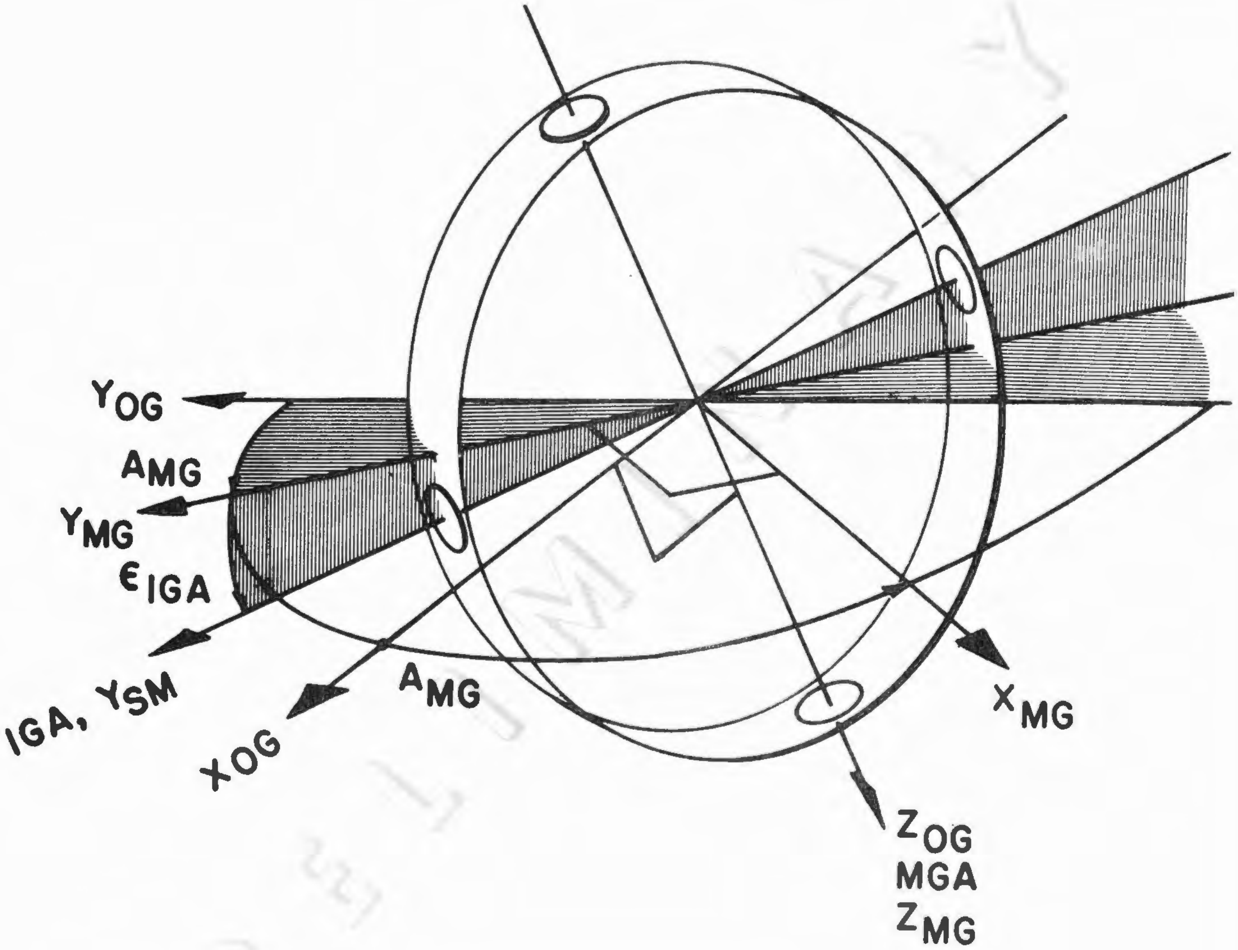


Gimbal Case Fixed Axes: X_{GC}, Y_{GC}, Z_{GC}

Outer Gimbal Fixed Axes: X_{OG}, Y_{OG}, Z_{OG}

Middle Gimbal Fixed Axes: X_{MG}, Y_{MG}, Z_{MG}

Figure I-6. IMU Outer Gimbal Showing Outer Gimbal Angle and Middle Gimbal Axis Error.



Outer Gimbal Fixed Axes: X_{OG}, Y_{OG}, Z_{OG}

Middle Gimbal Fixed Axes: X_{MG}, Y_{MG}, Z_{MG}

Stable Member Fixed Axes: X_{SM}, Y_{SM}, Z_{SM}

Figure I-7. IMU Middle Gimbal Showing Middle Gimbal Angle and Inner Gimbal Axis Error.

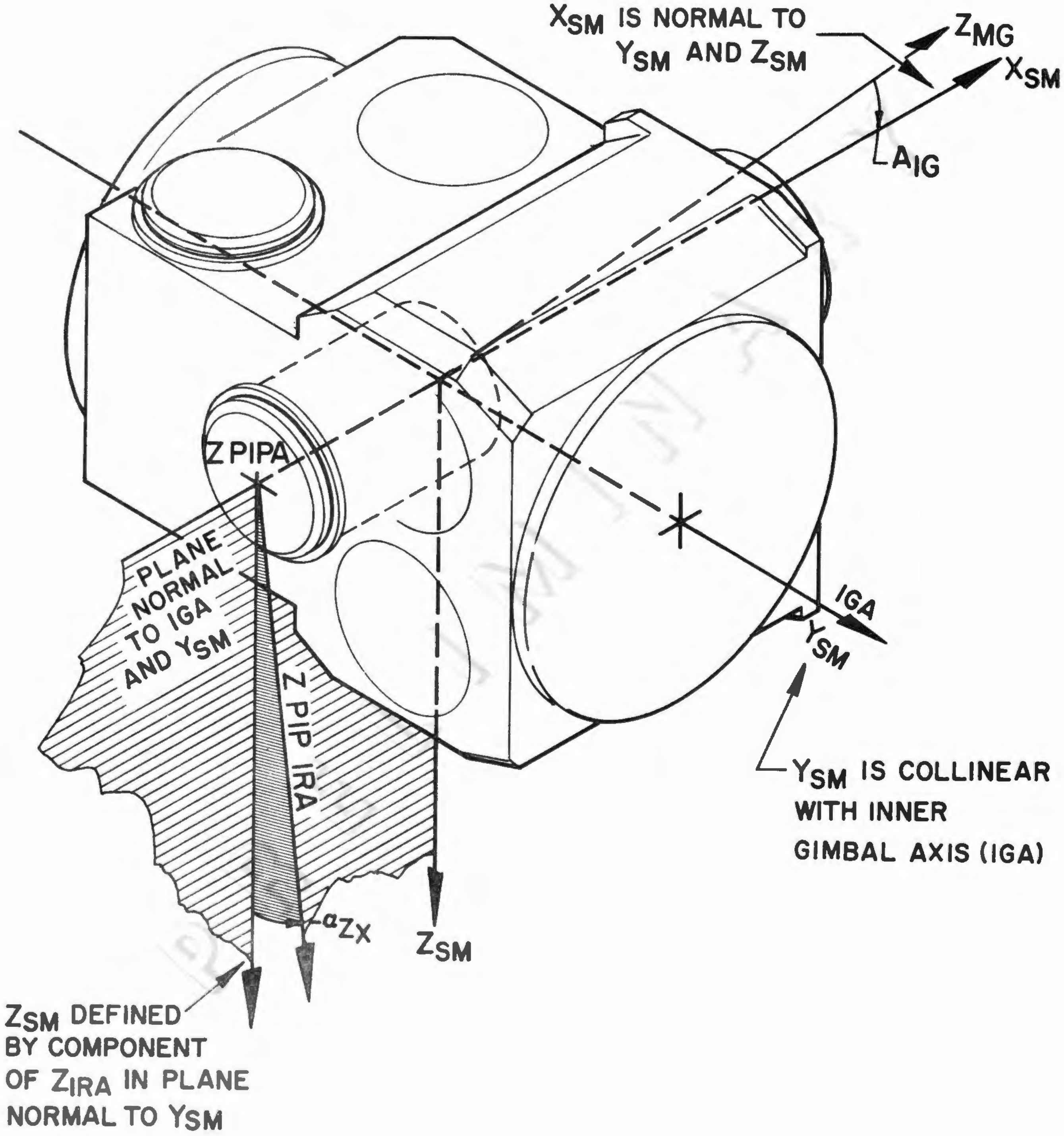


Figure I-8. IMU Stable Member Showing Definition of Stable Member Triad.

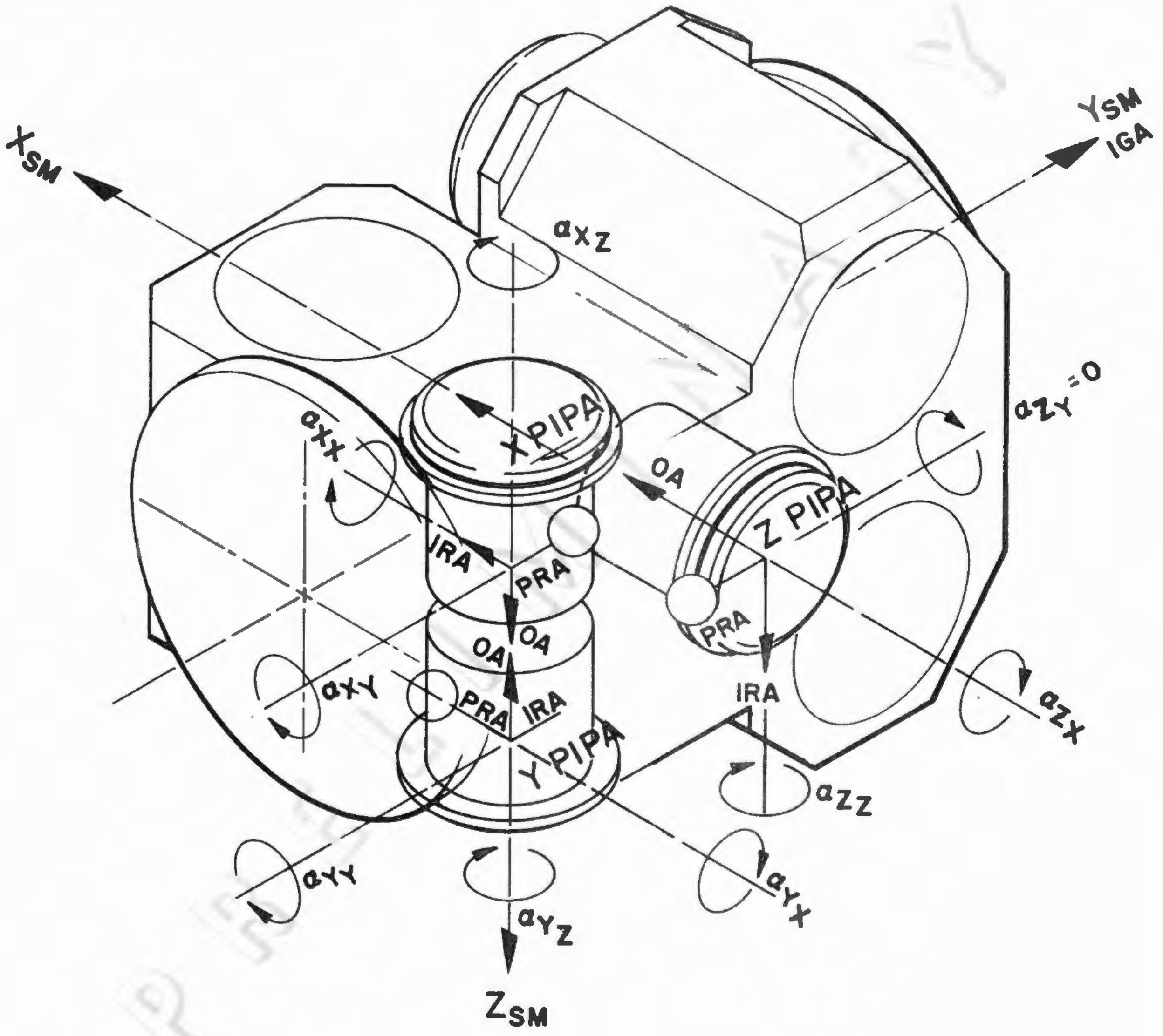


Figure I-9. PIPA Misalignments.

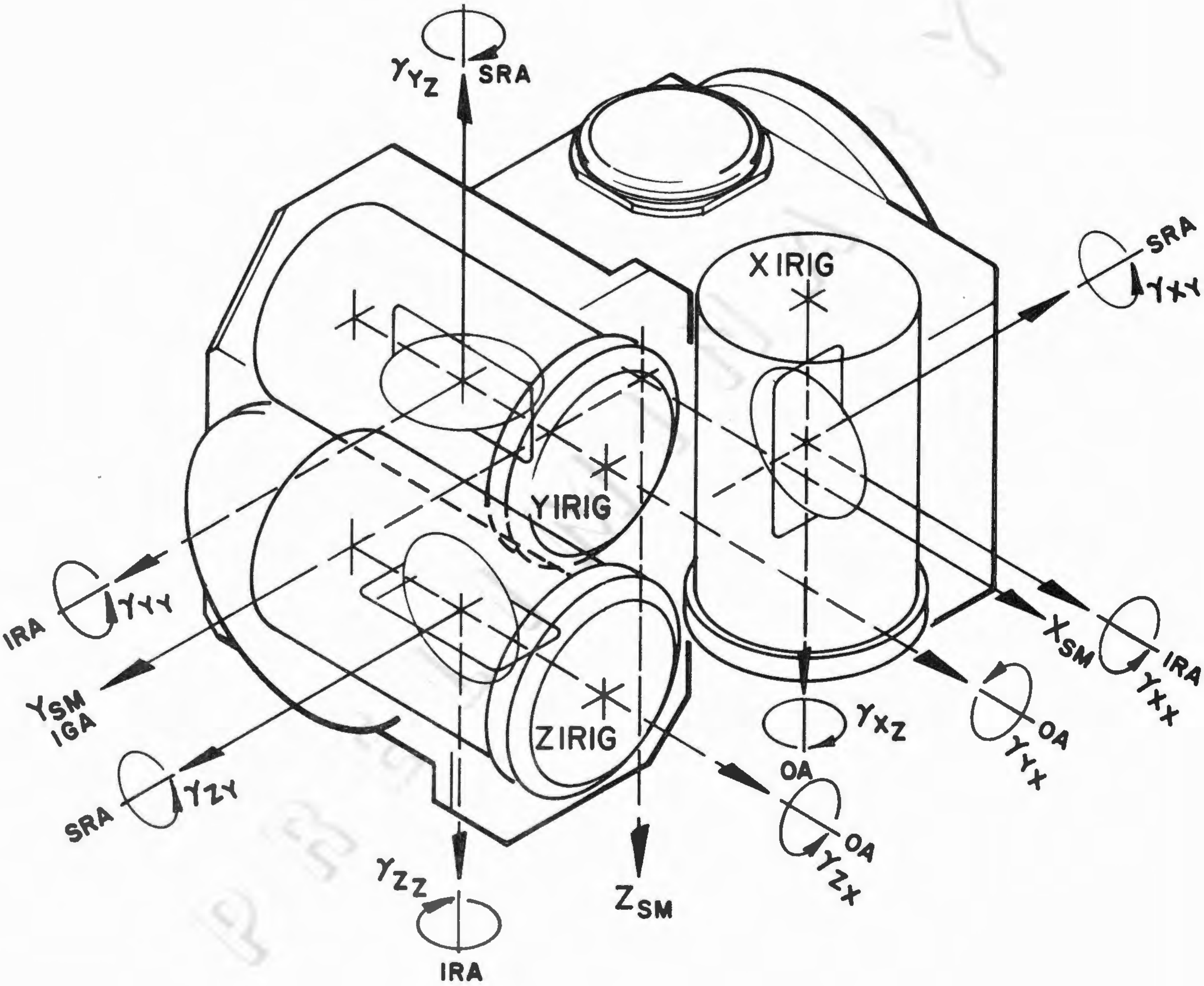


Figure I-10. IRIG Misalignments.

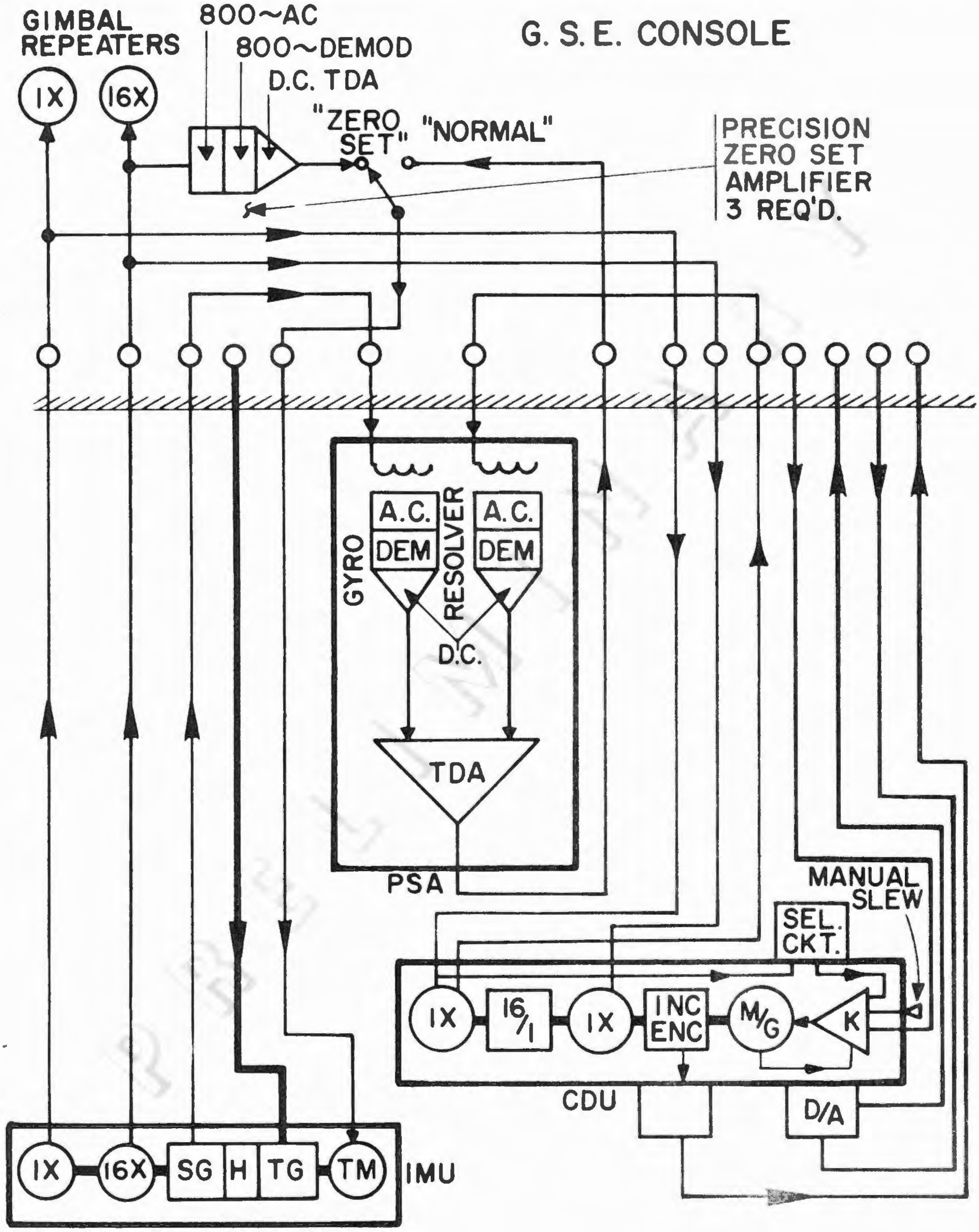


Figure I-11. 16X Resolver Loop, Simplified Signal Diagram.

II. PIPA ALIGNMENT THEORY

This analysis is preliminary and should be revised using actual table data when available.

A. SUMMARY.

Maximum Expected Uncertainties:

$$\alpha_{B_X} = 4.1 \ \widehat{SEC}$$

$$\alpha_{B_Y} = 4.1 \ \widehat{SEC}$$

$$\alpha_{B_Z} = 4.1 \ \widehat{SEC}$$

$$\epsilon_{MGA} = 5.0 \ \widehat{SEC}$$

$$\epsilon_{IGA} = 7.1 \ \widehat{SEC}$$

$$\epsilon_{MGR} = 7.1 \ \widehat{SEC}$$

$$\epsilon_{IGR} = 4.1 \ \widehat{SEC}$$

$$\epsilon_{OGR} = 8.4 \ \widehat{SEC}$$

$$\epsilon_{F_Y} = 6.5 \ \widehat{SEC}$$

$$\theta_{H_{OGA}} = 5.8 \ \widehat{SEC}$$

$$\theta_{H_{IGA}} = 4.1 \ \widehat{SEC}$$

$$\Phi_{H_{RA}} = 5.8 \ \widehat{SEC}$$

$$\Phi_{H_{MGA}} = 5.8 \ \widehat{SEC}$$

$$\Phi'_{H_{MGA}} = 5.8 \ \widehat{SEC}$$

$$\alpha_{X_Z} = 5.8 \ \widehat{SEC}$$

$$\alpha_{Z_X} = 5.8 \ \widehat{SEC}$$

$$\alpha_{X_Y} = 7.1 \ \widehat{SEC}$$

$$\alpha_{Y_X} = 4.1 \ \widehat{SEC}$$

$$\alpha_{Y_Z} = 4.1 \ \widehat{SEC}$$

B. ERROR IN A SINGLE TABLE READING.

The maximum expected deviation in finding PIPA null is 3 $\widehat{\text{SEC}}$. This deviation will be reduced somewhat if several readings are taken. The maximum table deviation will be 5 $\widehat{\text{SEC}}$. We will expect this maximum deviation to be reduced by using table calibration corrections.

Based on maximum deviations, the expected uncertainity of any single table reading will be:

$$U_{(\theta_i,\ \Phi_j)} = \sqrt{(U_{TABLE})^2 + (U_{PIPA})^2}$$

$$= \sqrt{(5^2 + 3^2)\ \widehat{\text{SEC}}^2}$$

$$= 5.8\ \widehat{\text{SEC}}$$

C. DETAILED DERIVATIONS.

JDC 35.0001:

(See figure II-1.)

$$a_{B_X} = \frac{\theta_2 - \theta_1 - 180^\circ}{2}$$

$$U(a_{B_X})_{\theta_2} = U(a_{B_X})_{\theta_1} = \left(\frac{\partial a_{B_X}}{\partial \theta_2}\right) U_{\theta_2}$$

$$= \tfrac{1}{2}\ (5.8\ \widehat{\text{SEC}})$$

$$= 2.9\ \widehat{\text{SEC}}$$

$$U_{(a_{B_X})} = \sqrt{U_{(a_{B_X})_{\theta_2}}{}^2 + U_{(a_{B_X})_{\theta_1}}{}^2}$$

$$= 4.1\ \widehat{\text{SEC}}$$

JDC 35.0002:

(See figure II-2.)

$$\theta_{\mathrm{HOGA}} = \frac{\theta_3 + \theta_4}{2} - a_{\mathrm{B_X}}$$

$$U(\theta_{\mathrm{HOGA}})_{\theta_3} = U(\theta_{\mathrm{HOGA}})_{\theta_4} = \left(\frac{\partial\theta_{\mathrm{HOGA}}}{\partial\theta_3}\right) U_{\theta_3}$$

$$= \tfrac{1}{2}\,(5.8\ \widehat{\mathrm{SEC}})$$

$$= 2.9\ \widehat{\mathrm{SEC}}$$

$$U(\theta_{\mathrm{HOGA}})_{a_{\mathrm{B_X}}} = \left(\frac{\partial\theta_{\mathrm{HOGA}}}{\partial a_{\mathrm{B_X}}}\right) U_{a_{\mathrm{B_X}}}$$

$$= 4.1\ \widehat{\mathrm{SEC}}$$

$$U(\theta_{\mathrm{HOGA}}) = \sqrt{U(\theta_{\mathrm{HOGA}})_{\theta_3}^{\,2} + U(\theta_{\mathrm{HOGA}})_{\theta_4}^{\,2} + U(\theta_{\mathrm{HOGA}})_{a_{\mathrm{B_X}}}^{\,2}}$$

$$= 5.8\ \widehat{\mathrm{SEC}}$$

JDC 35.0003:

(See figure II-3.)

$$a_{\mathrm{B_Y}} = \frac{\theta_6 - \theta_5 \pm 180^\circ}{2}$$

$$U(a_{\mathrm{B_Y}})_{\theta_6} = U(a_{\mathrm{B_Y}})_{\theta_5} = \left(\frac{\partial a_{\mathrm{B_Y}}}{\partial\theta_6}\right) U_{\theta_6}$$

$$= 2.9\ \widehat{\mathrm{SEC}}$$

$$U(a_{\mathrm{B_Y}}) = \sqrt{U(a_{\mathrm{B_Y}})_{\theta_6}^{\,2} + U(a_{\mathrm{B_Y}})_{\theta_5}^{\,2}}$$

$$= 4.1\ \widehat{\mathrm{SEC}}$$

JDC 35.0004:

(See figure II-4.)

$$a_{B_Z} = \frac{\theta_7 - \theta_8 + 180^\circ}{2}$$

$$U_{(a_{B_Z})_{\theta_7}} = U_{(a_{B_Z})_{\theta_8}} = \left(\frac{\partial a_{B_Z}}{\partial \theta_7}\right) U_{\theta_7}$$

$$= 2.9 \ \widehat{\text{SEC}}$$

$$U_{(a_{B_Z})} = \sqrt{U_{(a_{B_Z})_{\theta_7}}^{\ 2} + U_{(a_{B_Z})_{\theta_8}}^{\ 2}}$$

$$= 4.1 \ \widehat{\text{SEC}}$$

JDC 35.0005:

(See figure II-5.)

$$\Phi_{H_{RA}} = \frac{\Phi_9 + \Phi_{10}}{2} + a_{B_X}$$

$$U_{(\Phi_{H_{RA}})_{\Phi_9}} = U_{(\Phi_{H_{RA}})_{\Phi_{10}}} = \left(\frac{\partial \Phi_{H_{RA}}}{\partial \Phi_9}\right) U_{\Phi_9}$$

$$= 2.9 \ \widehat{\text{SEC}}$$

$$U_{(\Phi_{H_{RA}})_{a_{B_X}}} = \left(\frac{\partial \Phi_{H_{RA}}}{\partial a_{B_X}}\right) U_{a_{B_X}}$$

$$= 4.1 \ \widehat{\text{SEC}}$$

$$U_{(\Phi_{H_{RA}})} = \sqrt{U_{(\Phi_{H_{RA}})_{\Phi_9}}^{\ 2} + U_{(\Phi_{H_{RA}})_{\Phi_{10}}}^{\ 2} + U_{(\Phi_{H_{RA}})_{a_{B_X}}}^{\ 2}}$$

$$= 5.8 \ \widehat{\text{SEC}}$$

JDC 35.0006, Part A:

(See figure II-6.)

$$\Phi_{H_{MGA}} = \frac{\Phi_{11} + \Phi_{12}}{2} + a_{B_Z}$$

$$U_{(\Phi_{H_{MGA}})_{\Phi_{11}}} = U_{(\Phi_{H_{MGA}})_{\Phi_{12}}} = \left(\frac{\partial \Phi_{H_{MGA}}}{\partial \Phi_{11}}\right) U_{\Phi_{11}}$$

$$= 2.9\ \widehat{\text{SEC}}$$

$$U_{(\Phi_{H_{MGA}})_{a_{B_Z}}} = \left(\frac{\partial \Phi_{H_{MGA}}}{\partial a_{B_Z}}\right) U_{a_{B_Z}}$$

$$= 4.1\ \widehat{\text{SEC}}$$

$$U_{(\Phi_{H_{MGA}})} = \sqrt{U_{(\Phi_{H_{MGA}})_{\Phi_{11}}}^{\ 2} + U_{(\Phi_{H_{MGA}})_{\Phi_{12}}}^{\ 2} + U_{(\Phi_{H_{MGA}})_{a_{B_Z}}}^{\ 2}}$$

$$= 5.8\ \widehat{\text{SEC}}$$

JDC 35.0006, Part B:

(See figure II-6.)

$$\epsilon_{OGR} = \frac{\Phi_{11} + \Phi_{12}}{2} - \Phi_{H_{RA}} + a_{B_Z} + \epsilon_{F_X}$$

$$U_{(\epsilon_{OGR})_{\Phi_{11}}} = U_{(\epsilon_{OGR})_{\Phi_{12}}} = \left(\frac{\partial(\epsilon_{OGR})}{\partial \Phi_{11}}\right) U_{\Phi_{11}}$$

$$= 2.9\ \widehat{\text{SEC}}$$

$$U_{(\epsilon_{OGR})_{\Phi_{H_{RA}}}} = \left(\frac{\partial(\epsilon_{OGR})}{\partial \Phi_{H_{RA}}}\right) U_{\Phi_{H_{RA}}}$$

$$= 5.8\ \widehat{\text{SEC}}$$

$$U_{(\epsilon_{OGR})_{a_{B_Z}}} = \left(\frac{\partial(\epsilon_{OGR})}{\partial a_{B_Z}}\right) U_{a_{B_Z}}$$

$$= 4.1\ \widehat{\text{SEC}}$$

$$U_{(\epsilon_{OGR})\,\epsilon_{F_X}} = \left(\frac{\partial(\epsilon_{OGR})}{\partial \epsilon_{F_X}}\right) U_{\epsilon_{F_X}}$$

$$= 2.0\ \widehat{\text{SEC}}$$

$$U_{(\epsilon_{OGR})} = \sqrt{U_{(\epsilon_{OGR})_{\Phi_{11}}}^{\ 2} + U_{(\epsilon_{OGR})_{\Phi_{12}}}^{\ 2} + U_{(\epsilon_{OGR})_{\Phi_{H_{RA}}}}^{\ 2} + U_{(\epsilon_{OGR})_{a_{B_Z}}}^{\ 2} + U_{(\epsilon_{OGR})\,\epsilon_{F_X}}^{\ 2}}$$

$$= 8.4\ \widehat{\text{SEC}}$$

JDC 35.0008:

(See figure II-7.)

$$\Phi'_{H_{MGA}} = \frac{\Phi_{13} + \Phi_{14}}{2} + a_{B_Z}$$

$$U\,(\Phi'_{H_{MGA}})_{\Phi_{13}} = U\,(\Phi'_{H_{MGA}})_{\Phi_{14}} = \left(\frac{\partial \Phi'_{H_{MGA}}}{\partial \Phi_{13}}\right) U_{\Phi_{13}}$$

$$= 2.9 \ \widehat{\mathrm{SEC}}$$

$$U\,(\Phi'_{H_{MGA}})_{a_{B_Z}} = \left(\frac{\partial \Phi'_{H_{MGA}}}{\partial a_{B_Z}}\right) U_{a_{B_Z}}$$

$$= 4.1 \ \widehat{\mathrm{SEC}}$$

$$U_{(\Phi'_{H_{MGA}})} = \sqrt{U_{(\Phi'_{H_{MGA}})_{\Phi_{13}}}{}^2 + U_{(\Phi'_{H_{MGA}})_{\Phi_{14}}}{}^2 + U_{(\Phi'_{H_{MGA}})_{a_{B_Z}}}{}^2}$$

$$= 5.8 \ \widehat{\mathrm{SEC}}$$

JDC 35.0009, Part A:

(See figure II-8.)

$$\epsilon_{MGA} = \frac{(\Phi_{13} + \Phi_{14}) - (\Phi_{15} + \Phi_{16})}{4} + a_{B_Z}$$

$$U_{(\epsilon_{MGA})_{\Phi_{13} \rightarrow 16}} = \left(\frac{\partial \epsilon_{MGA}}{\partial \Phi_{13 \rightarrow 16}} \right) U_{\Phi_{13 \rightarrow 16}}$$

$$= 1.5 \ \overset{\frown}{\text{SEC}}$$

$$U_{(\epsilon_{MGA})_{a_{B_Z}}} = \left(\frac{\partial \epsilon_{MGA}}{\partial a_{B_Z}} \right) U_{a_{B_Z}}$$

$$= 4.1 \ \overset{\frown}{\text{SEC}}$$

$$U_{(\epsilon_{MGA})} = \sqrt{U_{(\epsilon_{MGA})_{\Phi_{13}}}{}^2 + \ldots\ldots + U_{(\epsilon_{MGA})_{\Phi_{16}}}{}^2 + U_{(\epsilon_{MGA})_{a_{B_Z}}}{}^2}$$

$$= 5.0 \ \overset{\frown}{\text{SEC}}$$

JDC 35.0009, Part B:

(See figure II-8.)

$$\epsilon_{F_Y} = \frac{\Phi_{13} + \Phi_{14} + \Phi_{15} + \Phi_{16}}{4} - \Phi_{H_{RA}}$$

$$U_{(\epsilon_{F_Y})_{\Phi_{13} \rightarrow 16}} = \left(\frac{\partial \epsilon_{F_Y}}{\partial \Phi_{13 \rightarrow 16}} \right) U_{\Phi_{13 \rightarrow 16}}$$

$$= 1.5 \ \overset{\frown}{\text{SEC}}$$

$$U_{(\epsilon_{F_Y})_{\Phi_{H_{RA}}}} = \left(\frac{\partial \epsilon_{F_Y}}{\partial \Phi_{H_{RA}}} \right) U_{\Phi_{H_{RA}}}$$

$$= 5.8 \ \overset{\frown}{\text{SEC}}$$

$$U_{(\epsilon_{F_Y})} = \sqrt{U_{(\epsilon_{F_Y})_{\Phi_{13}}}{}^2 + \ldots\ldots + U_{(\epsilon_{F_Y})_{\Phi_{16}}}{}^2 + U_{(\epsilon_{F_Y})_{\Phi_{H_{RA}}}}{}^2}$$

$$= 6.5 \ \overset{\frown}{\text{SEC}}$$

JDC 35.0010, Part A:

(See figure II-9.)

$$\epsilon_{MGR} = \frac{\theta_{17} + \theta_{18}}{2} - \theta_{H_{OGA}}$$

$$U(\epsilon_{MGR})_{\theta_{17}} = U(\epsilon_{MGR})_{\theta_{18}} = \left(\frac{\partial \epsilon_{MGR}}{\partial \theta_{17}}\right) U_{\theta_{17}}$$

$$= 2.9 \ \widehat{\text{SEC}}$$

$$U(\epsilon_{MGR})_{\theta_{H_{OGA}}} = \left(\frac{\partial \epsilon_{MGR}}{\partial \theta_{H_{OGA}}}\right) U_{\theta_{H_{OGA}}}$$

$$= 5.8 \ \widehat{\text{SEC}}$$

$$U_{(\epsilon_{MGR})} = \sqrt{U_{(\epsilon_{MGR})_{\theta_{17}}}^{2} + U_{(\epsilon_{MGR})_{\theta_{18}}}^{2} + U_{(\epsilon_{MGR})_{\theta_{H_{OGA}}}}^{2}}$$

$$= 7.1 \ \widehat{\text{SEC}}$$

JDC 35.0010 Part B:

(See figure II-9.)

$$\theta_{H_{IGA}} = \frac{\theta_{17} + \theta_{18}}{2} - 90^\circ$$

$$U_{(\theta_{H_{IGA}})} = \sqrt{U_{(\theta_{H_{IGA}})_{\theta_{17}}}^{2} + U_{(\theta_{H_{IGA}})_{\theta_{18}}}^{2}}$$

$$= 4.1 \ \widehat{\text{SEC}}$$

JDC 35.0010, Part C:

(See figure II-9.)

$$\alpha_{x_Z} = \frac{\theta_{18} - \theta_{17}}{2} + \alpha_{B_X}$$

$$U(\alpha_{x_Z})_{\theta_{17}} = U(\alpha_{x_Z})_{\theta_{18}} = \left(\frac{\partial \alpha_{x_Z}}{\partial \theta_{17}}\right) U_{\theta_{17}}$$

$$= 2.9\ \widehat{\text{SEC}}$$

$$U(\alpha_{x_Z})_{\alpha_{B_X}} = \left(\frac{\partial \alpha_{x_Z}}{\partial \alpha_{B_X}}\right) U_{\alpha_{B_X}}$$

$$= 4.1\ \widehat{\text{SEC}}$$

$$U_{(\alpha_{x_Z})} = \sqrt{U_{(\alpha_{x_Z})_{\theta_{17}}}^{2} + U_{(\alpha_{x_Z})_{\theta_{18}}}^{2} + U_{(\alpha_{x_Z})_{\alpha_{B_X}}}^{2}}$$

$$= 5.8\ \widehat{\text{SEC}}$$

JDC 35.0012, Part A:

(See figure II-10.)

$$\epsilon_{IGA} = \Phi_{H_{MGA}} - \frac{\Phi_{19} + \Phi_{20}}{2}$$

$$U_{(\epsilon_{IGA})\Phi_{19}} = U_{(\epsilon_{IGA})\Phi_{20}} = \left(\frac{\partial \epsilon_{IGA}}{\partial \Phi_{20}}\right) U_{\Phi_{20}}$$

$$= 2.9\ \widehat{\text{SEC}}$$

$$U_{(\epsilon_{IGA})\Phi_{H_{MGA}}} = \left(\frac{\partial \epsilon_{IGA}}{\partial \Phi_{H_{MGA}}}\right) U_{\Phi_{H_{MGA}}}$$

$$= 5.8\ \widehat{\text{SEC}}$$

$$U_{(\epsilon_{IGA})} = \sqrt{U_{(\epsilon_{IGA})\Phi_{19}}{}^2 + U_{(\epsilon_{IGA})\Phi_{20}}{}^2 + U_{(\epsilon_{IGA})\Phi_{H_{MGA}}}{}^2}$$

$$= 7.1\ \widehat{\text{SEC}}$$

JDC 35.0012, Part B:

(See figure II-10.)

$$a_{Z_X} = \frac{\Phi_{20} - \Phi_{19}}{2} - a_{B_Z}$$

$$U_{(a_{Z_X})\Phi_{20}} = U_{(a_{Z_X})\Phi_{19}} = \left(\frac{\partial a_{Z_X}}{\partial \Phi_{19}}\right) U_{\Phi_{19}}$$

$$= 2.9\ \widehat{\text{SEC}}$$

$$U_{(a_{Z_X})a_{B_Z}} = \left(\frac{\partial a_{Z_X}}{\partial a_{B_Z}}\right) U_{a_{B_Z}}$$

$$= 4.1\ \widehat{\text{SEC}}$$

$$U_{(a_{Z_X})} = \sqrt{U_{(a_{Z_X})\Phi_{20}}{}^2 + U_{(a_{Z_X})\Phi_{19}}{}^2 + U_{(a_{Z_X})a_{B_Z}}{}^2}$$

$$= 5.8\ \widehat{\text{SEC}}$$

JDC 35.0013:

(See figure II-11.)

$$\epsilon_{IGR} = \frac{\Phi_{22} - \Phi_{21}}{2}$$

$$U_{(\epsilon_{IGR})_{\Phi_{22}}} = U_{(\epsilon_{IGR})_{\Phi_{21}}} = \left(\frac{\partial \epsilon_{IGR}}{\partial \Phi_{21}}\right) U_{\Phi_{21}}$$

$$= 2.9 \ \widehat{\text{SEC}}$$

$$U_{(\epsilon_{IGR})} = \sqrt{{U_{(\epsilon_{IGR})_{\Phi_{22}}}}^2 + {U_{(\epsilon_{IGR})_{\Phi_{21}}}}^2}$$

$$= 4.1 \ \widehat{\text{SEC}}$$

JDC 35.0015:

(See figure II-12.)

$$a_{Y_Z} = \frac{\theta_{24} - \theta_{23}}{2}$$

$$U_{(a_{Y_Z})_{\theta_{24}}} = U_{(a_{Y_Z})_{\theta_{23}}} = \left(\frac{\partial a_{Y_Z}}{\partial \theta_{24}}\right) U_{\theta_{24}}$$

$$= 2.9 \ \widehat{\text{SEC}}$$

$$U_{(a_{Y_Z})} = \sqrt{{U_{(a_{Y_Z})_{\theta_{24}}}}^2 + {U_{(a_{Y_Z})_{\theta_{23}}}}^2}$$

$$= 4.1 \ \widehat{\text{SEC}}$$

JDC 35.0016:

(See figure II-13.)

$$a_{Y_X} = \frac{\theta_{26} - \theta_{25}}{2}$$

$$U_{(a_{Y_X})_{\theta_{26}}} = U_{(a_{Y_X})_{\theta_{25}}} = \left(\frac{\partial a_{Y_X}}{\partial \theta_{26}}\right) U_{\theta_{26}}$$

$$= 2.9 \ \widehat{\text{SEC}}$$

$$U_{(a_{Y_X})} = \sqrt{U_{(a_{Y_X})_{\theta_{26}}}{}^2 + U_{(a_{Y_X})_{\theta_{25}}}{}^2}$$

$$= 4.1 \ \widehat{\text{SEC}}$$

JDC 35.0017:

(See figure II-14.)

$$a_{X_Y} = \frac{\theta_{27} - \theta_{28}}{2} + \epsilon_{IGR} - a_{B_X}$$

$$U_{(a_{X_Y})_{\theta_{27}}} = U_{(a_{X_Y})_{\theta_{28}}} = \left(\frac{\partial a_{X_Y}}{\partial \theta_{27}}\right) U_{\theta_{27}}$$

$$= 2.9 \ \widehat{\text{SEC}}$$

$$U_{(a_{X_Y})_{\epsilon_{IGR}}} = \left(\frac{\partial a_{X_Y}}{\partial \epsilon_{IGR}}\right) U_{\epsilon_{IGR}}$$

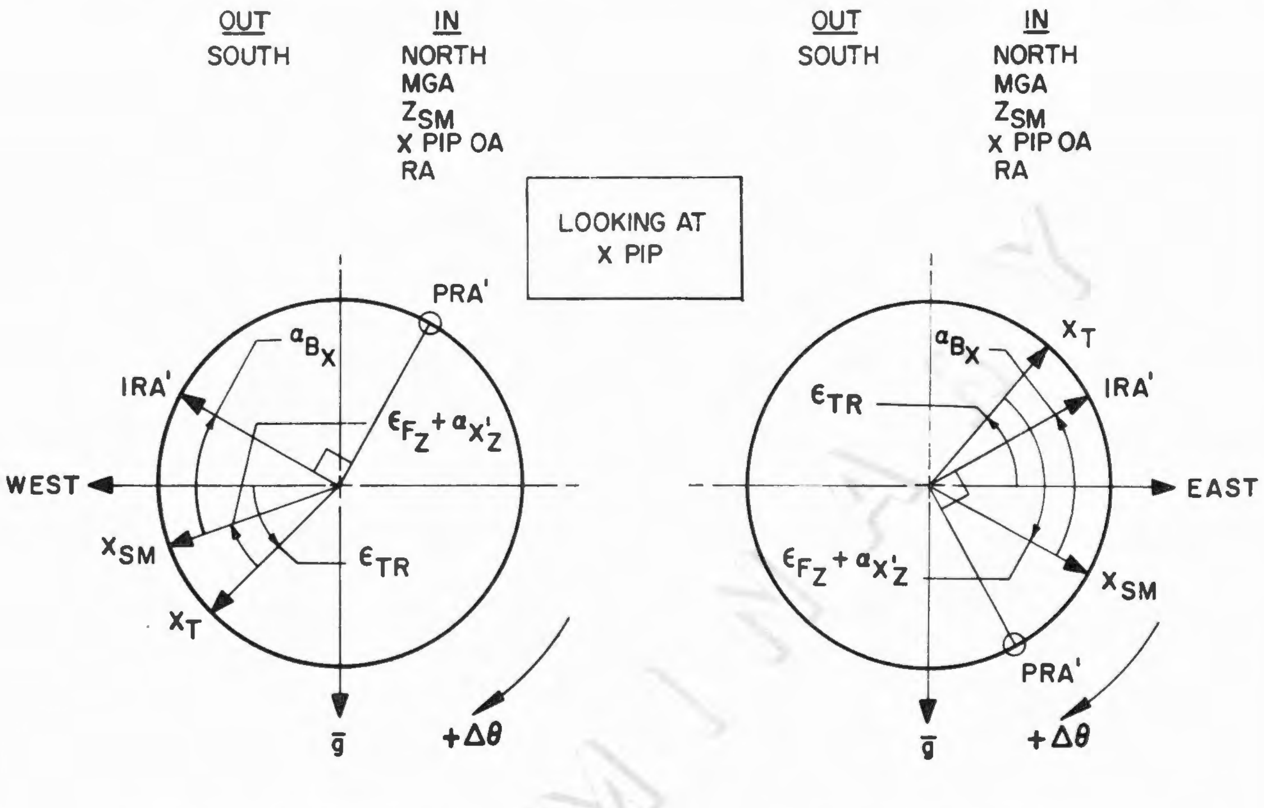
$$= 4.1 \ \widehat{\text{SEC}}$$

$$U_{(a_{X_Y})_{a_{B_X}}} = \left(\frac{\partial a_{X_Y}}{\partial a_{B_X}}\right) U_{a_{B_X}}$$

$$= 4.1 \ \widehat{\text{SEC}}$$

$$U_{(a_{X_Y})} = \sqrt{U_{(a_{X_Y})_{\theta_{27}}}{}^2 + U_{(a_{X_Y})_{\theta_{28}}}{}^2 + U_{(a_{X_Y})_{\epsilon_{IGR}}}{}^2 + U_{(a_{B_X})_{a_{B_X}}}{}^2}$$

$$= 7.1 \ \widehat{\text{SEC}}$$



First Null Measurement

Second Null Measurement

$$\theta_1 = 90^\circ - \alpha_{X'_Z} - \alpha_{B_X} - \epsilon_{F_Z} + \epsilon_{TR}$$

$$\alpha_{B_X} = 90^\circ - \theta_1 - \alpha_{X'_Z} - \epsilon_{F_Z} + \epsilon_{TR}$$

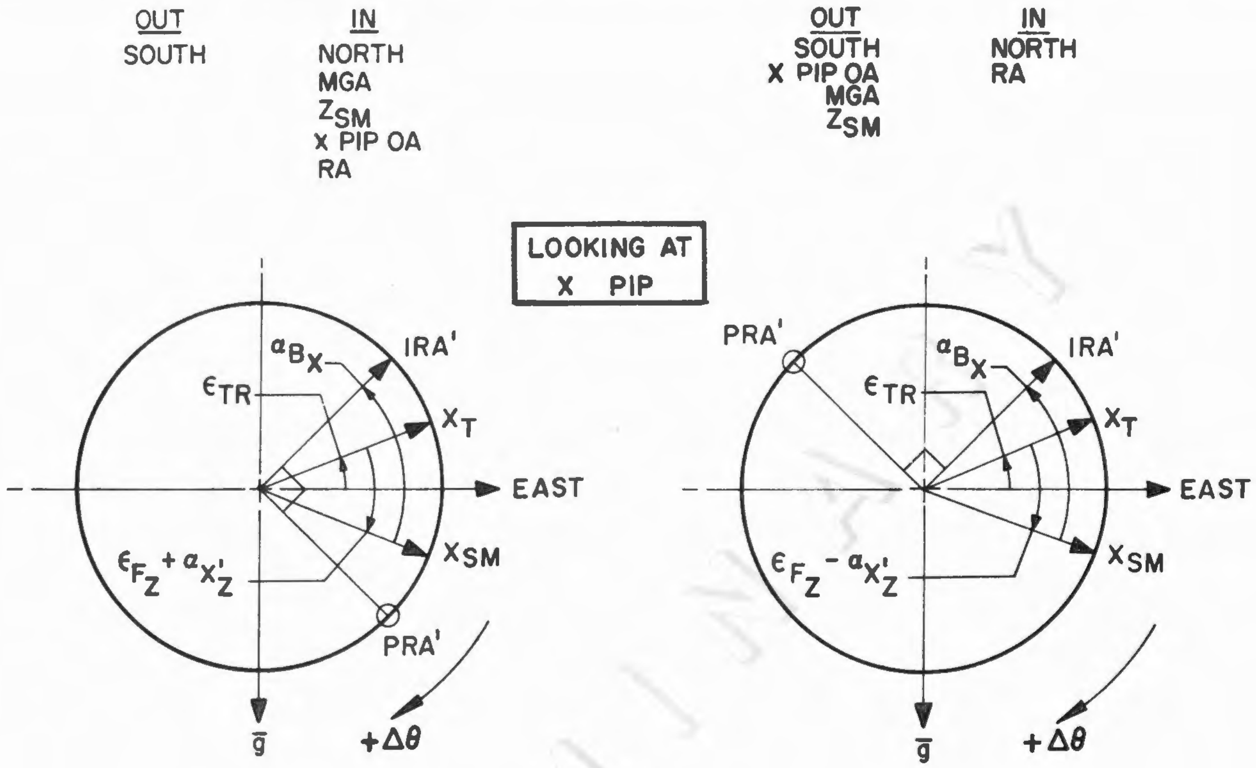
$$\theta_2 = 270^\circ - \alpha_{X'_Z} + \alpha_{B_X} - \epsilon_{F_Z} + \epsilon_{TR}$$

$$\alpha_{B_X} = \theta_2 - 270^\circ + \alpha_{X'_Z} + \epsilon_{F_Z} - \epsilon_{TR}$$

$$2\alpha_{B_X} = \theta_2 - \theta_1 - 180^\circ$$

$$\alpha_{B_X} = \frac{\theta_2 - \theta_1 - 180^\circ}{2}$$

Figure II-1. Geometry and Derivation for JDC 35.0001.



First Null Measurement

Second Null Measurement

$$\theta_3 = 270^\circ - \alpha_{X'_Z} + \alpha_{B_X} + \epsilon_{TR} - \epsilon_{F_Z}$$

$$\theta_3 = \theta_{HOGA} - \alpha_{X'_Z} + \alpha_{B_X}$$

where

$$\theta_{HOGA} = 270^\circ + \epsilon_{TR} - \epsilon_{F_Z}$$

$$\theta_4 = 270^\circ + \alpha_{X'_Z} + \alpha_{B_X} + \epsilon_{T_R} - \epsilon_{F_Z}$$

$$\theta_4 = \theta_{HOGA} + \alpha_{X'_Z} + \alpha_{B_X}$$

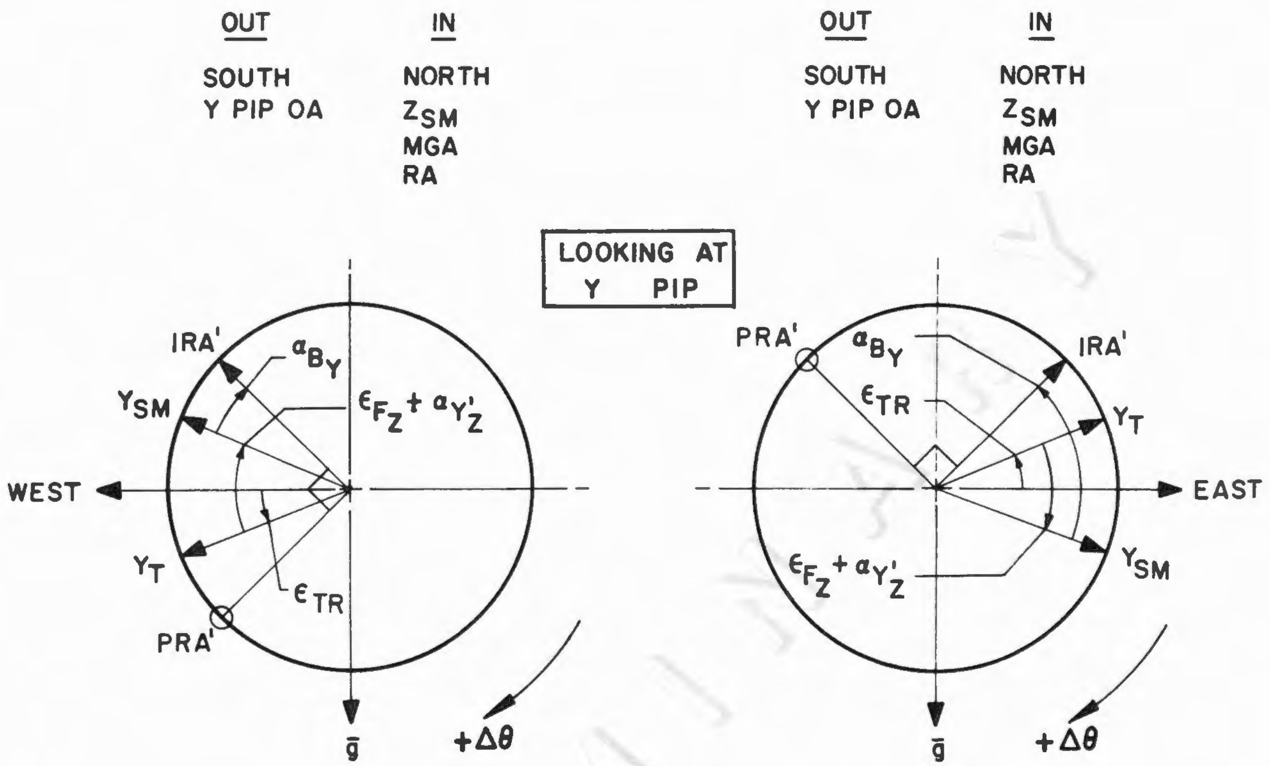
where

$$\theta_{HOGA} = 270^\circ + \epsilon_{TR} - \epsilon_{F_Z}$$

$$\theta_3 + \theta_4 = 2\theta_{HOGA} + 2\alpha_{B_X}$$

$$\theta_{HOGA} = \frac{\theta_3 + \theta_4}{2} - \alpha_{B_X}$$

Figure II-2. Geometry and Derivation for JDC 35.0002.



First Null Measurement

Second Null Measurement

$$\theta_5 = 0^\circ - a_{Y'_Z} - a_{B_Y} + \epsilon_{TR} - \epsilon_{F_Z}$$

$$a_{B_Y} = -\theta_5 - a_{Y'_Z} + \epsilon_{TR} - \epsilon_{F_Z}$$

$$\theta_6 = 180^\circ - a_{Y'_Z} + a_{B_Y} + \epsilon_{TR} - \epsilon_{F_Z}$$

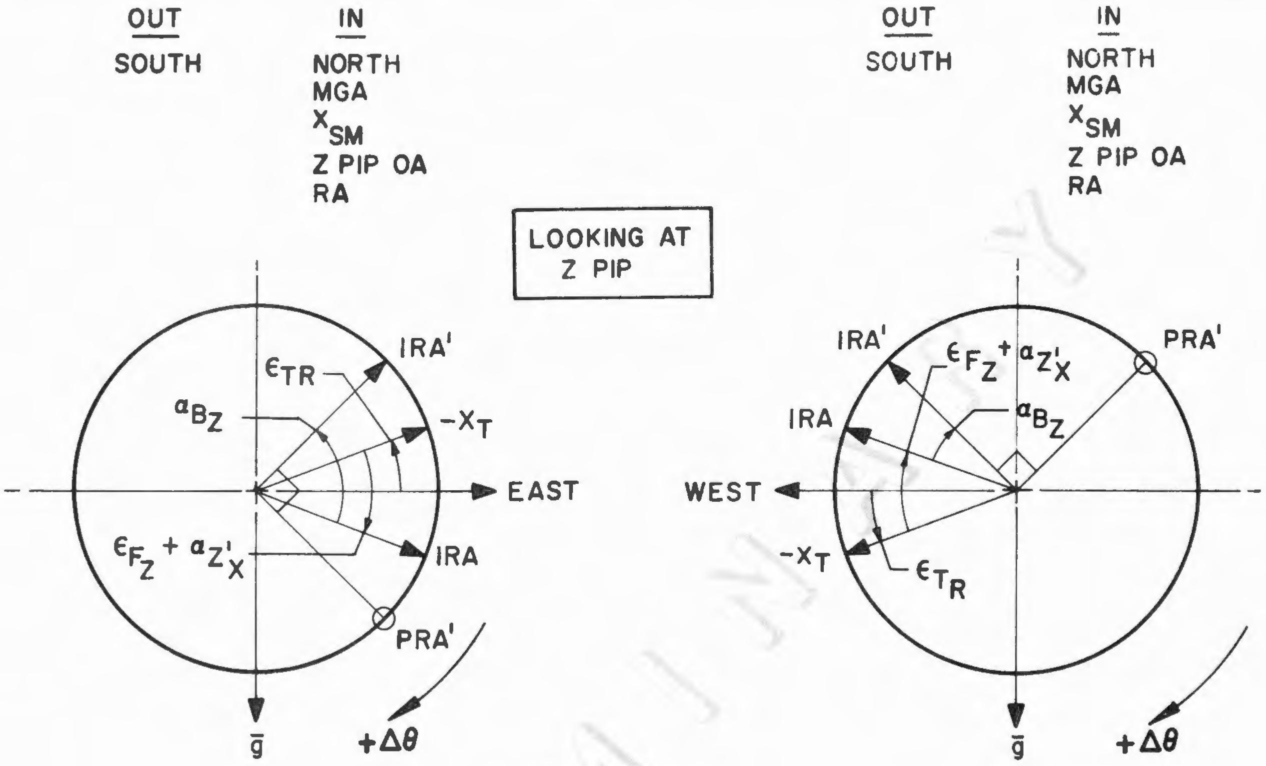
$$a_{B_Y} = \theta_6 - 180^\circ + a_{Y'_Z} - \epsilon_{TR} + \epsilon_{F_Z}$$

$$2a_{B_Y} = \theta_6 - \theta_5 - 180^\circ$$

$$a_{B_Y} = \frac{\theta_6 - \theta_5 - 180^\circ}{2}$$

IF $\theta_5 < 360^\circ$, USE: $a_{B_Y} = \dfrac{\theta_6 - \theta_5 + 180^\circ}{2}$

Figure II-3. Geometry and Derivation for JDC 35.0003.



First Null Measurement

Second Null Measurement

$$\theta_7 = 90^\circ + \alpha_{B_Z} - \alpha_{Z'_X} - \epsilon_{F_Z} + \epsilon_{TR}$$

$$\alpha_{B_Z} = \theta_7 - 90^\circ + \alpha_{Z'_X} + \epsilon_{F_Z} - \epsilon_{TR}$$

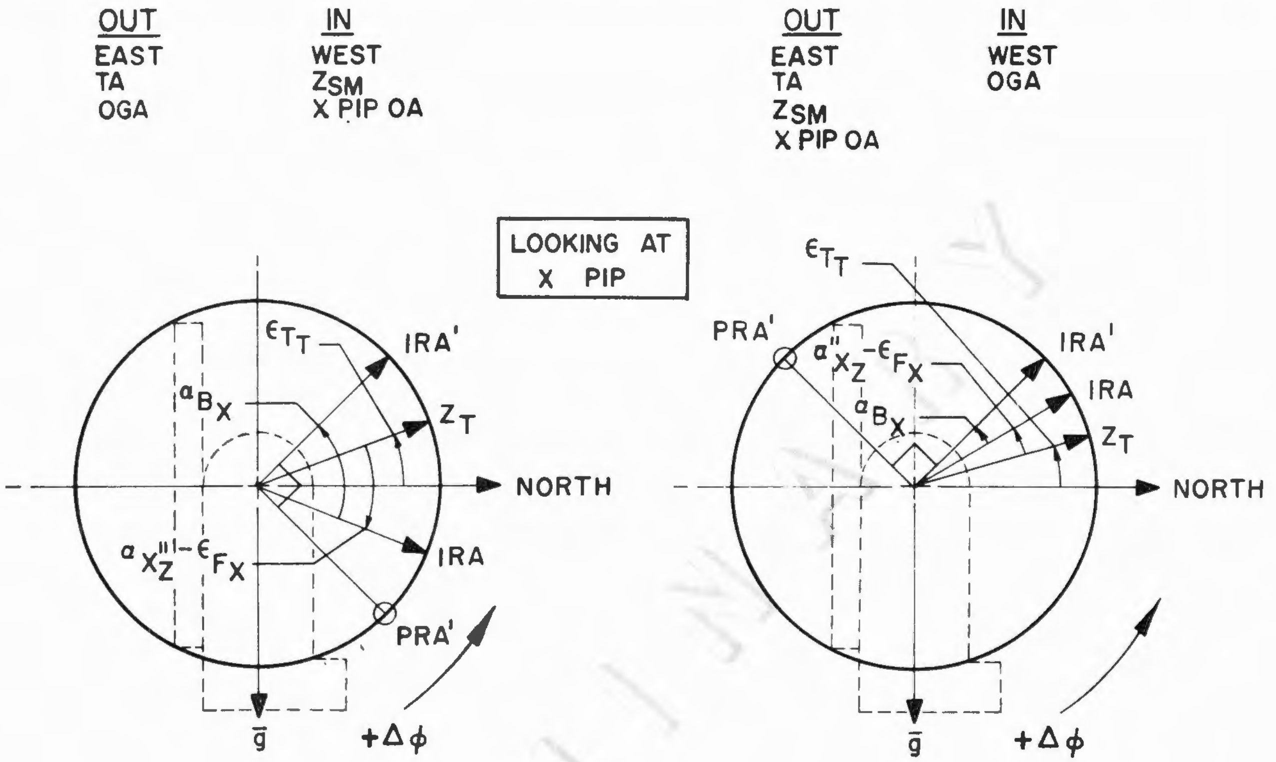
$$\theta_8 = 270^\circ - \alpha_{B_Z} - \alpha_{Z'_X} - \epsilon_{F_Z} + \epsilon_{TR}$$

$$\alpha_{B_Z} = -\theta_8 + 270^\circ - \alpha_{Z'_X} - \epsilon_{F_Z} + \epsilon_{TR}$$

$$2\alpha_{B_Z} = \theta_7 - \theta_8 + 180^\circ$$

$$\alpha_{B_Z} = \frac{\theta_7 - \theta_8 + 180^\circ}{2}$$

Figure II-4. Geometry and Derivation for JDC 35.0004.



First Null Measurement

Second Null Measurement

$$\Phi_9 = 90^\circ - \epsilon_{T_T} - \epsilon_{F_X} + \alpha_{X''_Z} - \alpha_{B_X}$$

$$\Phi_9 = \Phi_{H_{RA}} - \epsilon_{F_X} + \alpha_{X''_Z} - \alpha_{B_X}$$

where

$$\Phi_{H_{RA}} = 90^\circ - \epsilon_{T_T}$$

$$\Phi_{10} = 90^\circ - \epsilon_{T_T} + \epsilon_{F_X} - \alpha_{X''_Z} - \alpha_{B_X}$$

$$\Phi_{10} = \Phi_{H_{RA}} + \epsilon_{F_X} - \alpha_{X''_Z} - \alpha_{B_X}$$

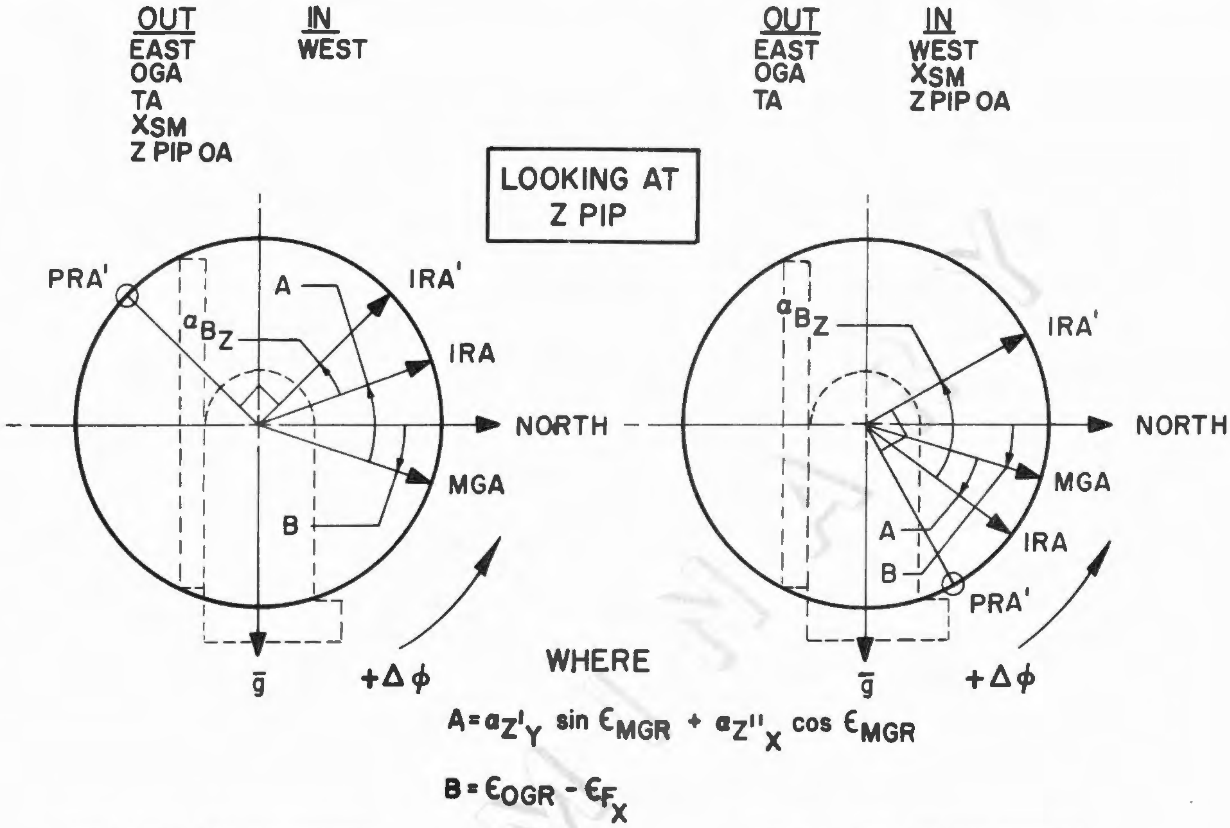
where

$$\Phi_{H_{RA}} = 90^\circ - \epsilon_{T_T}$$

$$\Phi_9 + \Phi_{10} = 2\Phi_{H_{RA}} - 2\alpha_{B_X}$$

$$\Phi_{H_{RA}} = \frac{\Phi_9 + \Phi_{10}}{2} + \alpha_{B_X}$$

Figure II-5. Geometry and Derivation for JDC 35.0005.

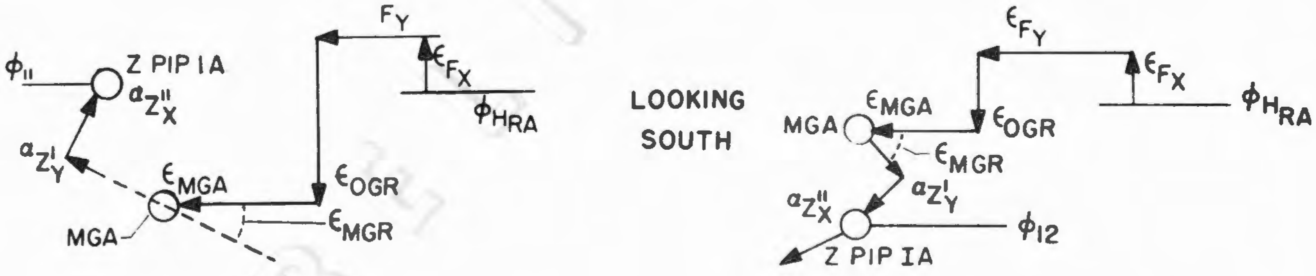


WHERE

$A = a_{Z'_Y} \sin \epsilon_{MGR} + a_{Z''_X} \cos \epsilon_{MGR}$

$B = \epsilon_{OGR} - \epsilon_{F_X}$

First Null Measurement Second Null Measurement



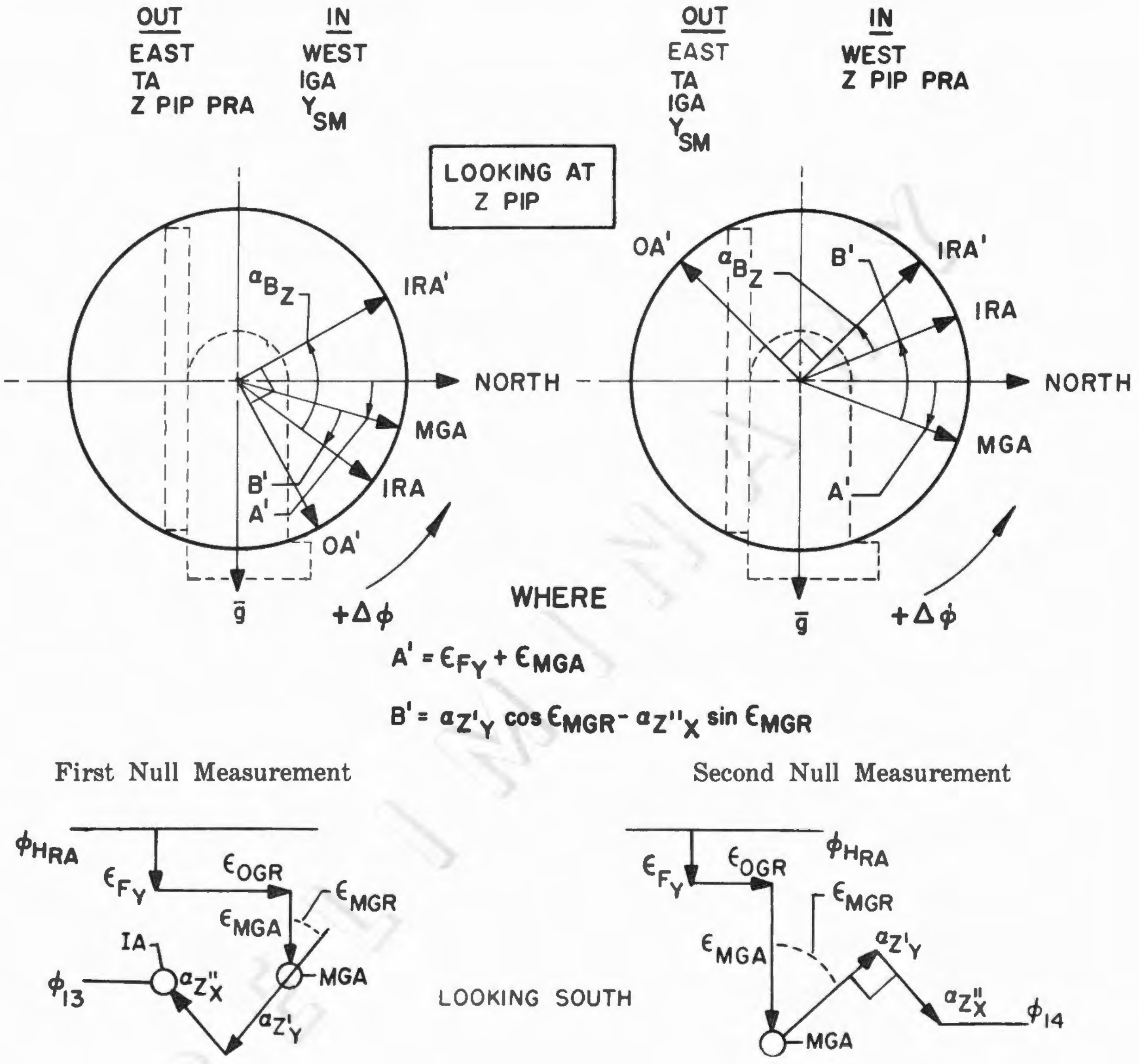
$$\Phi_{11} = \Phi_{H_{RA}} - \epsilon_{F_X} + \epsilon_{OGR} - a_{z'_Y} \sin \epsilon_{MGR} - a_{z''_X} \cos \epsilon_{MGR} - a_{B_Z}$$

$$\Phi_{12} = \Phi_{H_{RA}} - \epsilon_{F_X} + \epsilon_{OGR} + a_{z'_Y} \sin \epsilon_{MGR} + a_{z''_X} \cos \epsilon_{MGR} - a_{B_Z}$$

$$\text{(A)} \quad \Phi_{H_{MGA}} = \Phi_{H_{RA}} + \epsilon_{OGR} - \epsilon_{F_X} = \frac{\Phi_{11} + \Phi_{12}}{2} + a_{B_Z}$$

$$\text{(B)} \quad \epsilon_{OGR} = \frac{\Phi_{11} + \Phi_{12}}{2} - \Phi_{H_{RA}} + a_{B_Z} + \epsilon_{F_X}$$

Figure II-6. Geometry and Derivation for JDC 35.0006.



$$A' = \epsilon_{F_Y} + \epsilon_{MGA}$$

$$B' = a_{Z'_Y} \cos \epsilon_{MGR} - a_{Z''_X} \sin \epsilon_{MGR}$$

First Null Measurement

Second Null Measurement

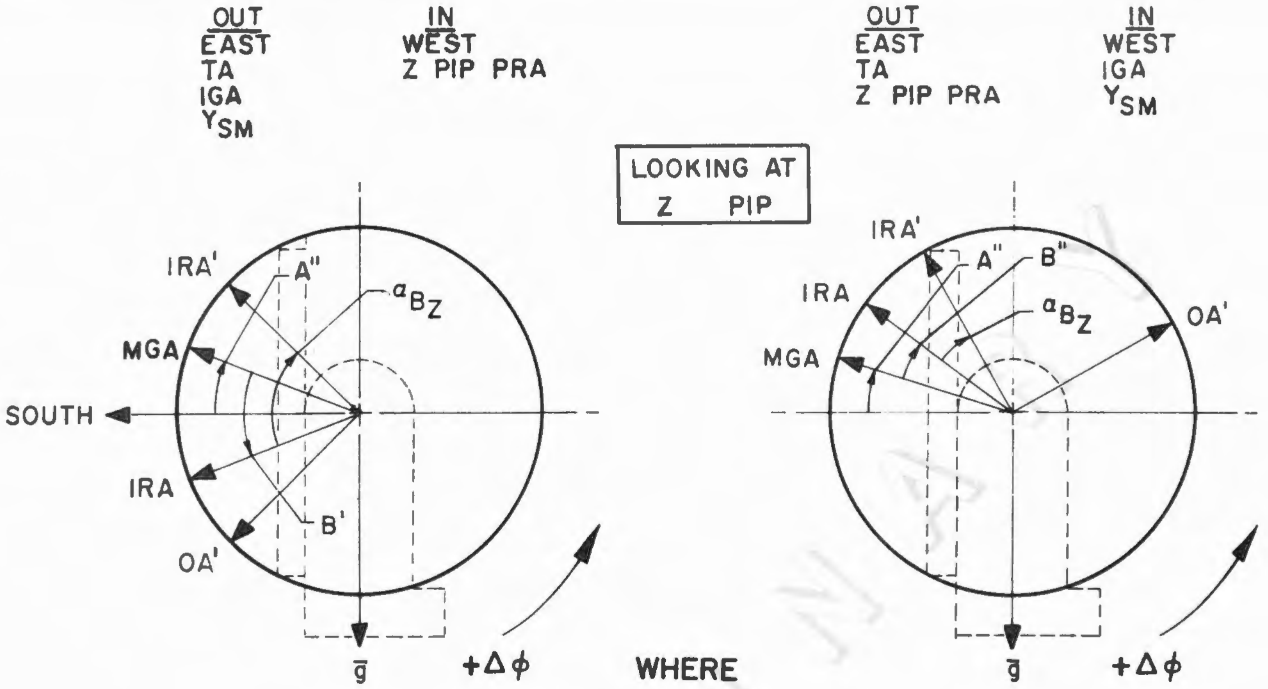
$$\Phi_{13} = \Phi_{H_{RA}} + \epsilon_{F_Y} + \epsilon_{MGA} - a_{B_Z} + a_{z'_Y} \cos \epsilon_{MGR} - a_{z''_X} \sin \epsilon_{MGR}$$

$$\Phi_{14} = \Phi_{H_{RA}} + \epsilon_{F_Y} + \epsilon_{MGA} - a_{B_Z} - a_{z'_Y} \cos \epsilon_{MGR} + a_{z''_X} \sin \epsilon_{MGR}$$

$$\Phi_{13} + \Phi_{14} = 2(\Phi_{H_{RA}} + \epsilon_{F_Y} + \epsilon_{MGA} - a_{B_Z})$$

$$\Phi'_{H_{MGA}} = \Phi_{H_{RA}} + \epsilon_{F_Y} + \epsilon_{MGA} = \frac{\Phi_{13} + \Phi_{14}}{2} + a_{B_Z}$$

Figure II-7. Geometry and Derivation for JDC 35.0008.



WHERE

$$A'' = \epsilon_{F_Y} - \epsilon_{MGA}$$

$$B' = a_{Z'_Y} \cos \epsilon_{MGR} - a_{Z''_X} \sin \epsilon_{MGR}$$

First Null Measurement　　　　Second Null Measurement

$$\Phi_{15} = \Phi_{H_{RA}} + \epsilon_{F_Y} - \epsilon_{MGA} - a_{z'_Y} \cos \epsilon_{MGR} + a_{z''_X} \sin \epsilon_{MGR} + a_{B_Z}$$

$$\Phi_{16} = \Phi_{H_{RA}} + \epsilon_{F_Y} - \epsilon_{MGA} + a_{z'_Y} \cos \epsilon_{MGR} - a_{z''_X} \sin \epsilon_{MGR} + a_{B_Z}$$

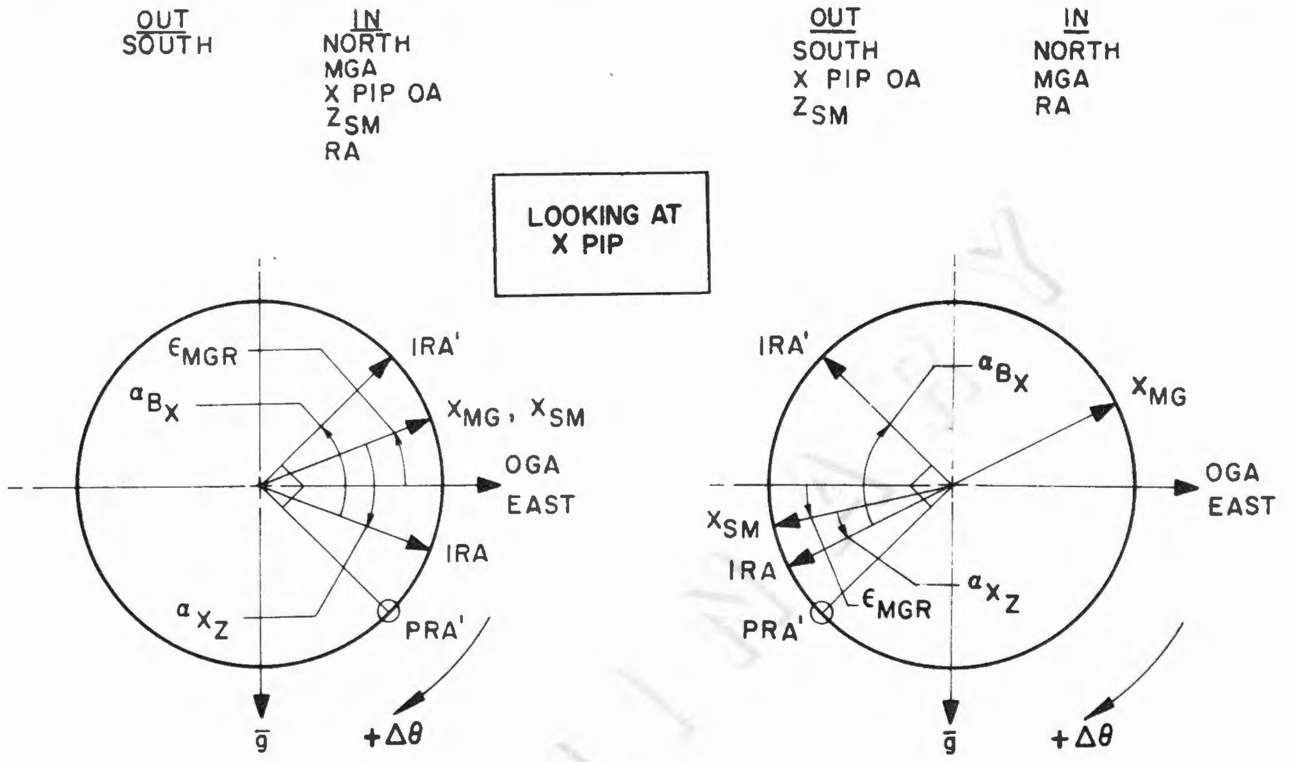
$$\Phi_{15} + \Phi_{16} = 2(\Phi_{H_{RA}} + \epsilon_{F_Y} - \epsilon_{MGA} + a_{B_Z})$$

$$\Phi_{13} + \Phi_{14} = 2(\Phi_{H_{RA}} + \epsilon_{F_Y} + \epsilon_{MGA} - a_{B_Z})$$

$$\text{(A)} \qquad \epsilon_{MGA} = \frac{(\Phi_{13} + \Phi_{14}) - (\Phi_{15} + \Phi_{16})}{4} + a_{B_Z}$$

$$\text{(B)} \qquad \epsilon_{F_Y} = \frac{\Phi_{13} + \Phi_{14} + \Phi_{15} + \Phi_{16}}{4} - \Phi_{H_{RA}}$$

Figure II-8. Geometry and Derivation for JDC 35.0009.



First Null Measurement

Second Null Measurement

$$\theta_{17} = \theta_{H_{OGA}} + \epsilon_{MGR} + \alpha_{B_X} - \alpha_{X_Z}$$

$$\theta_{18} = \theta_{H_{OGA}} + \epsilon_{MGR} - \alpha_{B_X} + \alpha_{X_Z}$$

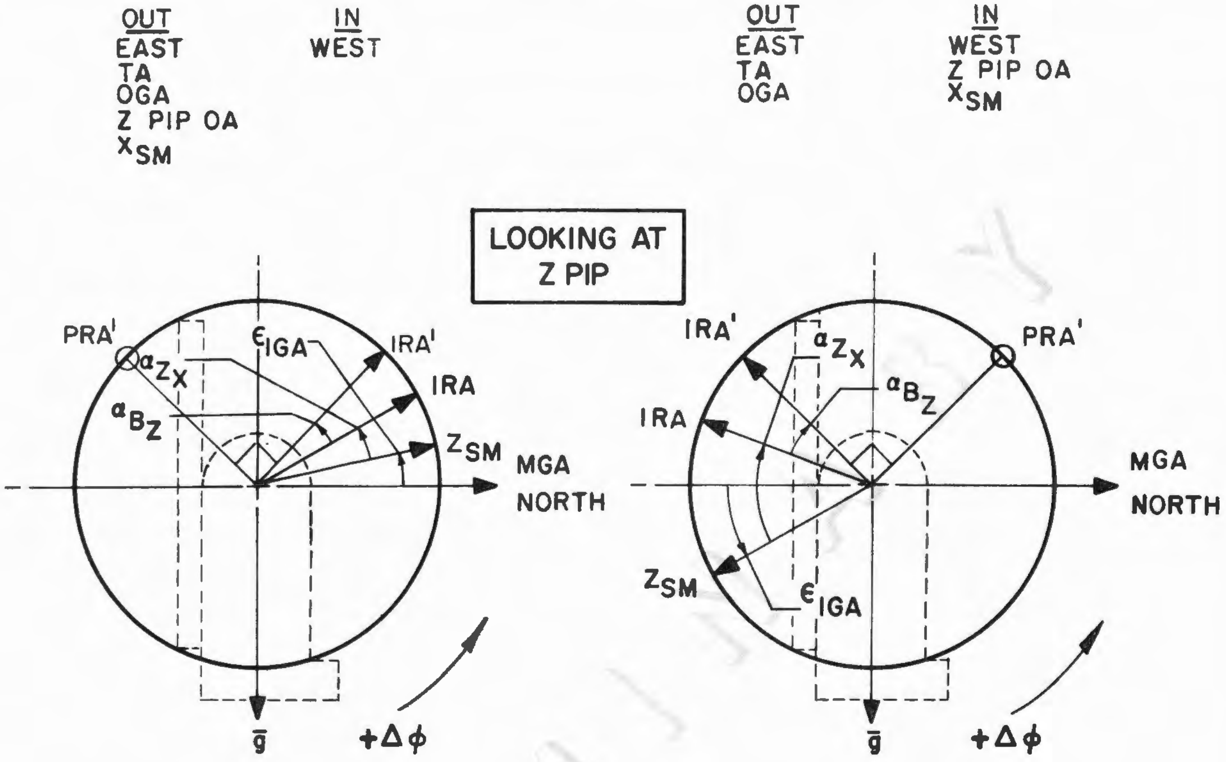
$$\theta_{17} + \theta_{18} = 2\,\theta_{H_{OGA}} + 2\,\epsilon_{MGR}$$

$$\text{(A)} \qquad \epsilon_{MGR} = \frac{\theta_{17} + \theta_{18}}{2} - \theta_{H_{OGA}}$$

$$\text{(B)} \qquad \theta_{H_{IGA}} = \theta_{H_{OGA}} + \epsilon_{MGR} - 90^\circ = \frac{\theta_{17} + \theta_{18}}{2} - 90^\circ$$

$$\text{(C)} \qquad \alpha_{X_Z} = \frac{\theta_{18} - \theta_{17}}{2} + \alpha_{B_X}$$

Figure II-9. Geometry and Derivation for JDC 35.0010.



First Null Measurement

Second Null Measurement

$$\Phi_{19} = \Phi_{H_{MGA}} - \epsilon_{IGA} - \alpha_{Z_X} - \alpha_{B_Z}$$

$$\Phi_{20} = \Phi_{H_{MGA}} - \epsilon_{IGA} + \alpha_{B_Z} + \alpha_{Z_X}$$

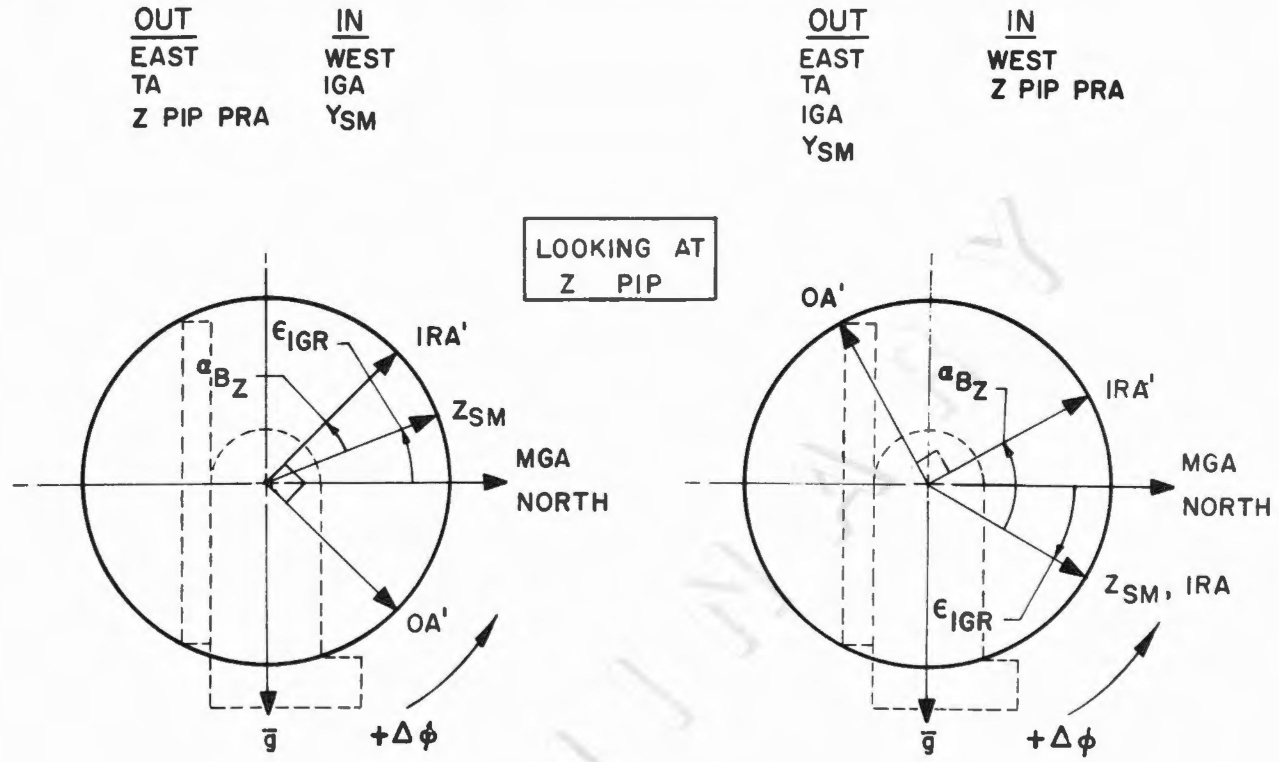
$$\Phi_{19} + \Phi_{20} = 2\,\Phi_{H_{MGA}} - 2\,\epsilon_{IGA}$$

$$\text{(A)} \qquad \epsilon_{IGA} = \Phi_{H_{MGA}} - \frac{\Phi_{19} + \Phi_{20}}{2}$$

$$\Phi_{20} - \Phi_{19} = 2\,\alpha_{Z_X} + 2\,\alpha_{B_Z}$$

$$\text{(B)} \qquad \alpha_{Z_X} = \frac{\Phi_{20} - \Phi_{19}}{2} - \alpha_{B_Z}$$

Figure II-10. Geometry and Derivation for JDC 35.0012.



First Null Measurement

Second Null Measurement

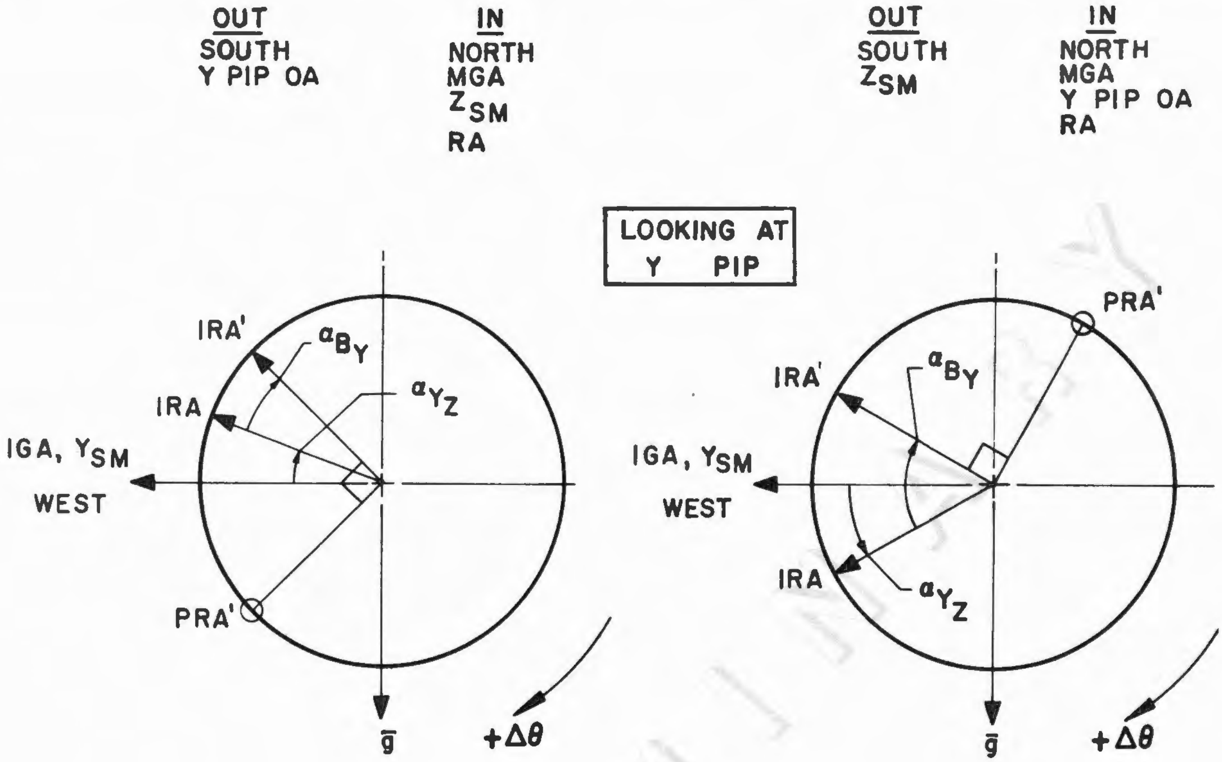
$$\Phi_{21} = \Phi'_{H_{MGA}} - \epsilon_{IGR} - \alpha_{B_Z}$$

$$\Phi_{22} = \Phi'_{H_{MGA}} + \epsilon_{IGR} - \alpha_{B_Z}$$

$$\Phi_{22} - \Phi_{21} = 2\,\epsilon_{IGR}$$

$$\epsilon_{IGR} = \frac{\Phi_{22} - \Phi_{21}}{2}$$

Figure II-11. Geometry and Derivation for JDC 35.0013.



First Null Measurement

Second Null Measurement

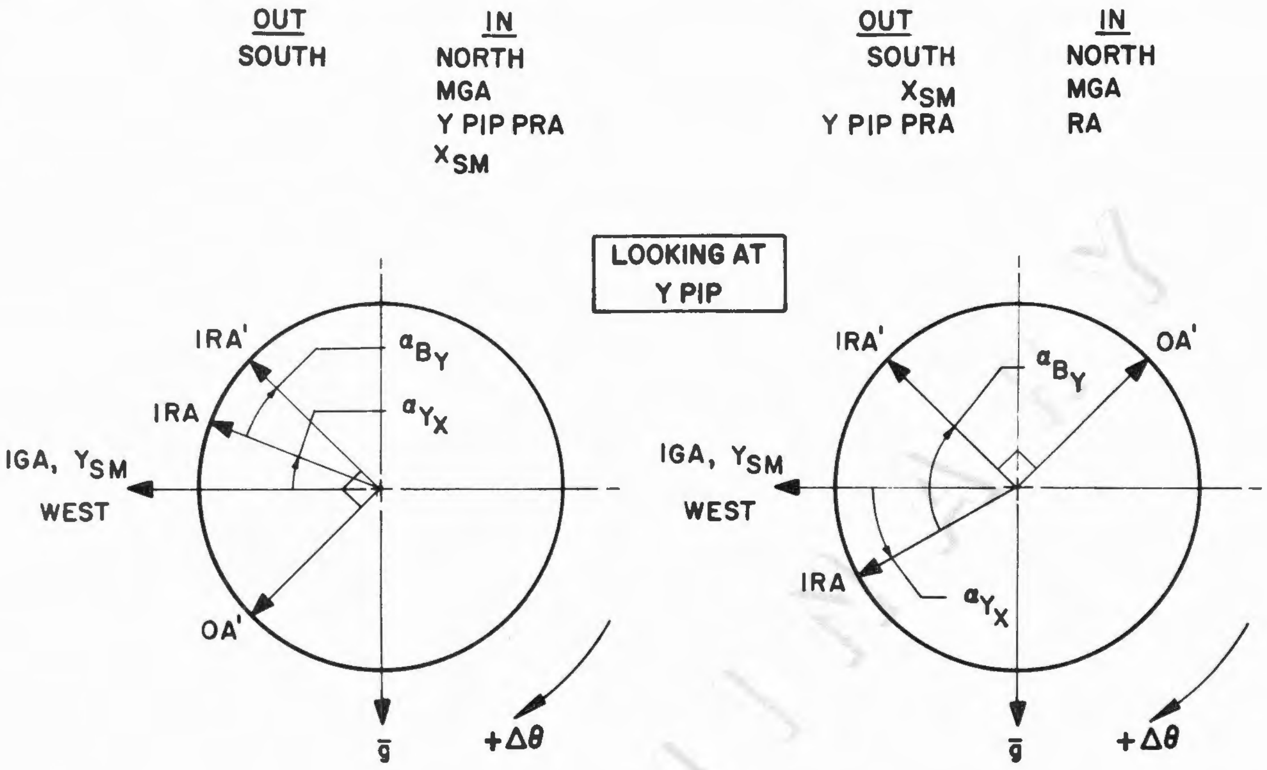
$$\theta_{23} = \theta_{H_{IGA}} - \alpha_{Y_Z} - \alpha_{B_Y}$$

$$\theta_{24} = \theta_{H_{IGA}} + \alpha_{Y_Z} - \alpha_{B_Y}$$

$$\theta_{24} - \theta_{23} = 2\,\alpha_{Y_Z}$$

$$\alpha_{Y_Z} = \frac{\theta_{24} - \theta_{23}}{2}$$

Figure II-12. Geometry and Derivation for JDC 35.0015.



First Null Measurement

Second Null Measurement

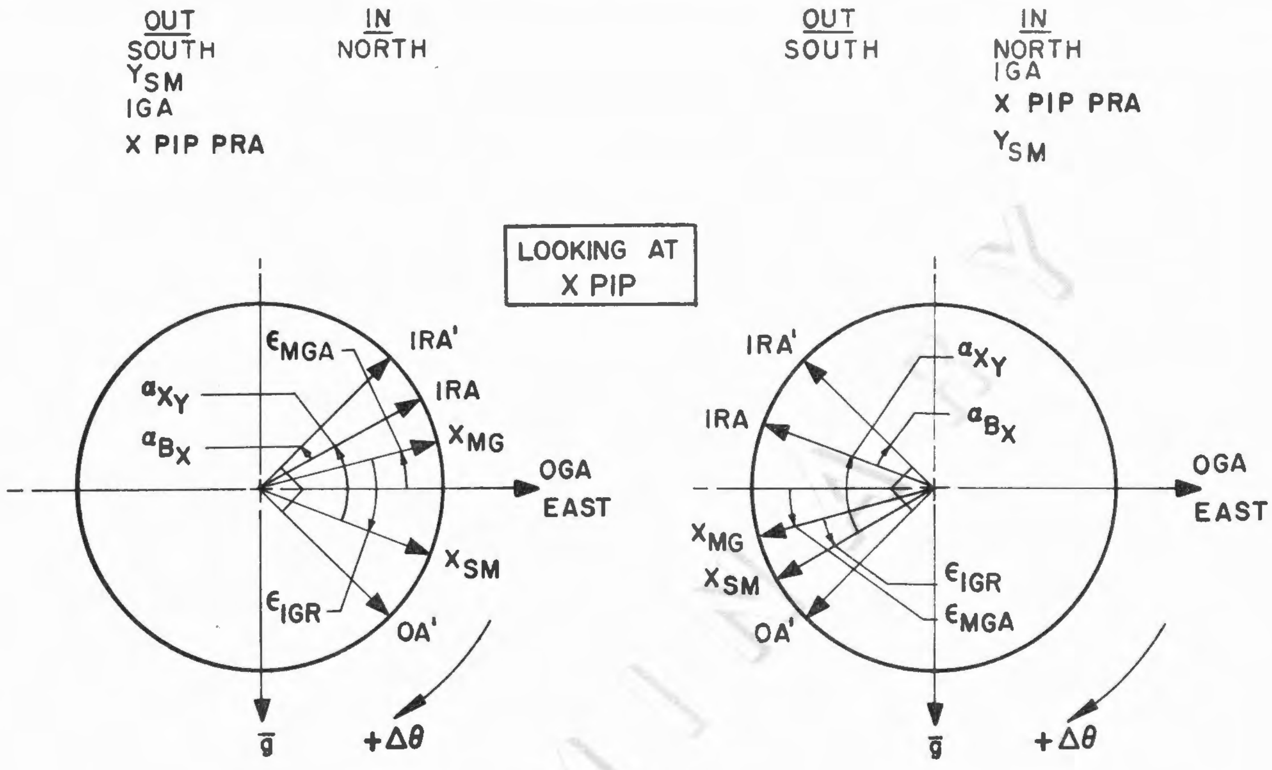
$$\theta_{25} = \theta_{H_{IGA}} - \alpha_{Y_X} - \alpha_{B_Y}$$

$$\theta_{26} = \theta_{H_{IGA}} + \alpha_{Y_X} - \alpha_{B_Y}$$

$$\theta_{26} - \theta_{25} = 2\,\alpha_{Y_X}$$

$$\alpha_{Y_X} = \frac{\theta_{26} - \theta_{25}}{2}$$

Figure II-13. Geometry and Derivation for JDC 35.0016.



First Null Measurement

Second Null Measurement

$$\theta_{27} = \theta_{H_{OGA}} + \epsilon_{MGA} - \epsilon_{IGR} + \alpha_{X_Y} + \alpha_{B_X}$$

$$\theta_{28} = \theta_{H_{OGA}} + \epsilon_{MGA} + \epsilon_{IGR} - \alpha_{X_Y} - \alpha_{B_X}$$

$$\theta_{27} - \theta_{28} = -2\,\epsilon_{IGR} + 2\,\alpha_{X_Y} + 2\,\alpha_{B_X}$$

$$\alpha_{X_Y} = \frac{\theta_{27} - \theta_{28}}{2} + \epsilon_{IGR} - \alpha_{B_X}$$

When Inner Gimbal resolver has been adjusted,

$$\alpha_{X_Y} = \frac{\theta_{27} - \theta_{28}}{2} - \alpha_{B_X}$$

Figure II-14. Geometry and Derivation for JDC 35.0017.

III. IRIG ALIGNMENT THEORY

IRIG Alignment Tests are based upon using the Gyro Preamp Output (E) to measure gyro response to gimbal motion about an axis which is supposedly orthogonal to the Input Axis. The misalignment angle determined from this response is γ', involving a combination of known quantities and the unknown misalignment γ.

Definitions of quantities used in these tests are in Sections I-7 and I-8 of this report. Figures III-1 through III-10 display the geometry for these tests.

In this theory section, the response equations are developed. Rotation about the Gyro's Output Axis produces one γ' relationship, which is measured in Part 2 of each of the three IRIG Alignment Tests. Rotation about the Gyro's Spin Reference Axis produces a second γ' relationship, which is measured in Part 3 of each of the three IRIG Alignment Tests.

In the Sensitivity Test, Parts 1 of each of the three IRIG Alignment Tests, the preamp voltage response to an angle change about the Input Axis is determined:

$$S = \frac{\Delta E}{\Delta A_I}$$

The actual measured quantity will be:

$$S = \frac{E}{A_I + \dfrac{W_{BD} T}{k}}$$

$$\text{where } k = \frac{H}{C}, \text{ the Gyro Gain Constant}$$

By expanding S (in terms of partial derivatives of the variables of S multiplied by the respective uncertainties of the variables), it can be shown that:

$$\left(\frac{U_S}{S}\right)^2 = \left(\frac{U_E}{E}\right)^2 + \left(\frac{U_{A_I}}{A_I}\right)^2 + \left(\frac{W_{BD} T}{A_I k}\right)^2 \left[\left(\frac{U_{BD}}{W_{BD}}\right)^2 + \left(\frac{U_T}{T}\right)^2 + \left(\frac{U_k}{k}\right)^2\right]$$

The following values are used:

$$\frac{U_E}{E} = 0.02, \text{ a } 2\% \text{ voltmeter}$$

$$\frac{U_{A_I}}{A_I} = \frac{\pm 9 \ \widehat{\text{SEC}} \text{ mispositioning}}{\pm 900 \ \widehat{\text{SEC}} \text{ input}}$$

$$= 0.01$$

$$\frac{W_{BD}T}{A_I k} = \frac{\text{NBD}\,(7 \times 10^{-5}) \ (30)}{(0.0045)\ (1.0)\ (1000)}$$

$$= \text{NBD} \times 0.000466$$

Note: $W_{BD} = \text{NBD}\left(\frac{W_{IE}}{1000}\right)$ where NBD is drift in Meru from all causes and is given on AGANI P. 52 or R348 Rev. A. P. 11

$$\frac{U_{BD}}{W_{BD}} = \frac{U_T}{T} = \frac{U_k}{k} = 1.0$$

then

$$\frac{U_S}{S} = \sqrt{(0.02)^2 + (0.01)^2 + (3)\,(\text{NBD} \times 4.66 \times 10^{-4})^2}$$

The Sensitivity measured in Part 1 of each of the three IRIG Alignment Tests is used in Part 2 of these tests, where each gyro is rotated about its output axis. The following analysis applies to these tests:

By definition:

$$S = \frac{E}{A_I}$$

$$S' = \frac{E}{A_F}$$

Since $A_F = kA_I$,

Then:

$$S' = \frac{S}{k}$$

$$E = S'(TW_{BD} - kW_{IE}T \, sin \, (\gamma + A_P) + kA_D \, sin \, \gamma')$$

$$= S'TW_{BD} - \gamma' S'k(W_{IE}T - A_D) - S'kW_{IE}TA_P$$

$$\gamma' = \frac{S'TW_{BD} - S'kW_{IE}TA_P - E}{S'k(W_{IE}T - A_D)}$$

$$= \frac{E}{SA_D}\left(\frac{\left(1 - \frac{S'TW_{BD}}{E} + \frac{S'kW_{IE}TA_P}{E}\right)}{\left(1 - \frac{W_{IE}T}{A_D}\right)}\right)$$

$$= \frac{E}{SA_D}\left(1 - \frac{STW_{BD}}{kE} + \frac{SW_{IE}TA_P}{E}\right)$$

$$= \frac{E}{SA_D} - \frac{TW_{BD}}{kA_D} + \frac{W_{IE}TA_P}{A_D}$$

The test specification calls only for one part in ten of a misalignment of 10 arc minutes or 2.91 milliradians. The errors introduced by bias drift and misalignment with earth rate can be evaluated as follows:

$$T = 60 \text{ seconds (maximum)}$$

$$A_P = \sqrt{2} \times 0.0174 \text{ rads.}$$

$$= 0.0246 \text{ rads.}$$

$$A_D = 1.60 \text{ rads.}$$

$$\frac{H}{C} = k = 1.0$$

$$\frac{E}{SA_D} = 0.00291 \text{ rads.}$$

$$= 2.91 \times 10^{-3}$$

$$\frac{W_{BD}T}{kA_D} = \frac{\left(\frac{NBD}{1000}\right)(7 \times 10^{-5})(60)}{(1.0)(1.60)}$$

$$= NBD \times 2.63 \times 10^{-6}$$

$$\frac{NBD \times 2.63 \times 10^{-6}}{2.91 \times 10^{-3}} = NBD \times 9.05 \times 10^{-4}$$

$$\frac{W_{IE}TA_P}{A_D} = \frac{(7 \times 10^{-5})\ (60)\ (0.0246)}{1.60}$$

$$= 6.45 \times 10^{-5}$$

$$\frac{6.45 \times 10^{-5}}{2.91 \times 10^{-3}} = 0.0222$$

On the basis of the above ratios, it appears that 10 arc minutes of misalignment can be measured to about 2 parts per 100, if the reading is taken within 60 seconds and the alignment to earth does not exceed 1 degree x $\sqrt{2}$.

An error analysis of Part 3 of each of the three IRIG Alignment Tests will now be made. In these tests, the IRIG is rotated about the axis that its own SRA (Spin Reference Axis) *should* occupy. If the SRA is misaligned, it will rotate about OA until it is lined up with the direction of test rotation. Our results are thus dependent upon measuring float angle (A_F) by reading the signal generator preamp. Unfortunately, the sensitivity measured in Part 1 of the IRIG Alignment Tests applies to Input Axis (A_I) rotation and not to A_F. A correction $\frac{H}{C}$ must be applied for each gyro. This is temperature and frequency sensitive, and the following error analysis will pay attention to this problem.

The fundamental equation for the IRIG Rotation about its Spin Reference Axis is in differential form because of the influence of changing float angle on the solution:

$$dE = S'dA_F$$

$$= S'[W_{BD}dT - W_{IE}k(\gamma' + A_P - A_F)\ dT] + S'[kdA_D\ (\gamma' - A_F)] \quad \text{(See figure III-10.)}$$

$$= S'\left[W_{BD}dT - W_{IE}k\left(\gamma' + A_P - \frac{E}{S'}\right)dT + k\left(\gamma' - \frac{E}{S'}\right)dA_D\right]$$

$$dE = S'\left[\left(W_{BD} - W_{IE}k(\gamma' + A_P) + k\gamma'\frac{dA_D}{dt}\right) + k\frac{E}{S'}\left(W_{IE} - \frac{dA_D}{dt}\right)\right]dT$$

$$S'dT = \frac{dE}{k\frac{E}{S'}\left(W_{IE}-\frac{dA_D}{dt}\right) + \left(W_{BD} - W_{IE}k(\gamma'+A_P) + k\gamma'\frac{dA_D}{dt}\right)}$$

$$kS'dT = \frac{dE}{\left(\frac{W_{IE}-\frac{dA_D}{dt}}{S'}\right)\left[E + S'\left(\frac{\frac{W_{BD}}{k} - W_{IE}\,(\gamma'+A_P) + \gamma'\frac{dA}{dt}}{W_{IE}-\frac{dA_D}{dt}}\right)\right]} = \frac{kS'dA_D}{W_D}$$

The test sequence consists of two parts. In the first part, the driven gimbal angle is being slewed at an approximately constant rate: $W_D = \frac{dA_D}{dt}$. In the second part, the voltage is being read and $\frac{dA_D}{dt} = 0$. If the test starts at $T = 0$ and $E = 0$, if the slewing stops at T_1 and E_1, and if the reading is finished at T_2 and E_2, then the differential equation can be put in the form of a definite integral. The expression will be evaluated first through T_1:

$$\frac{dA_D}{dt} = W_D > 0.15\frac{\text{rads}}{\widehat{\text{SEC}}}$$

$$\frac{\frac{dA_D}{W_D}}{kS'} = \frac{dE}{-\frac{W_D}{S'}\left(1-\frac{W_{IE}}{W_D}\right)\left[E+S'\left(\frac{(-W_D)\left(\frac{W_{IE}(\gamma'+A_P)-\frac{W_{BD}}{k}}{W_D} - \gamma'\right)}{(-W_D)\left(1-\frac{W_{IE}}{W_D}\right)}\right)\right]}$$

Simplification can now be made by cancellation and by recognizing that:

$$1 - \frac{W_{IE}}{W_D} = 1 - \frac{7\times10^{-5}}{(0.15)} \cong 1.0$$

$$\frac{dE}{E + S'\left(\frac{W_{IE}(\gamma'+A_P)-\frac{W_{BD}}{k}}{W_D} - \gamma'\right)} = -k\,dA_D$$

This expression can now be integrated between E_0 and E_1 with the following result:

$$-kA_D = ln\left[E + S'\left(\frac{W_{IE}(\gamma' + A_P) - \frac{W_{BD}}{k}}{kW_D} - \gamma' \right) \right] \Bigg|_{E_0 = 0}^{E_1}$$

$$e^{-kA_D} = \frac{E + S'\left(\frac{W_{IE}(\gamma' + A_P) - \frac{W_{BD}}{k}}{W_D} - \gamma' \right)}{S'\left(\frac{W_{IE}(\gamma' + A_P) - \frac{W_{BD}}{k}}{W_D} - \gamma' \right)}$$

$$E + S'\left(\frac{W_{IE}(\gamma' + A_P) - \frac{W_{BD}}{k}}{W_D} - \gamma' \right) = S'\left(\frac{W_{IE}(\gamma' + A_P) - \frac{W_{BD}}{k}}{W_D} - \gamma' \right) e^{-kA_D}$$

$$E + S'\left(1 - e^{-kA_D}\right)\left(\frac{W_{IE}A_P - \frac{W_{BD}}{k}}{W_D} \right) = S'\gamma'\left(1 - e^{-kA_D}\right)\left(1 - \cancel{\frac{W_{IE}}{W_D}}\right)$$

[See simplification on page 49.]

$$\gamma' = \frac{E}{\left(1 - e^{-kA_D}\right) S'} + \frac{W_{IE}A_P - \frac{W_{BD}}{k}}{W_D}$$

$$= \frac{Ek}{\left(1 - e^{-kA_D}\right) S} + \frac{W_{IE}A_P - \frac{W_{BD}}{k}}{W_D}$$

$$= \frac{Ek}{\left(1 - e^{-kA_D}\right) S} + W_{IE}\frac{A_P - \frac{NBD}{1000k}}{W_D}$$

But $A_D = \frac{3\pi}{2}$, $e^{-kA_D} = 0.0089$

Therefore:

$$\gamma' \cong \frac{Ek}{S} + W_{IE}\frac{A_P - \frac{NBD}{1000k}}{W_D}$$

Again, the test specification calls only for one part in ten of a misalignment of 10 arc minutes or 2.91 milliradians. The errors introduced by bias drift and misalignment with earth rate can be evaluated as before:

$$W_{BD} = \frac{NBD}{1000} \times W_{IE} \text{ from all causes}$$

$$A_P = \sqrt{2} \times 0.0174 \text{ rads.}$$

$$= 0.0246 \text{ rads.}$$

$$\frac{H}{C} = k = 1.0$$

$$W_D = 0.15 \frac{\text{rads.}}{\widehat{\text{SEC}}} (\text{minimum})$$

$$\frac{W_{IE} A_P}{W_D} = \frac{(7 \times 10^{-5})\ (0.0246)}{(0.15)}$$

$$= 11.48 \times 10^{-6}$$

$$\frac{11.48 \times 10^{-6}}{2.91 \times 10^{-3}} = 3.94 \times 10^{-3} \quad \text{Where } 2.91 \times 10^{-3} \text{ rads.} = 10 \text{ arc minutes}$$

$$\frac{W_{IE}\left(\frac{NBD}{1000k}\right)}{W_D} = \frac{7 \times 10^{-5}\left(\frac{NBD}{1000k}\right)}{(0.15)}$$

$$= NBD \times 4.67 \times 10^{-7}$$

$$\frac{NBD \times 4.67 \times 10^{-7}}{2.91 \times 10^{-3}} = NBD \times 16.0 \times 10^{-5}$$

Thus, within the required accuracy:

$$\gamma' = \frac{E}{\frac{H}{C} S}$$

However, a more detailed look at the effect of uncertainty in $\frac{H}{C}$ is required.

$$\left(\frac{U\gamma'}{\gamma'}\right)^2 = \left(\frac{\frac{\partial\gamma'}{\partial E} U_E}{\gamma'}\right)^2 + \left(\frac{\frac{\partial\gamma'}{\partial S} U_S}{\gamma'}\right)^2 + \left(\frac{\frac{\partial\gamma}{\partial k} U_k}{\gamma'}\right)^2$$

$$= \left(\frac{U_E}{E}\right)^2 + \left(\frac{U_S}{S}\right)^2 + \left(\frac{U_k}{k}\right)^2$$

The uncertainty in $\frac{H}{C}$ to achieve the test specification can now be calculated, using $\frac{U_{\gamma'}}{\gamma'} = 0.05$ to allow a margin for drift during reading.

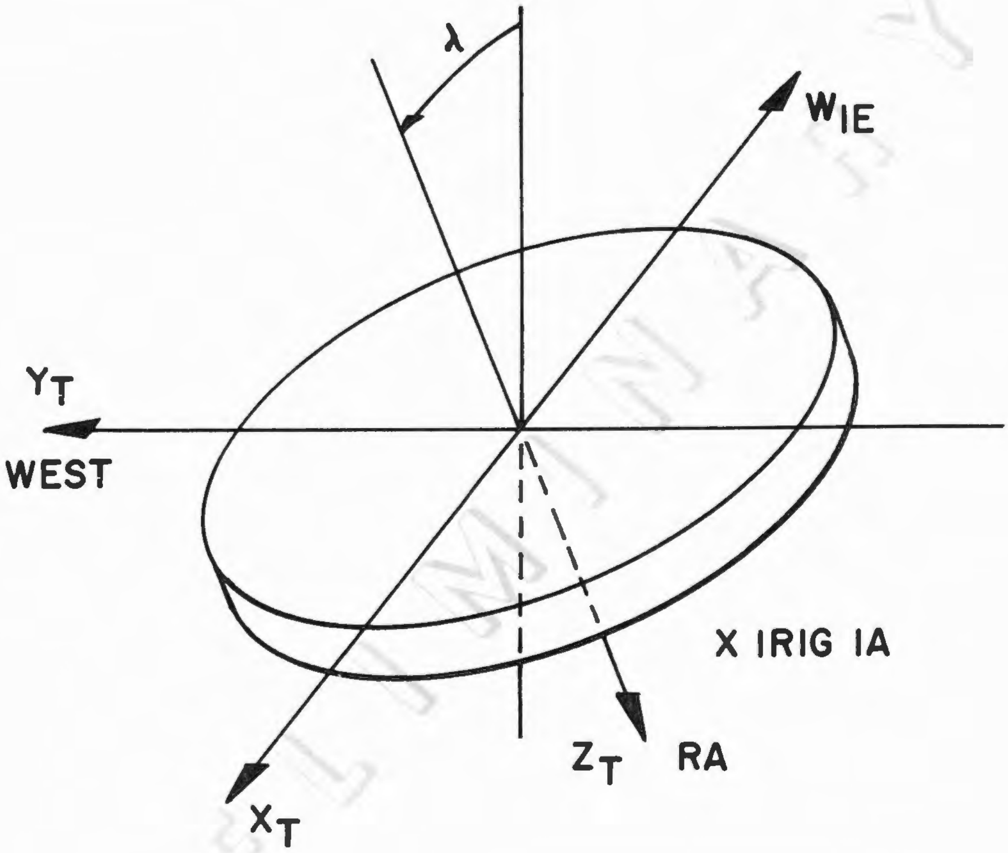
$$\frac{U_k}{k} = \sqrt{\left(\frac{U_{\gamma'}}{\gamma'}\right)^2 - \left(\frac{U_E}{E}\right)^2 - \left(\frac{U_S}{S}\right)^2}$$

$$= \sqrt{(0.05)^2 - (0.02)^2 - \left(\frac{U_S}{S}\right)^2}$$

Where $\frac{U_S}{S}$ is the quantity referred to on page 46.

GEOMETRIC THEORY FOR X IRIG ALIGNMENT

JDC 35.0020, Part 1:



SET:

$\Phi = \lambda$

$\theta = 0°$

GIMBAL ANGLES:

$A_{OG} = 0°*$

$A_{MG} = 0°*$

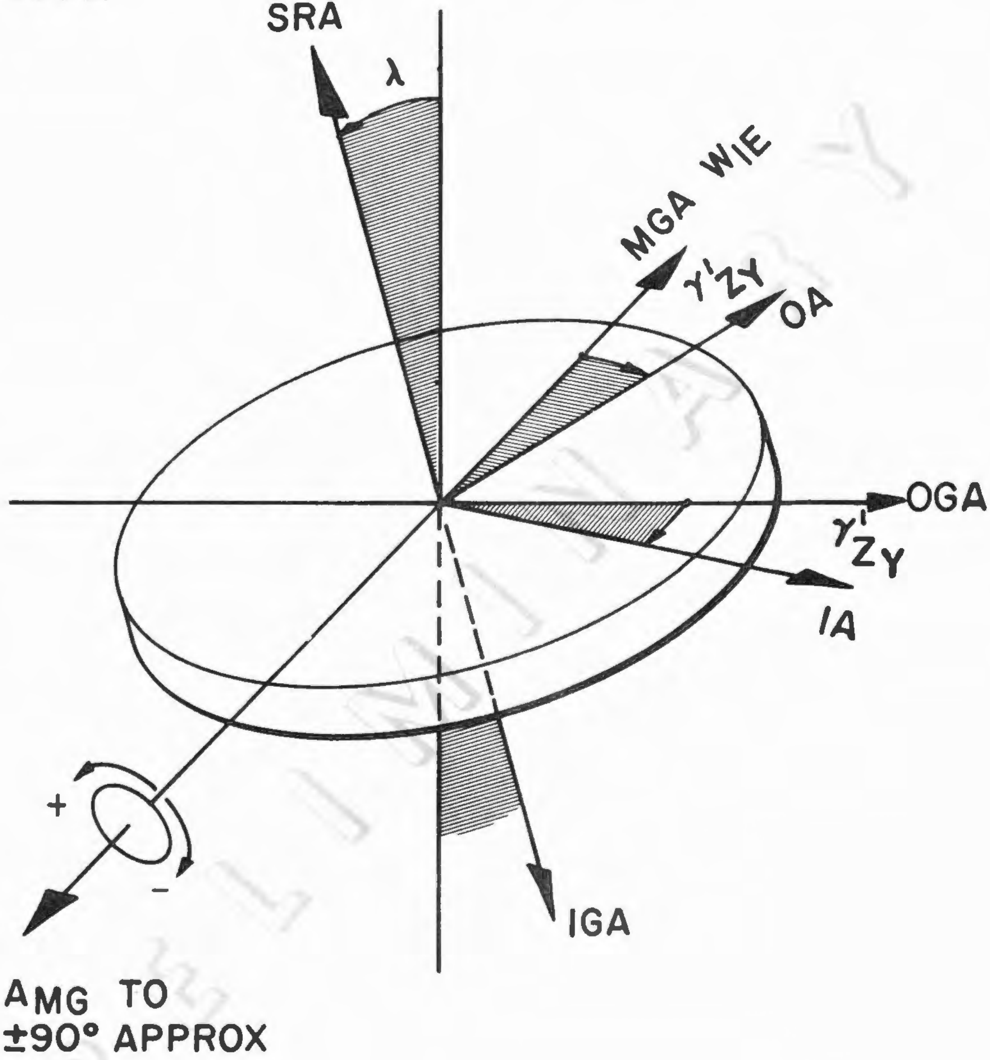
$A_{IG} = 0°*$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-1. X IRIG, Input Angle to Preamp Voltage Sensitivity Test.

GEOMETRIC THEORY FOR X IRIG ALIGNMENT

JDC 35.0020, Part 2:



SET:

$\Phi = \lambda$

$\theta = \theta_{H_{OGA}}$

GIMBAL ANGLES:

$A_{OG} = 270^\circ$

$A_{MG} = 0^\circ$

$A_{IG} = 0^\circ *$

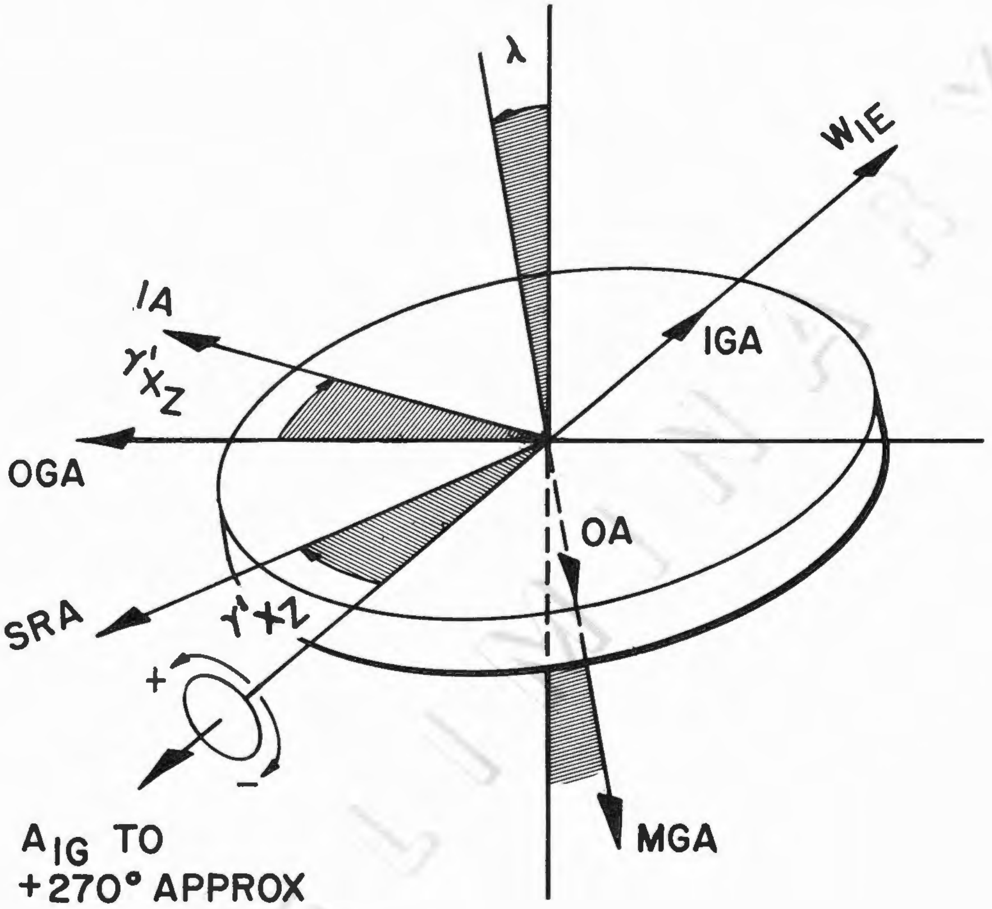
$$\gamma_{X_Y} = \gamma'_{X_Y} + \epsilon_{IGR}$$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-2. Measurement of γ_{X_Y} by Rotation About X IRIG OA.

GEOMETRIC THEORY FOR X IRIG ALIGNMENT

JDC 35.0020, Part 3:



SET:

$\Phi = \lambda$

$\theta = \theta_{H_{OGA}} \pm 180^\circ$

GIMBAL ANGLES:

$A_{OG} = 0^\circ$*

$A_{MG} = 0^\circ$*

$A_{IG} = 0^\circ$

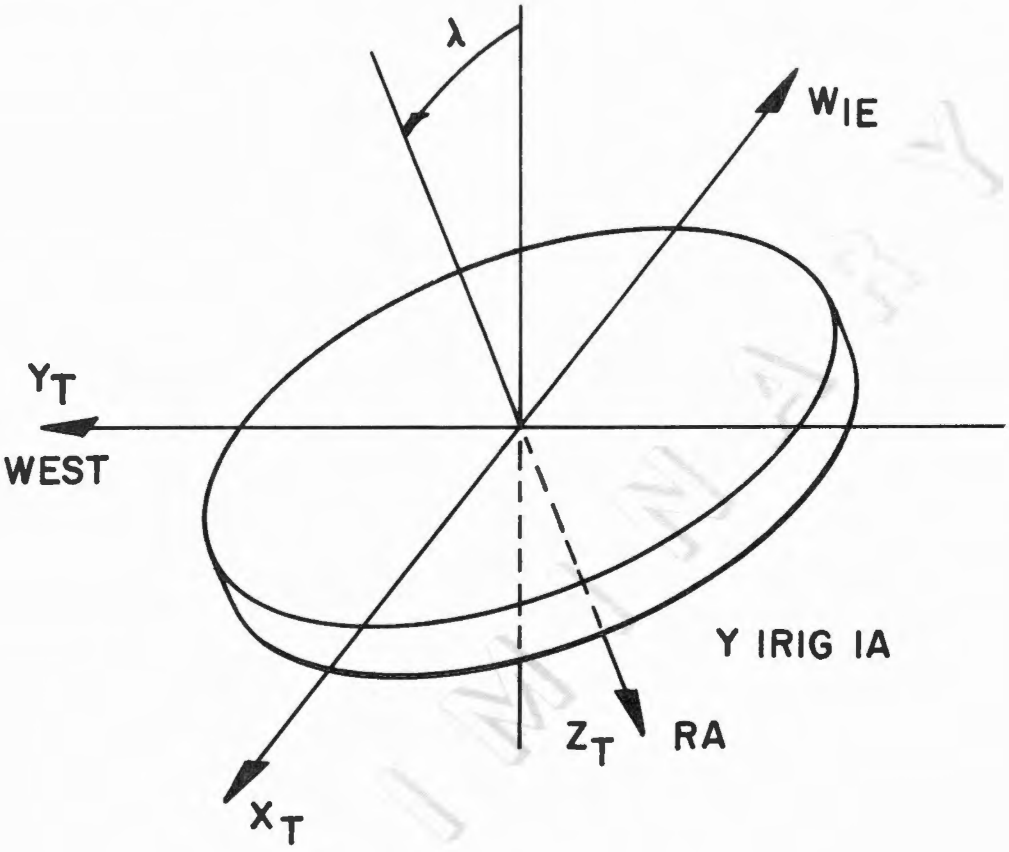
$$\gamma_{X_Z} = \gamma'_{X_Z} + 00 = \gamma'_{X_Z}$$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-3. Measurement of γ_{X_Z} *by Negative Rotation About X IRIG SRA.*

GEOMETRIC THEORY FOR Y IRIG ALIGNMENT

JDC 35.0021, Part 1:



SET:

$\Phi = \lambda$

$\theta = 0^\circ$

GIMBAL ANGLES:

$A_{OG} = 270^\circ$

$A_{MG} = 0^\circ *$

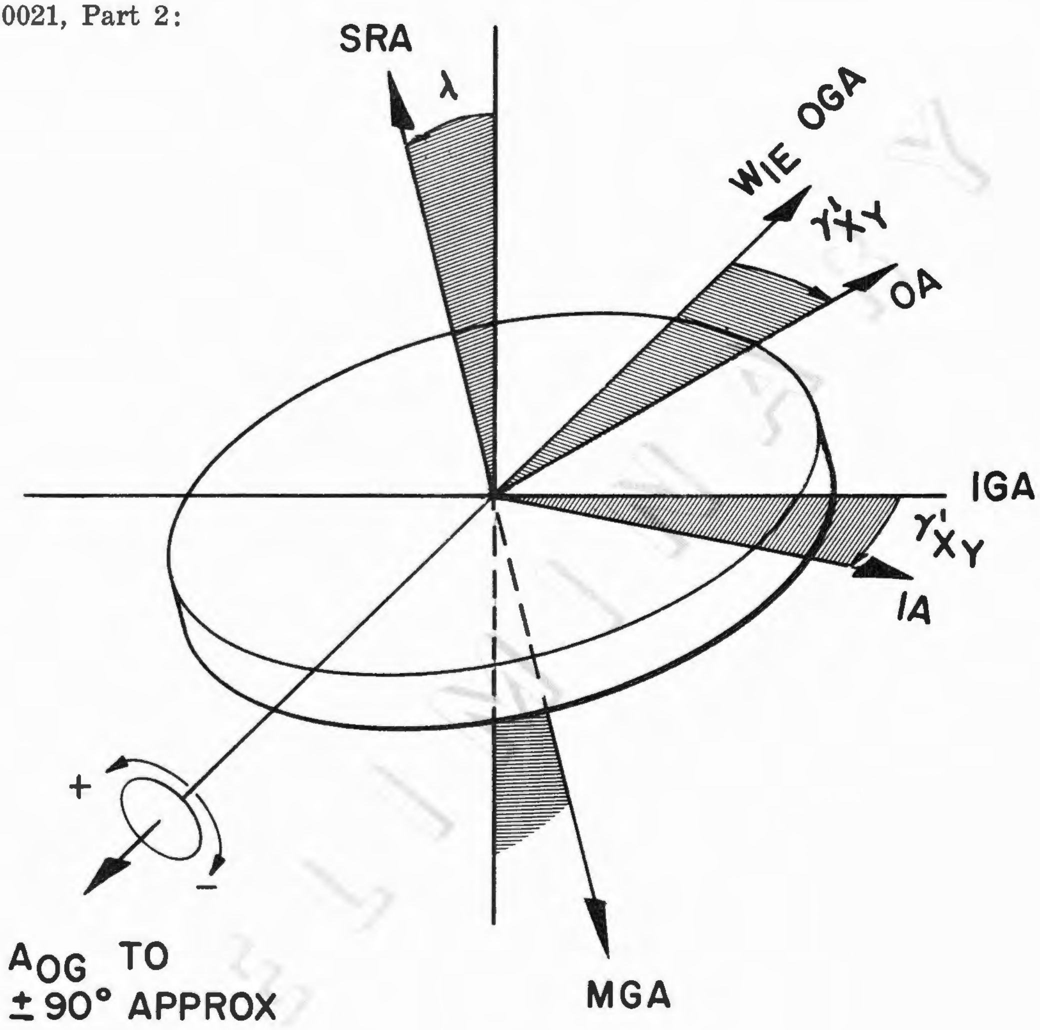
$A_{IG} = 0^\circ *$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-4. Y IRIG, Input Angle to Preamp Voltage Sensitivity Test.

GEOMETRIC THEORY FOR Y IRIG ALIGNMENT

JDC 35.0021, Part 2:



SET:

$\Phi = \lambda$

$\theta = \theta_{H_{OGA}} - 90°$

GIMBAL ANGLES:

$A_{OG} = 0°$

$A_{MG} = 0°*$

$A_{IG} = 0°*$

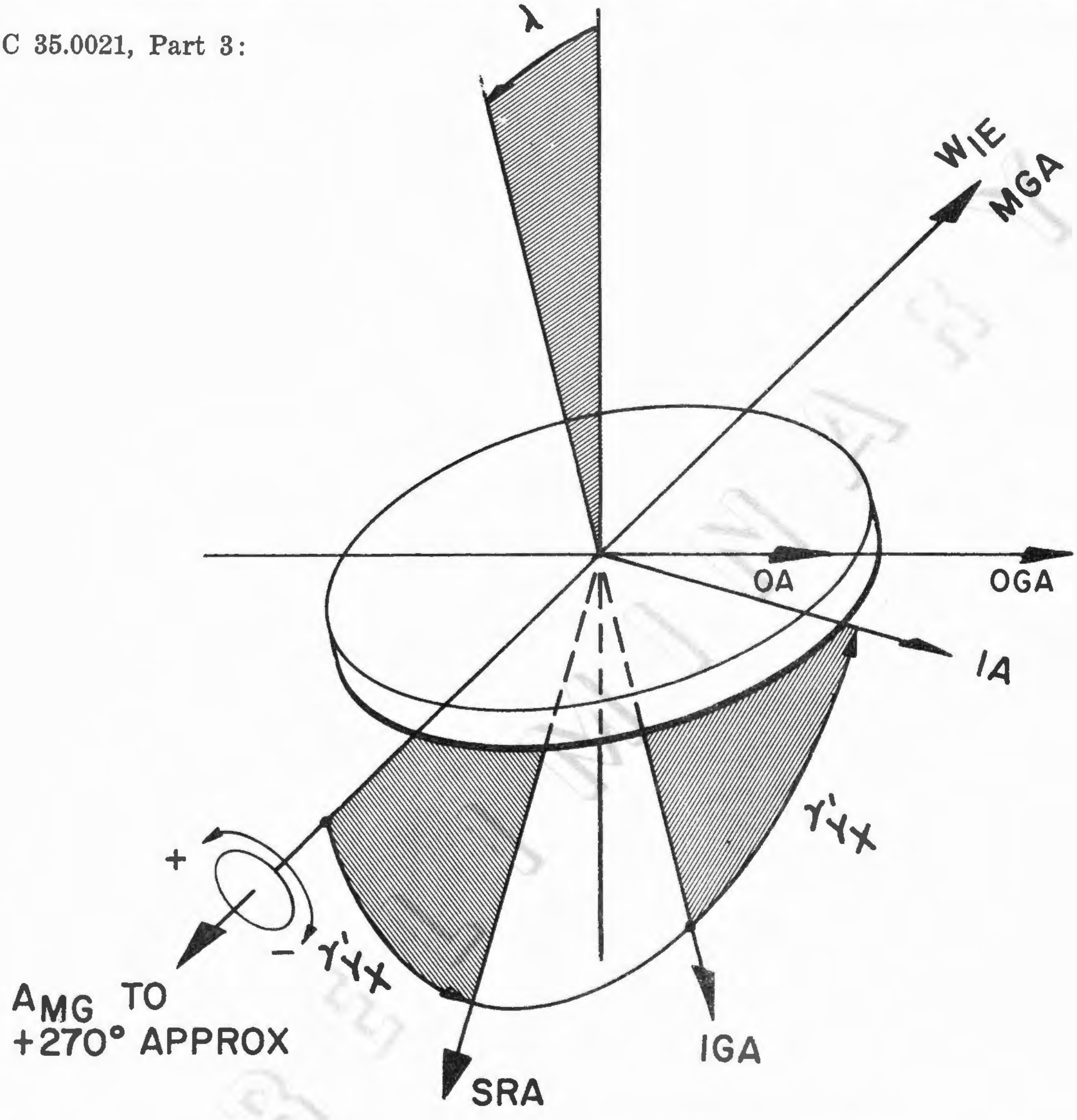
$$\gamma_{Y_Z} = \gamma'_{Y_Z} + \epsilon_{MGR}$$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-5. Measurement of γ_{Y_Z} by Rotation About Y IRIG OA.

GEOMETRIC THEORY FOR Y IRIG ALIGNMENT

JDC 35.0021, Part 3:



SET:

$\Phi = \lambda$

$\theta = \theta_{H_{OGA}}$

GIMBAL ANGLES:

$A_{OG} = 270°$

$A_{MG} = 0°$

$A_{IG} = 0°*$

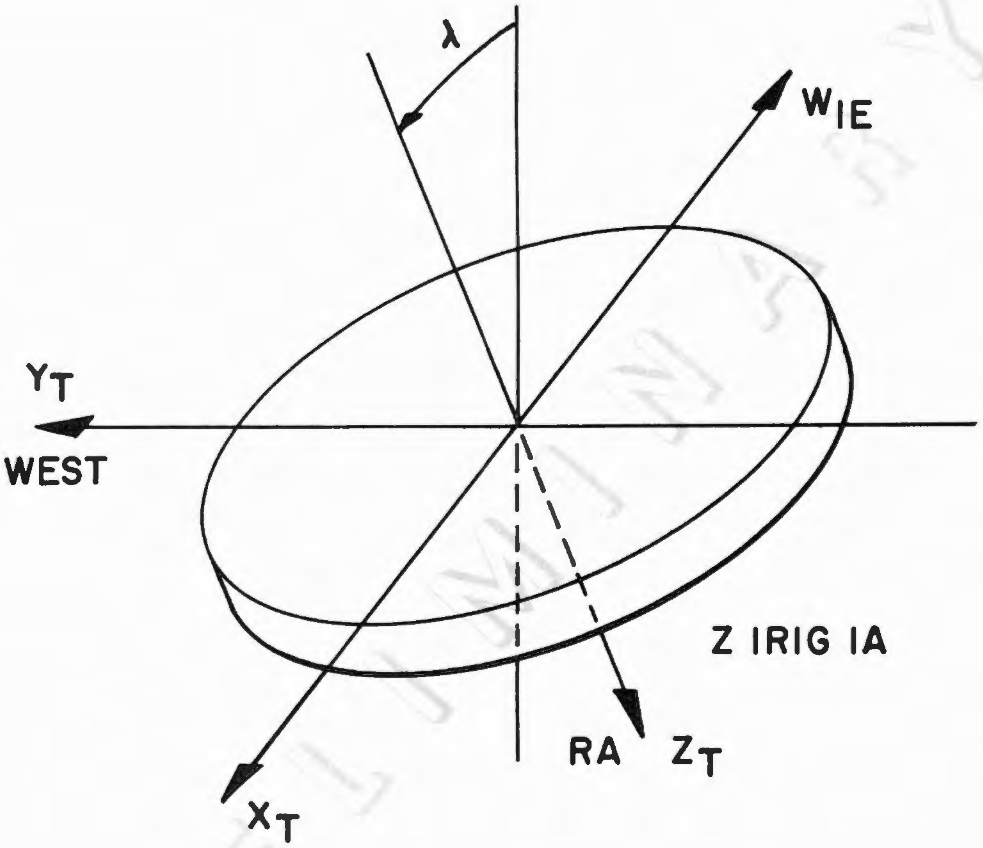
$$\gamma_{Y_X} = \gamma'_{Y_X} + (-\epsilon_{IGA})$$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-6. Measurement of γ_{Y_X} *by Negative Rotation About Y IRIG SRA.*

GEOMETRIC THEORY FOR Z IRIG ALIGNMENT

JDC 35.0022, Part 1:



SET:

$\Phi = \lambda$

$\theta = 0°$

GIMBAL ANGLES:

$A_{OG} = 0°*$

$A_{MG} = 0°*$

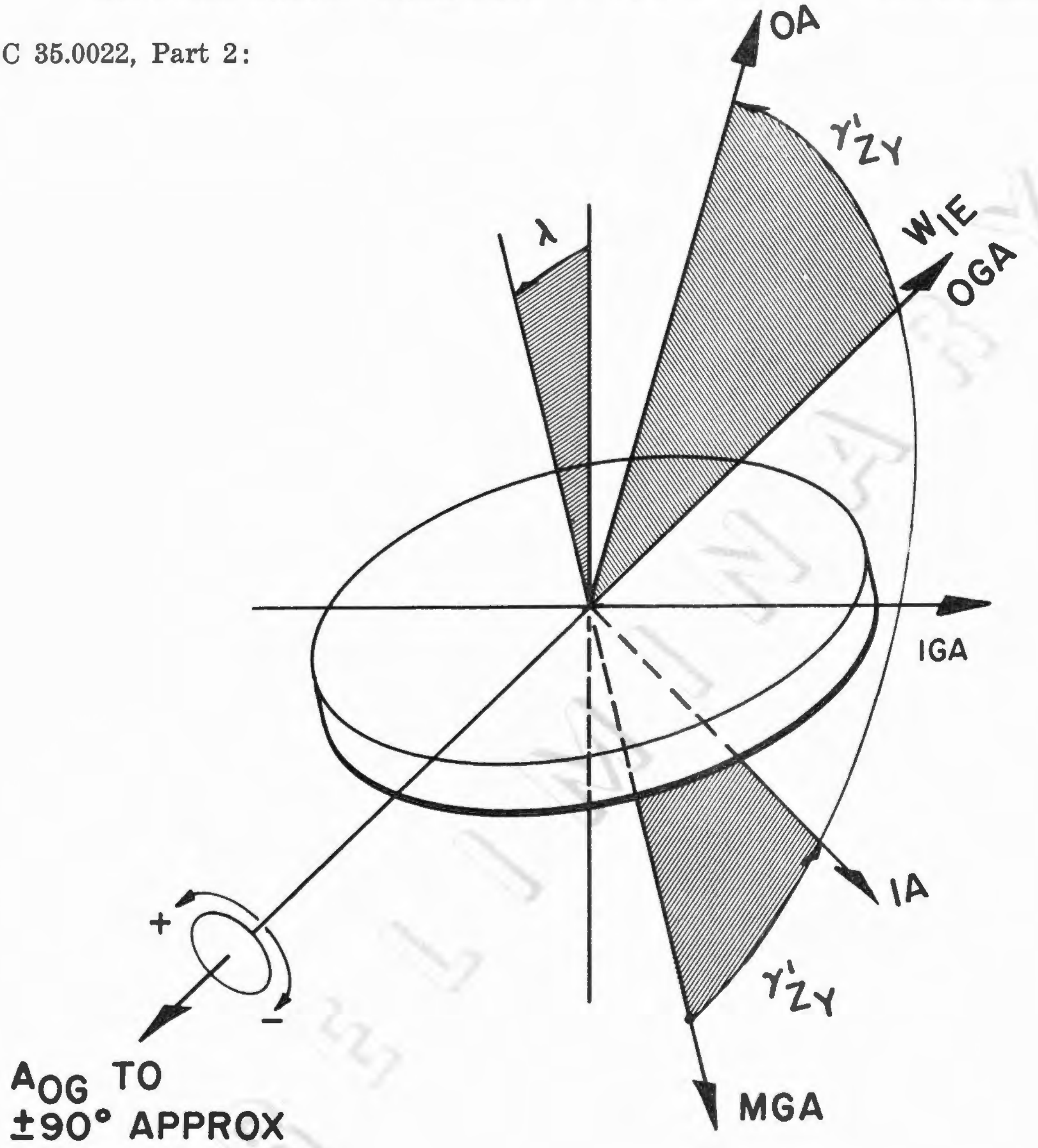
$A_{IG} = 90°$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-7. Z IRIG, Input Angle to Preamp Voltage Sensitivity Test.

GEOMETRIC THEORY FOR Z IRIG ALIGNMENT

JDC 35.0022, Part 2:



SET:

$\Phi = \lambda$

$\theta = \theta_{H_{OGA}} - 90°$

GIMBAL ANGLES:

$A_{OG} = 0°$

$A_{MG} = 0°*$

$A_{IG} = 0°*$

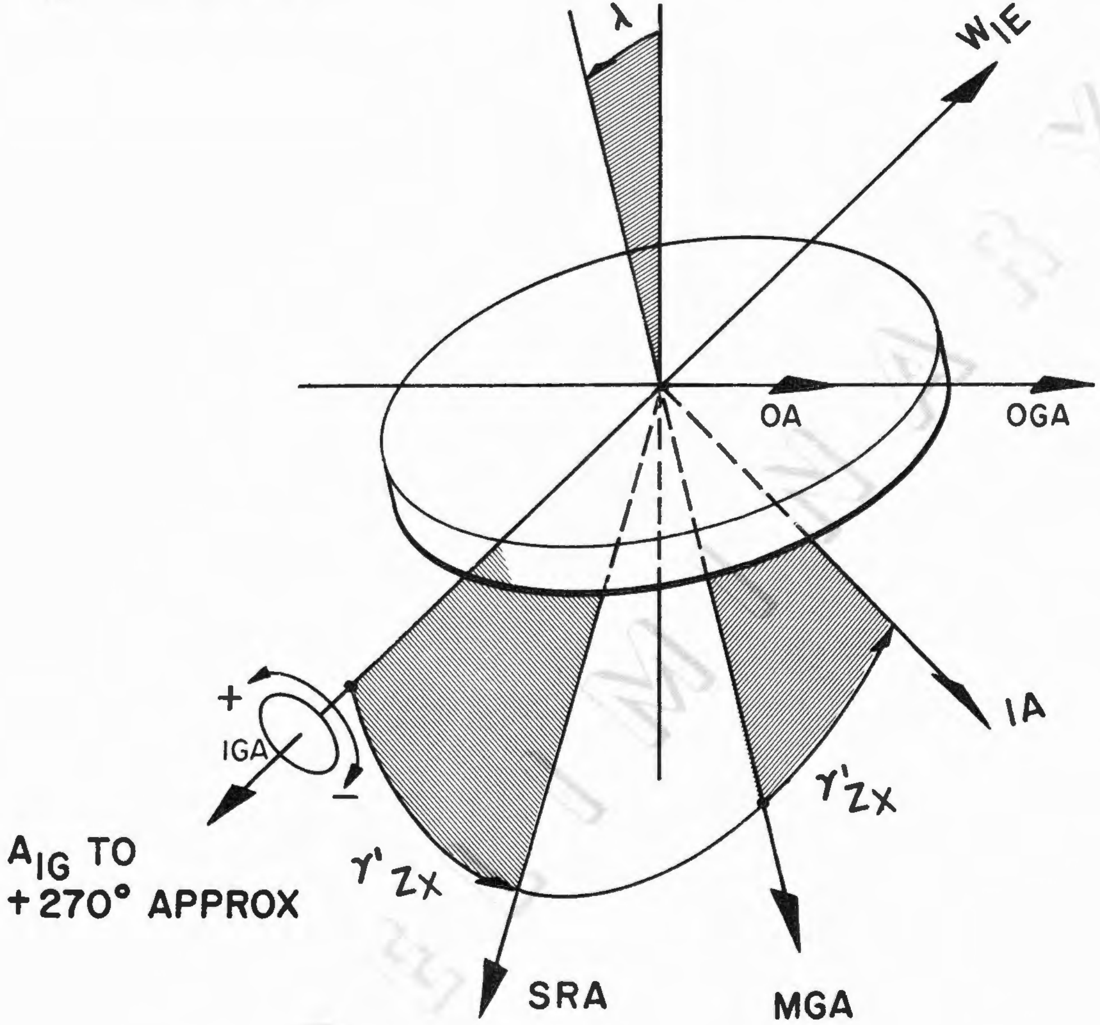
$$\gamma_{Z_Y} = \gamma'_{Z_Y} + \epsilon_{IGR} - \epsilon_{MGA}$$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-8. Measurement of γ_{Z_Y} by Rotation About Z IRIG OA.

GEOMETRIC THEORY FOR Z IRIG ALIGNMENT

JDC 35.0022, Part 3:



SET:

$\Phi = \lambda$

$\theta = \theta_{H_{OGA}}$

GIMBAL ANGLES:

$A_{OG} = 0°*$

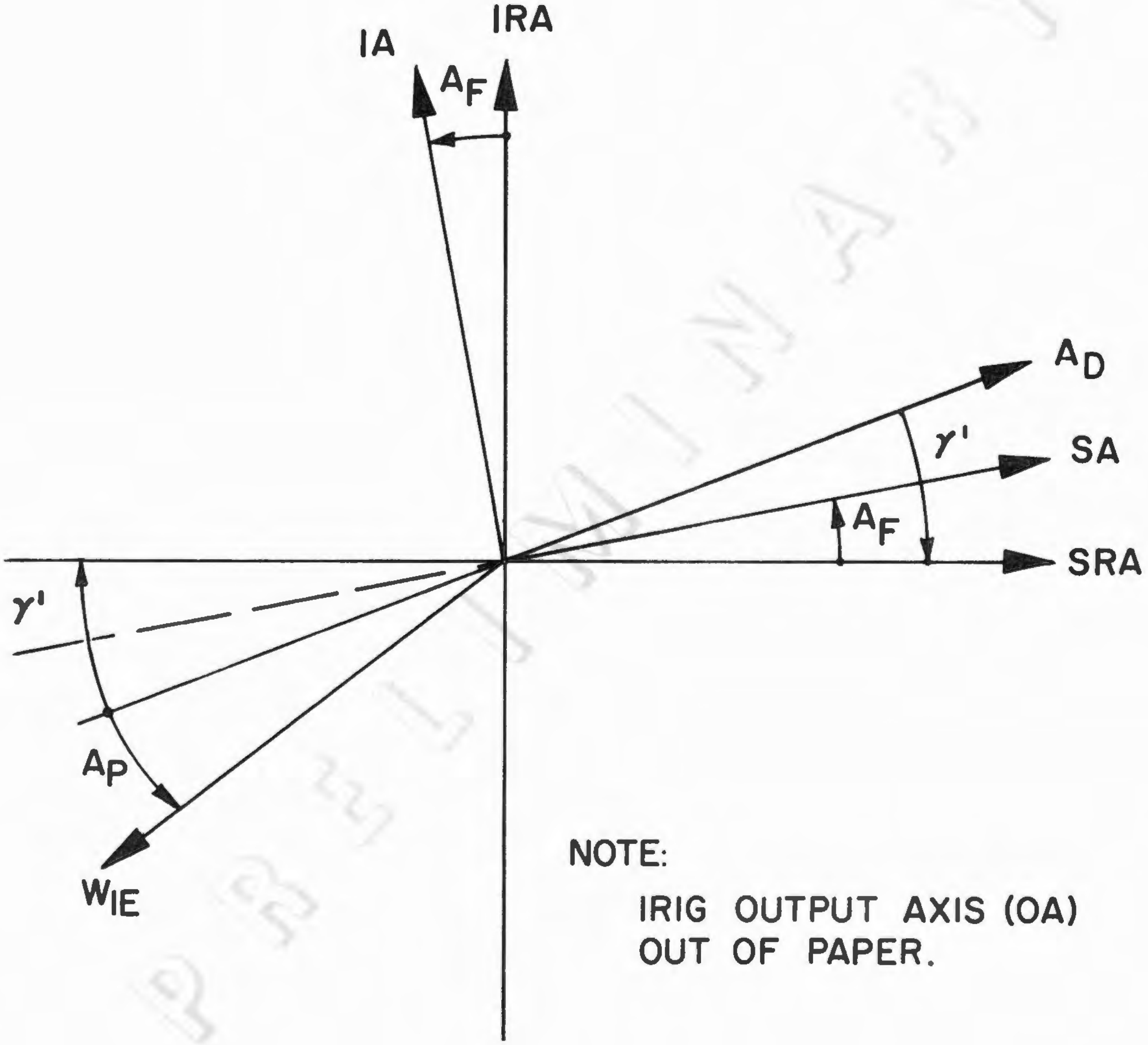
$A_{MG} = 0°*$

$A_{IG} = 0°$

$$\gamma_{z_x} = \gamma'_{z_x} + 00 = \gamma'_{z_x}$$

* MEANS "PRECISION ZERO SET" OF GIMBAL ANGLE

Figure III-9. Measurement of γ_{z_x} *by Negative Rotation About Z IRIG SRA.*



NOTE:

IRIG OUTPUT AXIS (OA)
OUT OF PAPER.

Figure III-10. Geometry Applicable to Part 3 in X, Y, and Z IRIG Alignment Test Equations.

IV. JOB DESCRIPTION CARDS (JDC's) FOR PIPA AND IRIG ALIGNMENT TESTS AND DATA SHEET FORMS

Figure IV-1. Flow Diagram Showing Interrelationship among Alignment Test JDC's.

A. PIPA ALIGNMENT TESTS.

JDC 35.0001	Test to determine α_{B_X}
JDC 35.0002	Test to determine $\theta_{H_{OGA}}$
JDC 35.0003	Test to determine α_{B_Y}
JDC 35.0004	Test to determine α_{B_Z}
JDC 35.0005	Test to determine $\Phi_{H_{RA}}$
JDC 35.0006	Test to determine $\Phi_{H_{MGA}}$ and ϵ_{OGR}
JDC 35.0007	Zero adjustment of the Outer Gimbal Resolver
JDC 35.0008	Test to determine $\Phi'_{H_{MGA}}$
JDC 35.0009	Test to determine ϵ_{MGA} and ϵ_{F_Y}
JDC 35.0010	Test to determine ϵ_{MGR} and α_{X_Z}
JDC 35.0011	Zero adjustment of the Middle Gimbal Resolver and test to determine $\theta_{H_{IGA}}$
JDC 35.0012	Test to determine ϵ_{IGA} and α_{Z_X}
JDC 35.0013	Test to determine ϵ_{IGR}
JDC 35.0014	Zero adjustment of the Inner Gimbal Resolver
JDC 35.0015	Test to determine α_{Y_Z}
JDC 35.0016	Test to determine α_{Y_X}
JDC 35.0017	Test to determine α_{X_Y}

B. IRIG ALIGNMENT TESTS.

JDC 35.0020 X IRIG Alignment Test

Part 1. Calibration of Input Angle to Preamp Voltage Output: S_X

Part 2. Measuring γ_{X_Y} by Rotation About X IRIG Output Axis.

Part 3. Measuring γ_{X_Z} by Rotation About X IRIG Spin Reference Axis.

JDC 35.0021 Y IRIG Alignment Test

Part 1. Calibration of Input Angle to Preamp Voltage Output: S_Y

Part 2. Measuring γ_{Y_Z} by Rotation About Y IRIG Output Axis.

Part 3. Measuring γ_{Y_X} by Rotation About Y IRIG Spin Reference Axis.

JDC 35.0022 Z IRIG Alignment Test

Part 1. Calibration of Input Angle to Preamp Voltage Output: S_Z

Part 2. Measuring γ_{Z_Y} by Rotation About Z IRIG Output Axis.

Part 3. Measuring γ_{Z_X} by Rotation About Z IRIG Spin Reference Axis.

C. JDC DATA SHEET FORMS.

PIPA ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-1

used with JDC 35.0001 through JDC 35.0006
JDC 35.0008 through JDC 35.0010
JDC 35.0012 and JDC 35.0013
JDC 35.0015 through JDC 35.0017

PIPA ALIGNMENT TEST
FINE RESOLVER ALIGNMENT TEST
DATA SHEET FORM E-1230 DS-2

used with JDC 35.0007, JDC 35.0011, and JDC 35.0014

IRIG ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-3 PART 1

used with JDC 35.0020 through JDC 35.0022

IRIG ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-3 PART 2

used with JDC 35.0020 through JDC 35.0022

IRIG ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-3 PART 3

used with JDC 35.0020 through JDC 35.0022

JOB: PIPA ALIGNMENT TESTS

JDC 35.0001 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{θ_x}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

B. PROCEDURE

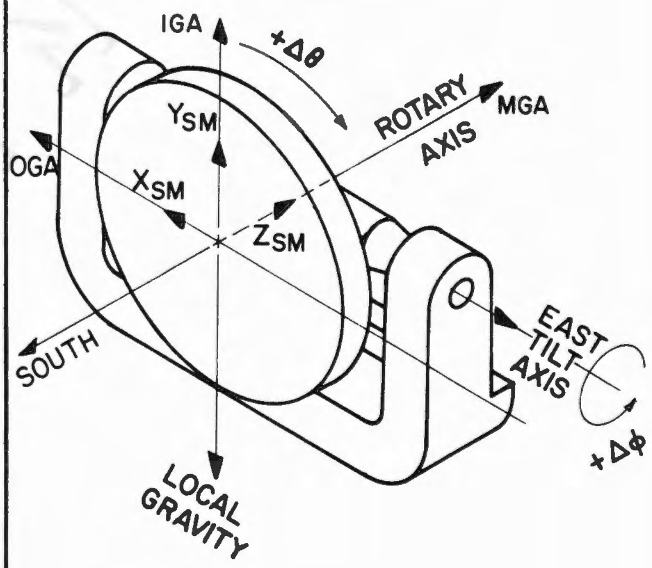
First Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the X PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_1



JOB: PIPA ALIGNMENT TESTS	**JDC** 35.0001 Sheet 2 of 2
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Test to Determine α_{B_X}	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT:	

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = 270°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

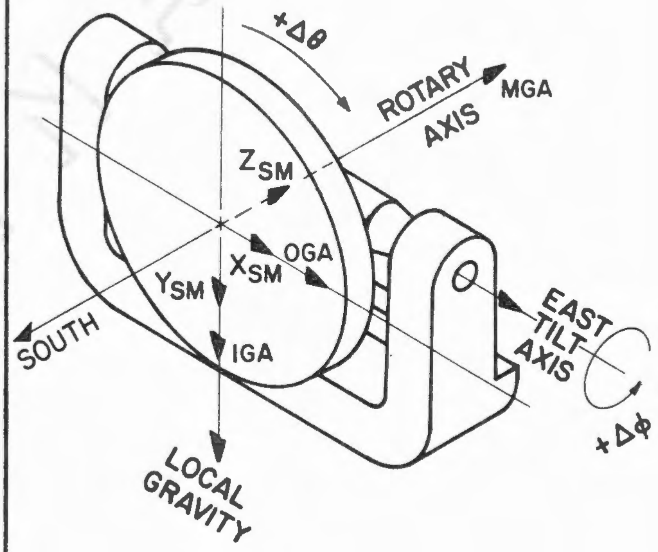
Second Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the X PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_2



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\alpha_{B_X} = \frac{\theta_2 - \theta_1 - 180^\circ}{2}$$

JOB: PIPA ALIGNMENT TEST

JDC 35.0002

Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine $\theta_{H_{OGA}}$

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0001 required to perform this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = 0°

   b. Middle Gimbal Angle (A_{MG}) = Precision 0°

   c. Inner Gimbal Angle (A_{IG}) = 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = 90°

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = 270°

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

B. PROCEDURE

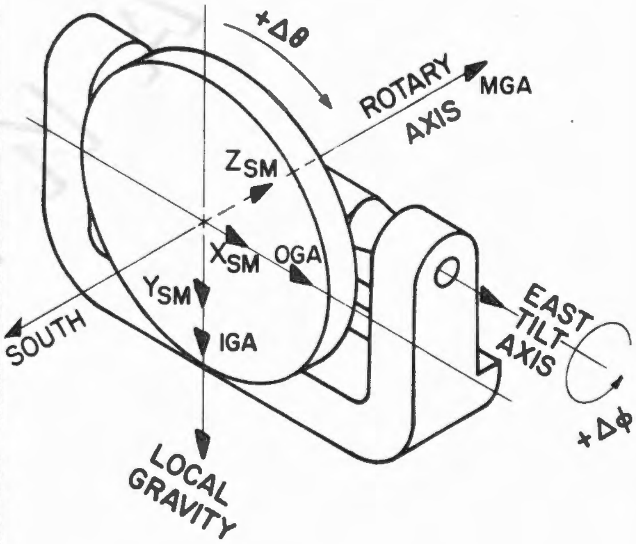
First Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the X PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_3



JOB: PIPA ALIGNMENT TEST

JDC 35.0002 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine $\theta_{H_{OGA}}$

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0001 required to perform this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
    - a. Outer Gimbal Angle (A_{OG}) = 180°
    - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
    - c. Inner Gimbal Angle (A_{IG}) = 0°
2. Test Table
    - a. Initial Tilt Angle (Φ)

      Desired Angle Designation = 90°

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
    - b. Initial Rotary Angle (θ)

      Desired Angle Designation = 270°

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

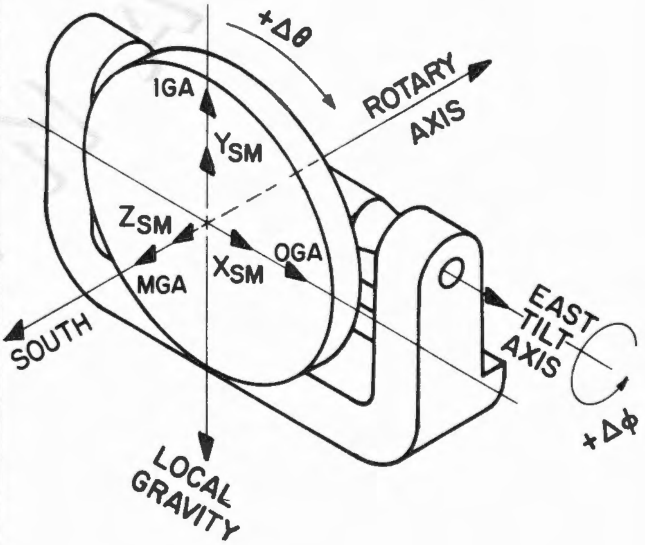
Second Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the X PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_4



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\theta_{H_{OGA}} = \frac{\theta_3 + \theta_4}{2} - \alpha_{B_X}$$

Value of α_{B_X} obtained from JDC 35.0001 Data Sheet Form E-1230 DS-1.

JOB: PIPA ALIGNMENT TEST

JDC 35.0003 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{B_Y}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

A. PREPARATION

Orientations required for first null measurement:

1. <u>Gimbal Assembly</u>
   - a. Outer Gimbal Angle (A_{OG}) = 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 0°
2. <u>Test Table</u>
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = 0°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

B. PROCEDURE

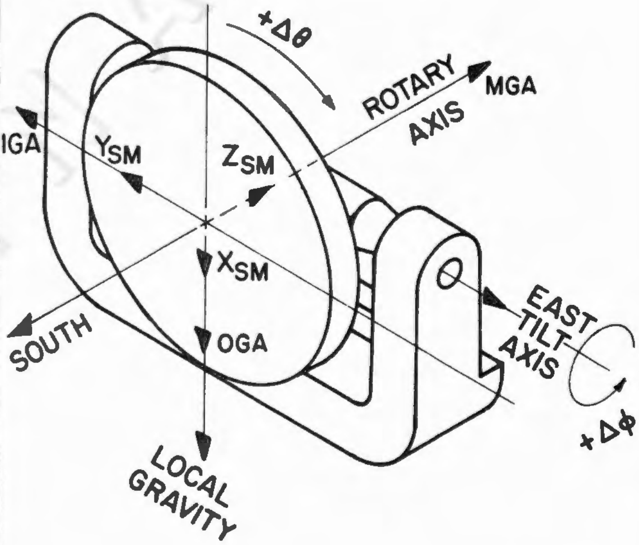
<u>First Null Measurement</u>

Rotate the table about the ROTARY AXIS until a null is obtained from the Y PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_5



JOB: PIPA ALIGNMENT TEST

JDC 35.0003 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{B_Y}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = 0°

   b. Middle Gimbal Angle (A_{MG}) = Precision 0°

   c. Inner Gimbal Angle (A_{IG}) = 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = 90°

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = 180°

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

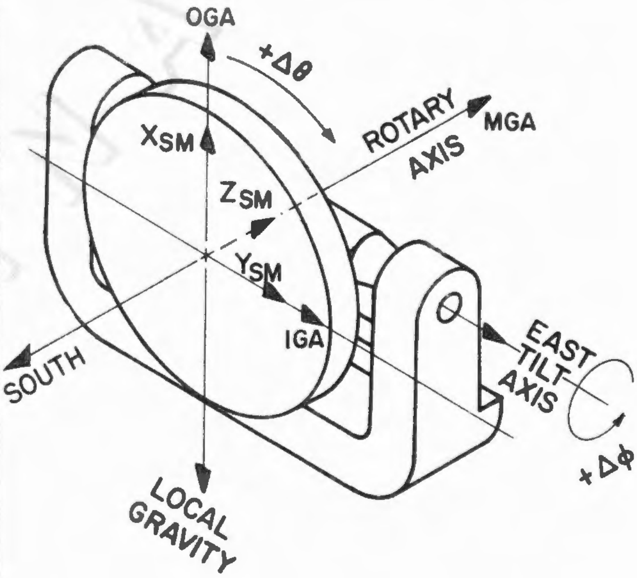
Second Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the Y PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_6



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\alpha_{B_Y} = \frac{\theta_6 - \theta_5 - 180°}{2}$$

If $\theta_5 < 360°$, use

$$\alpha_{B_Y} = \frac{\theta_6 - \theta_5 + 180°}{2}$$

JOB: PIPA ALIGNMENT TEST

JDC 35.0004 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{B_z}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 90°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

B. PROCEDURE

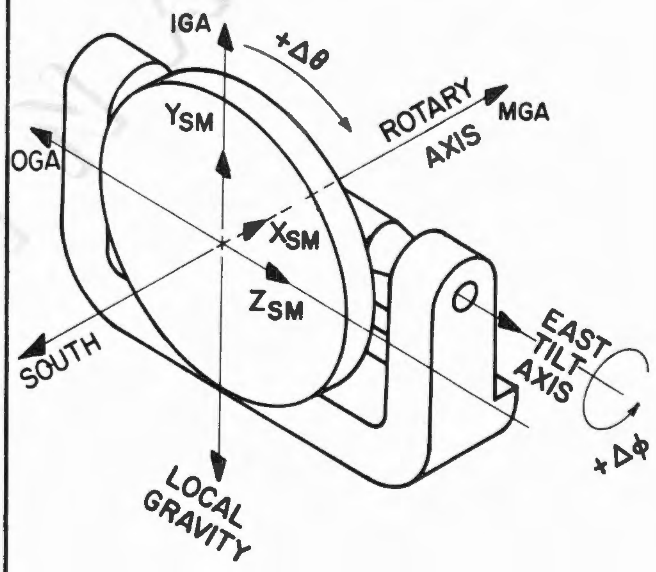
First Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the Z PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ



JOB: PIPA ALIGNMENT TEST	**JDC** 35.0004 Sheet 2 of 2
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Test to determine α_{B_Z}	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT:	

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 90°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = 270°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

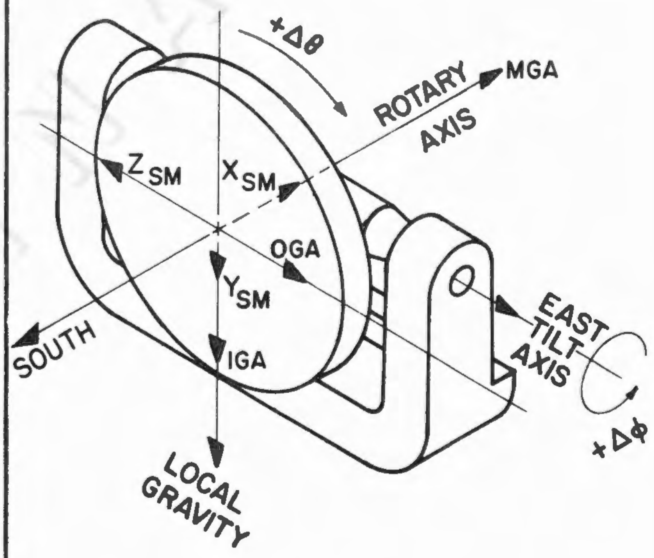
Second Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the Z PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_8



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\alpha_{B_Z} = \frac{\theta_7 - \theta_8 + 180°}{2}$$

JOB: PIPA ALIGNMENT TEST

JDC 35.0005 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine $\Phi_{r_{RA}}$

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0001 and JDC 35.0002 required to perform this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = 0°
   - c. Inner Gimbal Angle (A_{IG}) = 90°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = $\theta_{H_{OGA}}$

     Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

B. PROCEDURE

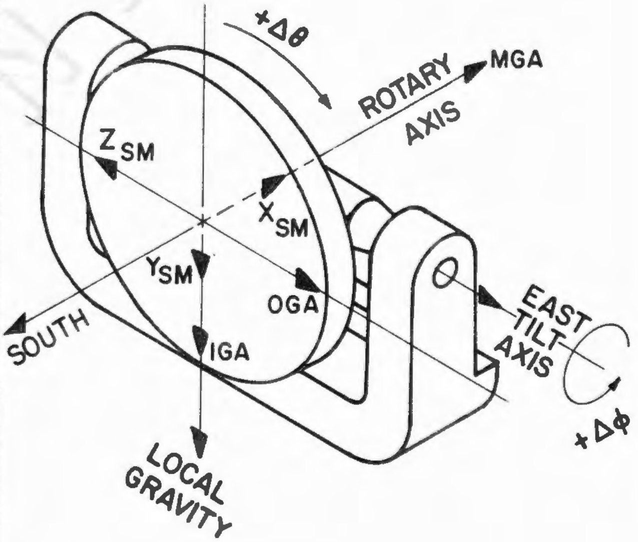
First Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the X PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Tilt Angle Φ_9



JOB: PIPA ALIGNMENT TEST	**JDC** 35.0005 Sheet 2 of 2
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Test to determine $\Phi_{H_{RA}}$	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT: Results from JDC 35.0001 and JDC 35.0002 required to perform this job.	

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = 0°
   - c. Inner Gimbal Angle (A_{IG}) = 90°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = 90°

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = $\theta_{H_{OGA}} + 180°$

     Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

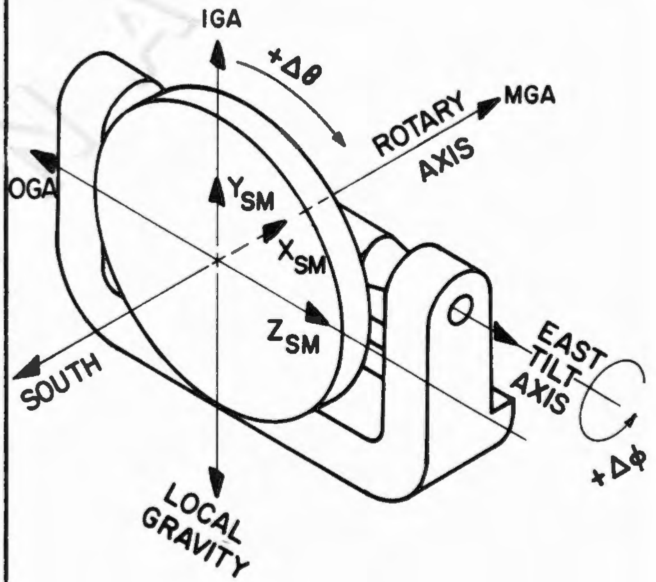
Second Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the X PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Tilt Angle Φ_{10}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\Phi_{H_{RA}} = \frac{\Phi_9 + \Phi_{10}}{2} + \alpha_{B_X}$$

Value of α_{B_X} obtained from JDC 35.0001 Data Sheet Form E-1230 DS-1.

JOB: PIPA ALIGNMENT TEST

JDC 35.0006 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine $\Phi_{H_{MGA}}$ and ϵ_{OGR}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002, JDC 35.0004, and JDC 35.0005 required to perform this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly
   a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   b. Middle Gimbal Angle (A_{MG}) = 0°
   c. Inner Gimbal Angle (A_{IG}) = 0°
2. Test Table
   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = $\Phi_{H_{RA}}$

      Value of $\Phi_{H_{RA}}$ obtained from JDC 35.0005 Data Sheet Form E-1230 DS-1.

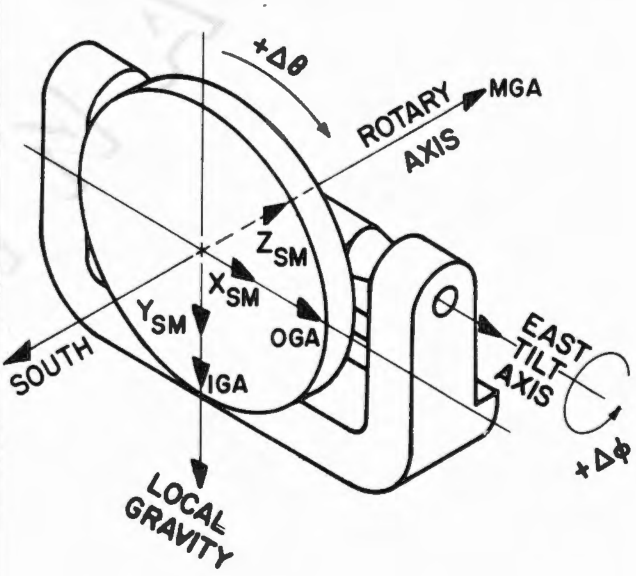
      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{OGA}}$

      Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.



B. PROCEDURE

First Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

1. Final Tilt Angle Φ_{11}
2. Final Rotary Angle θ_{11}

JOB: PIPA ALIGNMENT TEST

JDC 35.0006 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine $\Phi_{H_{MGA}}$ and ϵ_{OGR}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002, JDC 35.0004, and JDC 35.0005 required to perform this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = 180°
   - c. Inner Gimbal Angle (A_{IG}) = 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = $\Phi_{H_{RA}}$

     Value of $\Phi_{H_{RA}}$ obtained from JDC 35.0005 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = $\theta_{H_{OGA}}$

     Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

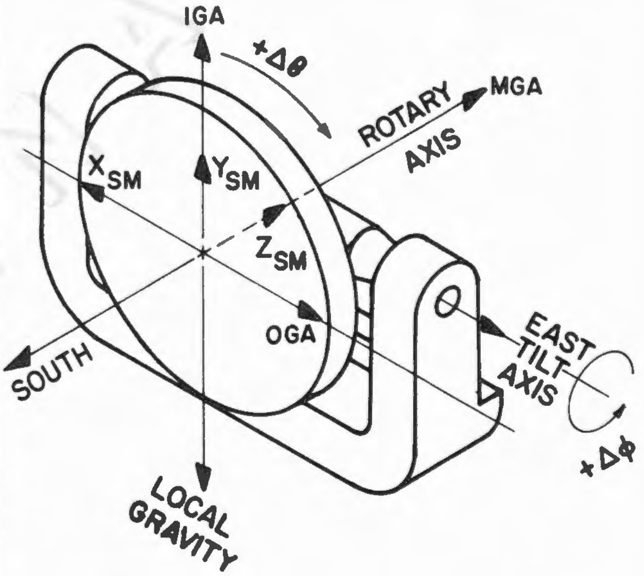
Second Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

F. RECORD

Use Data Sheet Form E-1230 to record:

1. Final Tilt Angle Φ_{12}
2. Final Rotary Angle θ_{12}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\Phi_{H_{MGA}} = \frac{\Phi_{11} + \Phi_{12}}{2} + \alpha_{B_Z}$$

$$\epsilon_{OGR} = \frac{\Phi_{11} + \Phi_{12}}{2} - \Phi_{H_{RA}} + \alpha_{B_Z} + \epsilon_{F_X}$$

Value of α_{B_Z} obtained from JDC 35.0004 Data Sheet Form E-1230 DS-1.

Value of ϵ_{F_X} obtained from fixture calibration.

JOB: PIPA ALIGNMENT TEST

JDC 35.0007 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Zero Adjustment of the Outer Gimbal Resolver

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0004, JDC 35.0005, and JDC 35.0006 required before performing this job.

A. PREPARATION

Orientations required:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = Precision 0°

   b. Middle Gimbal Angle (A_{MG}) = 0°

   c. Inner Gimbal Angle (A_{IG}) = 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = Φ_{11}

   Value of Φ_{11} obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = θ_{11}

   Value of θ_{11} obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.

The Z PIP should indicate a null. If not, repeat JDC 35.0006. If the repeat of JDC 35.0006 indicates that the value of ϵ_{OGR} has changed by ±8.0 sec, notify the responsible engineer.

B. PROCEDURE

1. Rotate test table about its TILT AXIS to:

   Desired Angle Designation (Φ_{11R}) = $\Phi_{11} - \epsilon_{OGR}$

   Value of Φ_{11} and ϵ_{OGR} obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.

2. Using "Zero Adjust" Potentiometer on the Outer Gimbal 16X Resolver, move the Outer Gimbal until the Z PIP again indicates a null.

JOB: PIPA ALIGNMENT TEST

JDC 35.0007 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Zero Adjustment of the Outer Gimbal Resolver

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0004, JDC 35.0005, and JDC 35.0006 required before performing this job.

C. PREPARATION

Orientations required:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = 180°
   - c. Inner Gimbal Angle (A_{IG}) = 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = Φ_{12}

     Value of Φ_{12} obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = θ_{12}

     Value of θ_{12} obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.

D. PROCEDURE

Secure Second Null Measurement from the Z PIP by rotating test table about its TILT AXIS.

E. RECORD

Use Data Sheet Form E-1230 DS-2 to record:

Final Tilt Angle Φ_{12R}

F. CHECK

Use Data Sheet Form E-1230 DS-2

1. Compute: $\frac{\Phi_{11R} + \Phi_{12R}}{2}$
2. Check the following equality:

   $$\frac{\Phi_{11R} + \Phi_{12R}}{2} = \Phi_{H_{RA}} - \alpha_{B_Z} - \epsilon_{F_X}$$ to be within ±8.0 $\widehat{\text{sec}}$.

   Value of $\Phi_{H_{RA}}$ obtained from JDC 35.0005 Data Sheet Form E-1230 DS-1.

   Value of α_{B_Z} obtained from JDC 35.0004 Data Sheet Form E-1230 DS-1.

   Value of ϵ_{F_X} obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.
3. If equality is not indicated, repeat JDC 35.0006 and JDC 35.0007.

JOB: PIPA ALIGNMENT TEST

JDC 35.0008 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine $\Phi'_{H_{MGA}}$

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002, JDC 35.0004, and JDC 35.0005 required before performing this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = Precision 0°

   b. Middle Gimbal Angle (A_{MG}) = 0°

   c. Inner Gimbal Angle (A_{IG}) = Precision 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = $\Phi_{H_{RA}}$

   Value of $\Phi_{H_{RA}}$ obtained from JDC 35.0005 Data Sheet Form E-1230 DS-1.

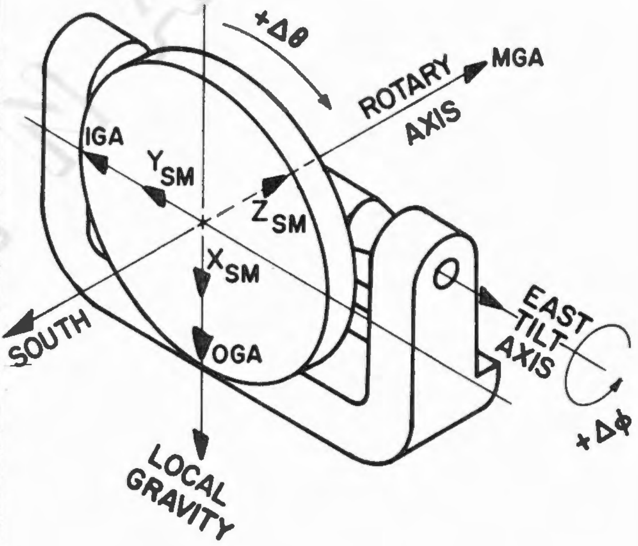
   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = $\theta_{H_{OGA}} + 90°$

   Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.



B. PROCEDURE

First Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Tilt Angle Φ_{13}

JOB: PIPA ALIGNMENT TEST

JDC 35.0008 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine $\Phi'_{H_{MGA}}$

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002, JDC 35.0004, and JDC 35.0005 required before performing this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = 180°
   - c. Inner Gimbal Angle (A_{IG}) = Precision 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = $\Phi_{H_{RA}}$

     Value of $\Phi_{H_{RA}}$ obtained from JDC 35.0005 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = $\theta_{H_{OGA}} + 90°$

     Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

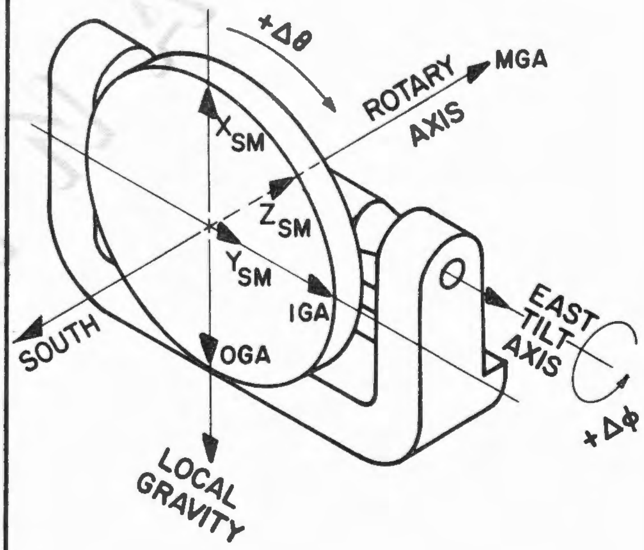
Second Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Tilt Angle Φ_{14}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\Phi'_{H_{MGA}} = \frac{\Phi_{13} + \Phi_{14}}{2} + \alpha_{B_Z}$$

Value of α_{B_Z} obtained from JDC 35.0004 Data Sheet Form E-1230 DS-1.

JOB: PIPA ALIGNMENT TEST

JDC 35.0009 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine ϵ_{MGA} and ϵ_{F_Y}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002, JDC 35.0004, and JDC 35.0005 required before performing this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = 180°

   b. Middle Gimbal Angle (A_{MG}) = 0°

   c. Inner Gimbal Angle (A_{IG}) = Precision 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = $\Phi_{H_{RA}}$

   Value of $\Phi_{H_{RA}}$ obtained from JDC 35.0005 Data Sheet Form E-1230 DS-1.

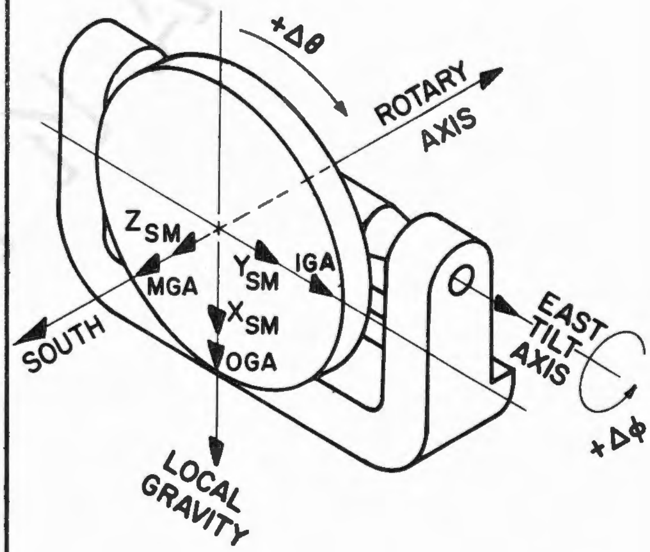
   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = $\theta_{H_{OGA}} + 90°$

   Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.



B. PROCEDURE

First Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Tilt Angle Φ_{15}

JOB: PIPA ALIGNMENT TEST

JDC 35.0009 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine ϵ_{MGA} and ϵ_{F_Y}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002, JDC 35.0004, and JDC 35.0005 required before performing this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = 180°

   b. Middle Gimbal Angle (A_{MG}) = 180°

   c. Inner Gimbal Angle (A_{IG}) = Precision 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = $\Phi_{H_{RA}}$

      Value of $\Phi_{H_{RA}}$ obtained from JDC 35.0005 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{OGA}} + 90°$

      Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

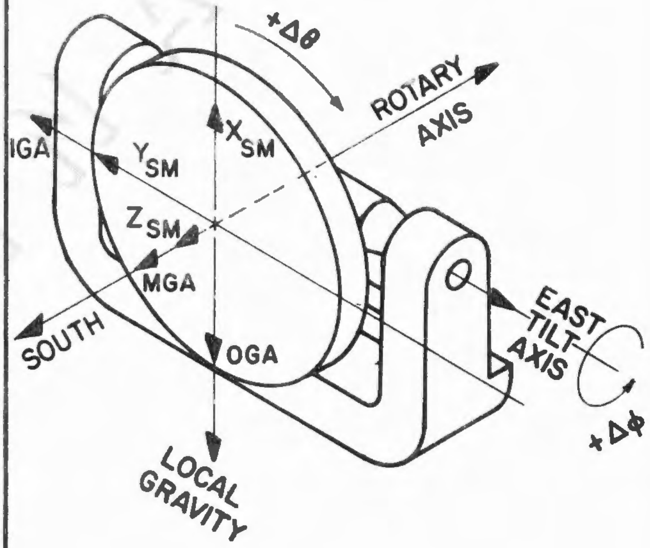
Second Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Tilt Angle Φ_{16}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\epsilon_{MGA} = \frac{(\Phi_{13} + \Phi_{14}) - (\Phi_{15} + \Phi_{16})}{4} + \alpha_{B_Z}$$

Value of α_{B_Z} obtained from JDC 35.0004 Data Sheet Form E-1230 DS-1.

$$\epsilon_{F_Y} = \frac{\Phi_{13} + \Phi_{14} + \Phi_{15} + \Phi_{16}}{4} - \Phi_{H_{RA}}$$

JOB: PIPA ALIGNMENT TEST

JDC 35.0010 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine ϵ_{MGR} and α_{X_Z}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0001, JDC 35.0002, and JDC 35.0006 required before performing this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = Precision 0°

   b. Middle Gimbal Angle (A_{MG}) = Precision 0°

   c. Inner Gimbal Angle (A_{IG}) = 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = $\Phi_{H_{MGA}}$

   Value of $\Phi_{H_{MGA}}$ obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

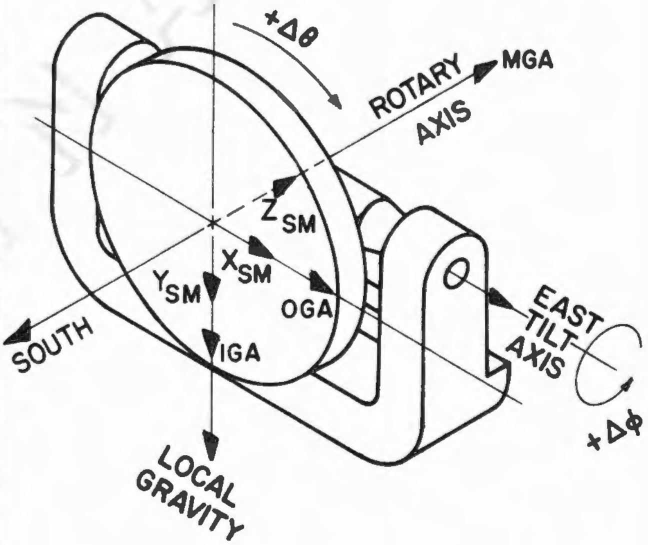
   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = $\theta_{H_{OGA}}$

   Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.



B. PROCEDURE

First Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the X PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

1. Final Tilt Angle Φ_{17}

2. Final Rotary Angle θ_{17}

JOB: PIPA ALIGNMENT TEST

JDC 35.0010 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine ϵ_{MGR} and α_{x_z}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0001, JDC 35.0002, and JDC 35.0006 required before performing this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 180°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = $\Phi_{H_{MGA}}$

     Value of $\Phi_{H_{MGA}}$ obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = $\theta_{H_{OGA}}$

     Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

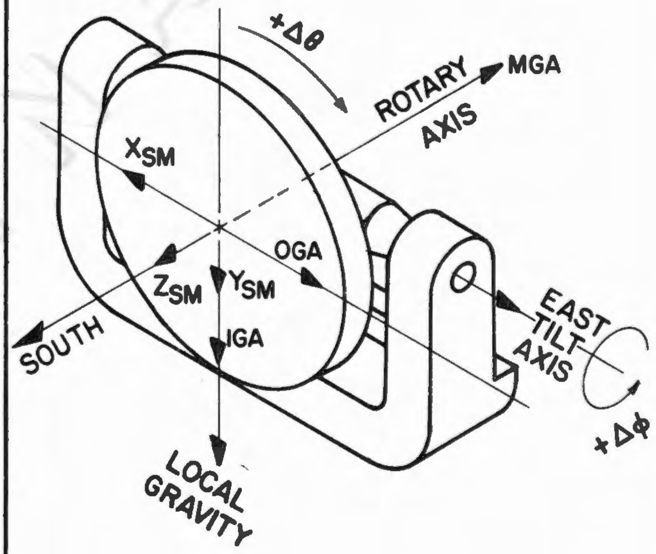
Second Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the X PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

1. Final Tilt Angle Φ_{18}
2. Final Rotary Angle θ_{18}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\epsilon_{MGR} = \frac{\theta_{17} + \theta_{18}}{2} - \theta_{H_{OGA}}$$

$$\alpha_{x_z} = \frac{\theta_{18} - \theta_{17}}{2} + \alpha_{B_x}$$

Value of α_{B_x} obtained from JDC 35.0001 Data Sheet Form E-1230 DS-1.

JOB: PIPA ALIGNMENT TEST	**JDC** 35.0011 Sheet 1 of 2
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Zero Adjustment of the Middle Gimbal Resolver and Test to determine $\theta_{H_{IGA}}$	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT: Results from JDC 35.0002 and JDC 35.0010 required before performing this job.	

A. PREPARATION

Orientations required:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = Φ_{17}

     Value of Φ_{17} obtained from JDC 35.0010 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = θ_{17}

     Value of θ_{17} obtained from JDC 35.0010 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.

   The X PIP should indicate a null. If not, repeat JDC 35.0010. If the repeat of JDC 35.0010 indicates that the value of ϵ_{MGR} has changed by ±7.0 sec, notify the responsible engineer.

B. PROCEDURE

1. Rotate test table about its ROTARY AXIS to:

   Desired Angle Designation (Φ_{17R}) = $\Phi_{17} - \epsilon_{MGR}$

   Value of Φ_{17} and ϵ_{MGR} obtained from JDC 35.0010 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.
2. Using "Zero Adjust" Potentiometer on the Inner Gimbal 16X Resolver, move the Inner Gimbal until the X PIP again indicates a null.

JOB:	PIPA ALIGNMENT TEST	**JDC** 35.0011	Sheet 2 of 2
SUBSYSTEM:	INERTIAL MEASUREMENT UNIT	**SYSTEM:**	AGE/
DESCRIPTION:	Zero Adjustment of the Middle Gimbal Resolver and Test to determine θ	**TYPE:** **INTERVAL:**	Alignment
TOOLS AND MATERIAL:		**REFERENCES:**	
IMPORTANT:	Results from JDC 35.0002 and JDC 35.0010 required before performing this job.		

D. PREPARATION

Orientations required:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 180°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = Φ_{18}

     Value of Φ_{18} obtained from JDC 35.0010 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = θ_{18}

     Value of θ_{18} obtained from JDC 35.0010 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.

E. PROCEDURE

Secure Second Null Measurement from the X PIP by rotating the test table about its ROTARY AXIS.

F. RECORD

Use Data Sheet Form E-1230 DS-2 to record:

Final Rotary Angle = θ_{18R}

G. CHECK

Use Data Sheet Form E-1230 DS-2

1. Compute: $\frac{\theta_{17R} + \theta_{18R}}{2}$
2. Check the following equality: $\frac{\theta_{17R} + \theta_{18R}}{2} = \theta_{H_{OGA}}$ to be within ±7.0 $\widehat{\text{sec}}$.

   Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.
3. If equality is not indicated, repeat JDC 35.0010 and JDC 35.0011.
4. Compute: $\theta_{H_{OGA}} = \frac{\theta_{17R} + \theta_{18R}}{2} - 90^\circ$

JOB: PIPA ALIGNMENT TEST

JDC 35.0012 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine ϵ_{IGA} and α_{Z_X}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0004, JDC 35.0006, and JDC 35.0011 required before performing this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = Precision 0°
   - b. Middle Gimbal Angle (A_{MG}) = 0°
   - c. Inner Gimbal Angle (A_{IG}) = 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = $\Phi_{H_{MGA}}$

     Value of $\Phi_{H_{MGA}}$ obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

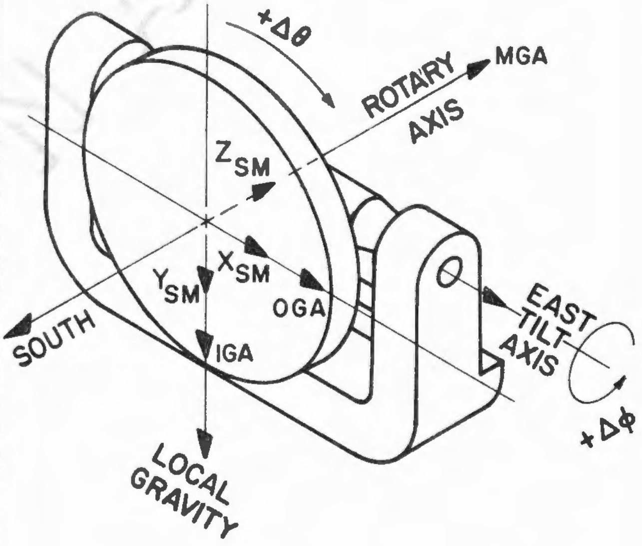
     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = $\theta_{H_{IGA}} + 90°$

     Value of $\theta_{H_{IGA}}$ obtained from JDC 35.0011 Data Sheet Form E-1230 DS-2.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.



B. PROCEDURE

First Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Tilt Angle Φ_{19}

JOB: PIPA ALIGNMENT TEST

JDC 35.0012 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine ϵ_{IGA} and α_{ZX}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0004, JDC 35.0006, and JDC 35.0011 required before performing this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = Precision 0°

   b. Middle Gimbal Angle (A_{MG}) = 0°

   c. Inner Gimbal Angle (A_{IG}) = 180°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = $\Phi_{H_{MGA}}$

   Value of $\Phi_{H_{MGA}}$ obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = $\theta_{H_{IGA}} + 90°$

   Value of $\theta_{H_{IGA}}$ obtained from JDC 35.0011 Data Sheet Form E-1230 DS-2.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

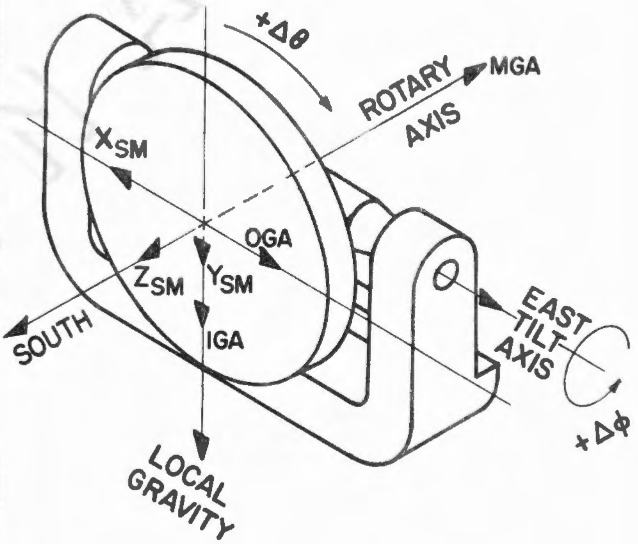
Second Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Tilt Angle Φ_{20}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\epsilon_{IGA} = \Phi_{H_{MGA}} - \frac{\Phi_{19} + \Phi_{20}}{2}$$

$$\alpha_{ZX} = \frac{\Phi_{20} - \Phi_{19}}{2} - \alpha_{B_Z}$$

Value of α_{B_Z} obtained from JDC 35.0004 Data Sheet Form E-1230 DS-1.

JOB: PIPA ALIGNMENT TEST

JDC 35.0013 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine ϵ_{IGR}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0008 and JDC 35.0011 required before performing this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = 0°

   b. Middle Gimbal Angle (A_{MG}) = 0°

   c. Inner Gimbal Angle (A_{IG}) = Precision 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = $\Phi'_{H_{MGA}}$

   Value of $\Phi'_{H_{MGA}}$ obtained from JDC 35.0008 Data Sheet Form E-1230 DS-1.

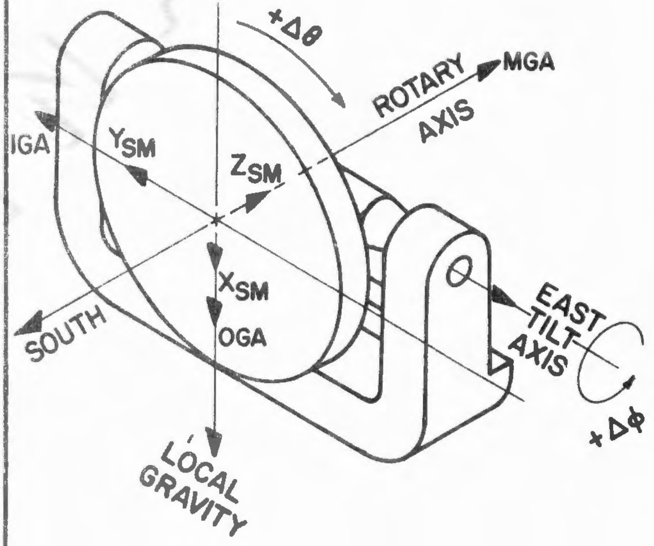
   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = $\theta_{H_{IGA}} - 180°$

   Value of $\theta_{H_{IGA}}$ obtained from JDC 35.0011 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.



B. PROCEDURE

First Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

1. Final Tilt Angle Φ_{21}

2. Final Rotary Angle θ_{21}

JOB: PIPA ALIGNMENT TEST

JDC 35.0013 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine ϵ_{IGR}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0008 and JDC 35.0011 required before performing this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   a. Outer Gimbal Angle (A_{OG}) = 0°
   b. Middle Gimbal Angle (A_{MG}) = 180°
   c. Inner Gimbal Angle (A_{IG}) = Precision 0°
2. Test Table
   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = $\Phi'_{H_{MGA}}$

      Value of $\Phi'_{H_{MGA}}$ obtained from JDC 35.0008 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{IGA}} - 180°$

      Value of $\theta_{H_{IGA}}$ obtained from JDC 35.0011 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

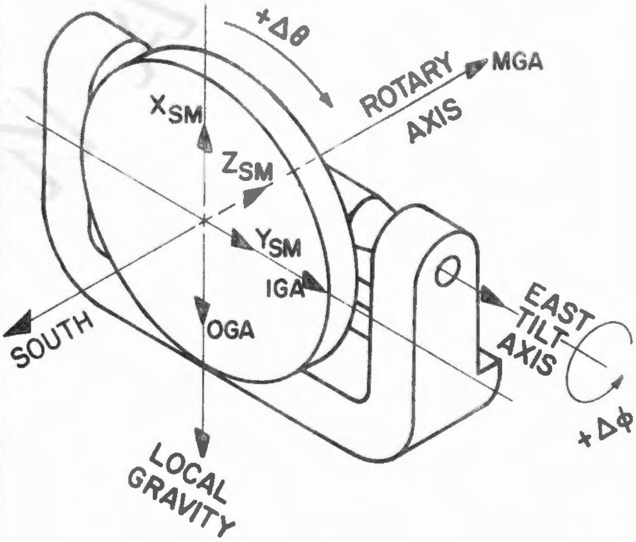
Second Null Measurement

Rotate the table about the TILT AXIS until a null is obtained from the Z PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

1. Final Tilt Angle Φ_{22}
2. Final Rotary Angle θ_{22}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\epsilon_{IGR} = \frac{\Phi_{22} - \Phi_{21}}{2}$$

JOB: PIPA ALIGNMENT TEST	**JDC** 35.0014 Sheet 1 of 2
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Zero Adjustment of the Inner Gimbal Resolver	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT: Results from JDC 35.0009 and JDC 35.0013 required before performing this job.	

A. PREPARATION

Orientations required:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = 0°
   - b. Middle Gimbal Angle (A_{MG}) = 0°
   - c. Inner Gimbal Angle (A_{IG}) = Precision 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = Φ_{21}

     Value of Φ_{21} obtained from JDC 35.0013 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = θ_{21}

     Value of θ_{21} obtained from JDC 35.0013 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.

The Z PIP should indicate a null. If not, repeat JDC 35.0013. If the repeat of JDC 35.0013 indicates that the value of ϵ_{IGR} has changed by ±4.0 sec, notify the responsible engineer.

B. PROCEDURE

1. Rotate test table about its TILT AXIS to:

   Desired Angle Designation (Φ_{21R}) = $\Phi_{21} + \epsilon_{IGR} - \epsilon_{MGA}$

   Value of Φ_{21} and ϵ_{IGR} obtained from JDC 35.0013 Data Sheet Form E-1230 DS-1.

   Value of ϵ_{MGA} obtained from JDC 35.0009 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.
2. Using "Zero Adjust" Potentiometer on the Inner Gimbal 16X Resolver, move the Inner Gimbal until the Z PIP again indicates a null.

JOB: PIPA ALIGNMENT TEST

JDC 35.0014 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Zero Adjustment of the Inner Gimbal Resolver

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0009 and JDC 35.0013 required before performing this job.

D. PREPARATION

Orientations required:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = 0°
   - b. Middle Gimbal Angle (A_{MG}) = 180°
   - c. Inner Gimbal Angle (A_{IG}) = Precision 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = Φ_{22}

     Value of Φ_{22} obtained from JDC 35.0013 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = θ_{22}

     Value of θ_{22} obtained from JDC 35.0013 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-2.

E. PROCEDURE

Secure Second Null Measurement from the Z PIP by rotating test table about its TILT AXIS.

F. RECORD

Use Data Sheet Form E-1230 DS-2 to record:

Final Tilt Angle = Φ_{22R}

G. CHECK

Use Data Sheet Form E-1230 DS-2:

1. Compute: $\frac{\Phi_{22R} \pm \Phi_{21R}}{2} - \epsilon_{M3A}$

   and check that it does not exceed ±5.0 $\widehat{\text{sec}}$.

   Value of ϵ_{MGA} obtained from JDC 35.0009 Data Sheet Form E-1230 DS-1.

2. If the result of this check exceeds ±5.0 $\widehat{\text{sec}}$, repeat JDC 35.0013 and JDC 35.0014.

JOB: PIPA ALIGNMENT TEST

JDC 35.0015 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{YZ}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0008 and JDC 35.0011 required before performing this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = 0°

   b. Middle Gimbal Angle (A_{MG}) = Precision 0°

   c. Inner Gimbal Angle (A_{IG}) = 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = $\Phi'_{H_{MGA}}$

      Value of $\Phi'_{H_{MGA}}$ obtained from JDC 35.0008 Data Sheet Form E-1230 DS-1.

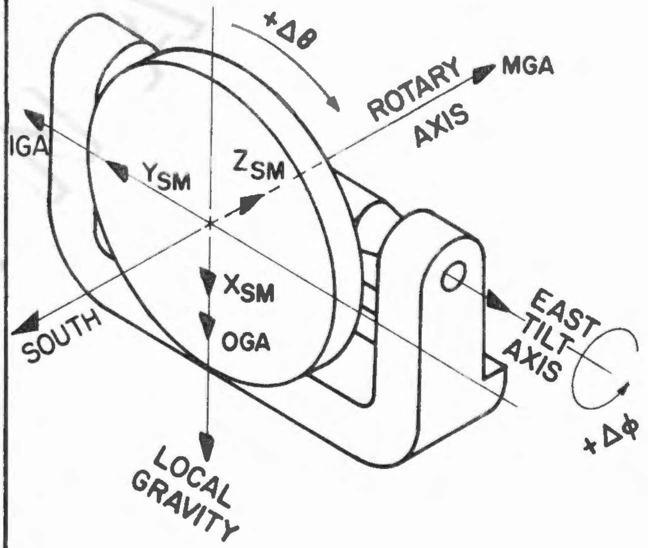
      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{IGA}}$ - 180°

      Value of $\theta_{H_{IGA}}$ obtained from JDC 35.0011 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.



B. PROCEDURE

First Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the Y PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_{23}

JOB: PIPA ALIGNMENT TEST

JDC 35.0015 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{Y_Z}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0008 and JDC 35.0011 required before performing this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = 0°
   - b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   - c. Inner Gimbal Angle (A_{IG}) = 180°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = $\Phi'_{H_{MGA}}$

     Value of $\Phi'_{H_{MGA}}$ obtained from JDC 35.0008 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = $\theta_{H_{IGA}} - 180°$

     Value of $\theta_{H_{IGA}}$ obtained from JDC 35.0011 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

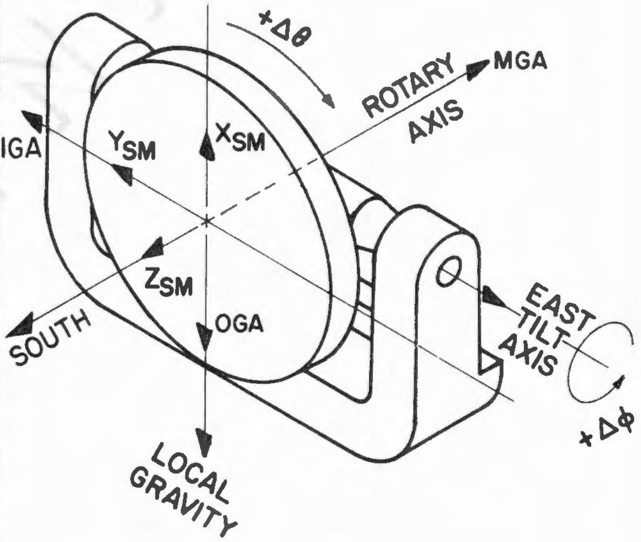
Second Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the Y PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_{24}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\alpha_{Y_Z} = \frac{\theta_{24} - \theta_{23}}{2}$$

JOB: PIPA ALIGNMENT TEST

JDC 35.0016 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{Y_X}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0008 and JDC 35.0011 required before performing this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = 0°

   b. Middle Gimbal Angle (A_{MG}) = Precision 0°

   c. Inner Gimbal Angle (A_{IG}) = 90°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = $\Phi'_{H_{MGA}}$

   Value of $\Phi'_{H_{MGA}}$ obtained from JDC 35.0008 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = $\theta_{H_{IGA}} - 180°$

   Value of $\theta_{H_{IGA}}$ obtained from JDC 35.0011 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

B. PROCEDURE

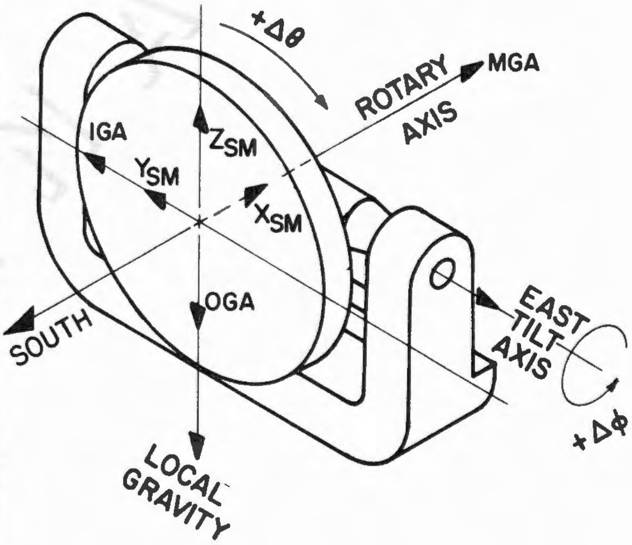
First Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the Y PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_{25}



JOB: PIPA ALIGNMENT TEST

JDC 35.0016 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{Y_X}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0008 and JDC 35.0011 required before performing this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   a. Outer Gimbal Angle (A_{OG}) = 0°
   b. Middle Gimbal Angle (A_{MG}) = Precision 0°
   c. Inner Gimbal Angle (A_{IG}) = 270°
2. Test Table
   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = $\Phi'_{H_{MGA}}$

      Value of $\Phi'_{H_{MGA}}$ obtained from JDC 35.0008 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{IGA}} - 180°$

      Value of $\theta_{H_{IGA}}$ obtained from JDC 35.0011 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

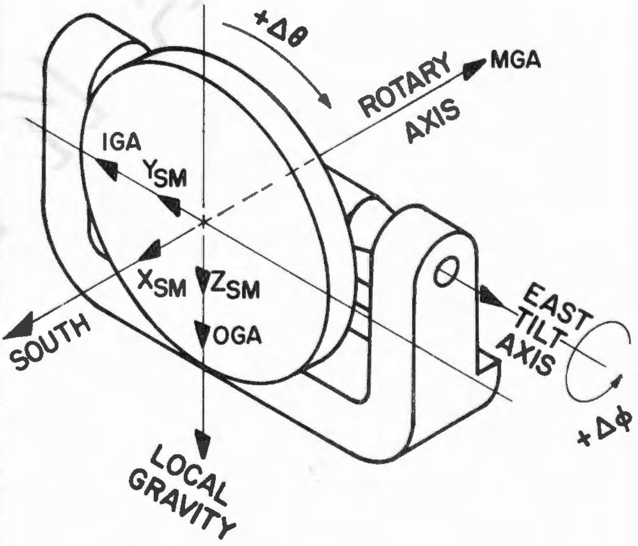
Second Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the Y PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_{26}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\alpha_{Y_X} = \frac{\theta_{26} - \theta_{25}}{2}$$

JOB: PIPA ALIGNMENT TEST

JDC 35.0017 Sheet 1 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{x_Y}.

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0001, JDC 35.0002, and JDC 35.0006 required before performing this job.

A. PREPARATION

Orientations required for first null measurement:

1. Gimbal Assembly

   a. Outer Gimbal Angle (A_{OG}) = 90°

   b. Middle Gimbal Angle (A_{MG}) = 0°

   c. Inner Gimbal Angle (A_{IG}) = Precision 0°

2. Test Table

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = $\Phi_{H_{MGA}}$

   Value of $\Phi_{H_{MGA}}$ obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

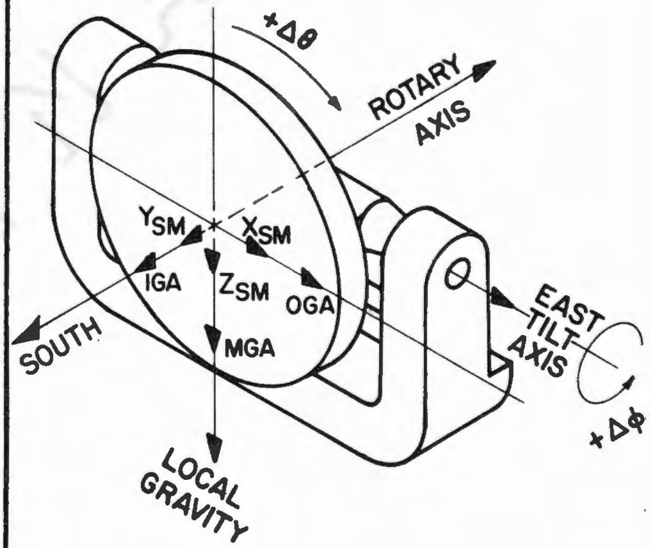
   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = $\theta_{H_{OGA}}$

   Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.



B. PROCEDURE

First Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the X PIP.

C. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_{27}

JOB: PIPA ALIGNMENT TEST

JDC 35.0017 Sheet 2 of 2

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Test to determine α_{X_Y}

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0001, JDC 35.0002, and JDC 35.0006 required before performing this job.

D. PREPARATION

Orientations required for second null measurement:

1. Gimbal Assembly
   - a. Outer Gimbal Angle (A_{OG}) = 90°
   - b. Middle Gimbal Angle (A_{MG}) = 180°
   - c. Inner Gimbal Angle (A_{IG}) = Precision 0°
2. Test Table
   - a. Initial Tilt Angle (Φ)

     Desired Angle Designation = $\Phi_{H_{MGA}}$

     Value of $\Phi_{H_{MGA}}$ obtained from JDC 35.0006 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.
   - b. Initial Rotary Angle (θ)

     Desired Angle Designation = $\theta_{H_{OGA}}$

     Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

     NOTE: Record Value, Indicator Error, and Readout Angle on Data Sheet Form E-1230 DS-1.

E. PROCEDURE

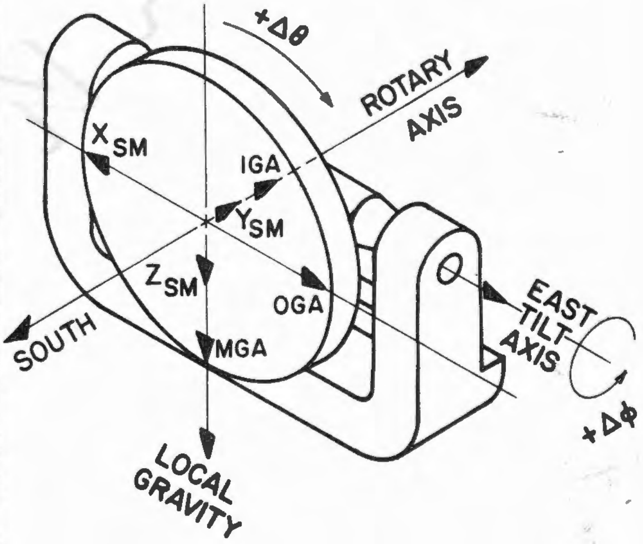
Second Null Measurement

Rotate the table about the ROTARY AXIS until a null is obtained from the X PIP.

F. RECORD

Use Data Sheet Form E-1230 DS-1 to record:

Final Rotary Angle θ_{28}



G. CALCULATIONS

Perform the following calculations using Data Sheet Form E-1230 DS-1:

$$\alpha_{X_Y} = \frac{\theta_{27} - \theta_{28}}{2} - \alpha_{B_X}$$

Value of α_{B_X} obtained from JDC 35.0001 Data Sheet Form E-1230 DS-1.

JOB: X IRIG ALIGNMENT TEST

JDC 35.0020 Sheet 1 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 1. Calibration of Input Angle to Preamp Voltage Output: S_x

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

A. PREPARATION

1. Test Table Orientations

   Set:

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = (λ) Local Latitude

   NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

   Initial Rotary Angle (θ) = 0°

2. Gimbal Assembly

   Set:

   a. Outer Gimbal Angle (A_{OG}) = Precision 0°

   b. Middle Gimbal Angle (A_{MG}) = Precision 0°

   c. Inner Gimbal Angle (A_{IG}) = 90°

3. IRIG Preamp

   Route X IRIG Preamp Output to PAVM.

B. PROCEDURE

1. Null X IRIG with manual pulses; shift PAVM scales as required.
2. Reset IRIG bias with two positive pulses; select PAVM 10-volt scale.
3. Set in following Rotary Angles; read within 30 seconds (time) the PAVM outputs, and record results on Data Sheet Form E-1230 DS-3 in order given:

   Set $\theta = +15'00''$ Read and record e_{x1} in (+) mv.

   Set $\theta = -15'00''$ Read and record e_{x2} in (-) mv.

   Return to $\theta = 0°$ and renull.

   Set $\theta = +15'00''$ Read and record e_{x3} in (+) mv.

   Set $\theta = -15'00''$ Read and record e_{x4} in (-) mv.

   Return to $\theta = 0°$ and renull.

   Set $\theta = +15'00''$ Read and record e_{x5} in (+) mv.

   Set $\theta = -15'00''$ Read and record e_{x6} in (-) mv.

   Return to $\theta = 0°$.

4. Compute and record $e_{+avg.}$ and $e_{-avg.}$ on Data Sheet Form E-1230 DS-3.

$$e_{+avg.} = \frac{e_{x1} + e_{x3} + e_{x5}}{3} \text{ mv}$$

$$e_{-avg.} = \frac{e_{x2} + e_{x4} + e_{x6}}{3} \text{ mv}$$

JOB: X IRIG ALIGNMENT TEST	**JDC** 35.0020 Sheet 2 of 6
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Part 1. Calibration of Input Angle to Preamp Voltage Output: S_x	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT:	

C. LINEARITY CHECK

1. Renull and set in following Rotary Angles; read the P/ VM outputs, and record results on Data Sheet Form E-1230 DS-3 in order given:

   Set $\theta = +10'00''$ Read and record e_{x7} in (+) mv.

   Set $\theta = -10'00''$ Read and record e_{x8} in (-) mv.

   Return to $\theta = 0°$ and renull.

   Set $\theta = +5'00''$ Read and record e_{x9} in (+) mv.

   Set $\theta = -5'00''$ Read and record e_{x10} in (-) mv.

   Return to $\theta = 0°$.

2. Compute and record on Data Sheet Form E-1230 DS-3:

   $$\frac{e_{x7}}{e_{+avg.}} \text{ and } -\frac{e_{x8}}{e_{-avg.}}$$

   Plot results on Data Sheet Form E-1230 DS-3 Linearity Plot.

3. Determine that:

   $$\frac{\left(\frac{e_{x7}}{e_{+avg.}}\right)}{\frac{2}{3}} = \frac{-\left(\frac{e_{x8}}{e_{-avg.}}\right)}{-\frac{2}{3}} = 1.00 \pm 0.01$$

4. Compute and record on Data Sheet Form E-1230 DS-3:

   $$\frac{e_{x9}}{e_{+avg.}} \text{ and } -\frac{e_{x10}}{e_{-avg.}}$$

   Plot results on Data Sheet Form E-1230 DS-3 Linearity Plot.

5. Determine that:

   $$\frac{\left(\frac{e_{x9}}{e_{+avg.}}\right)}{\frac{1}{3}} = \frac{-\left(\frac{e_{x10}}{e_{-avg.}}\right)}{-\frac{1}{3}} = 1.00 \pm 0.01$$

D. SENSITIVITY COMPUTATION

1. Use Data Sheet Form E-1230 DS-3 to compute Sensitivity.

   $$S_x = \frac{e_{+avg.} - e_{-avg.}}{8.727} \frac{mv}{mr}$$

2. Measure and record on Data Sheet Form E-1230 DS-3:

   a. Precision 3200-cps excitation voltage in mv.

   b. IRIG temperature deviation in °F.

JOB: X IRIG ALIGNMENT TEST

JDC 35.0020 Sheet 3 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 2. Measuring γ_{x_Y} by Rotation About X IRIG Output Axis

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002 are required before performing this job. JDC 35.0014 must also be performed.

A. PREPARATION

1. Test Table Orientations

   Set:

   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = (λ) Local Latitude

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{OGA}}$

      Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

2. Gimbal Assembly

   Gimbal orientation by using CDU's in "Coarse Align" Mode and "Precision Zero Set" where indicated by asterisk (*).

   a. Outer Gimbal Angle (A_{OG}) = 270°

   b. Middle Gimbal Angle (A_{MG}) = 0°

   c. Inner Gimbal Angle (A_{IG}) = 0°*

3. Ground Support Equipment Setup

   Set Middle Gimbal CDU in "Manual Align" Mode for operation by slew switch.

B. PROCEDURE

1. Null X IRIG with manual pulses; shift the PAVM scales as required.
2. Reset IRIG bias with two positive pulses; select PAVM 10-volt scale.
3. Use Middle Gimbal CDU slew switch to rotate the Middle Gimbal in a positive direction to A_{MG} equals 90° ±1°.

   NOTE: Do not use thumbwheel to set in an exact number for end of test.
   Take final reading upon stopping.

4. Within 60 seconds (time) of completing the slew position command (Step B3), read and record on Data Sheet E-1230 DS-3:

   a. e_{x11} in mv, shifting scales as necessary on the PAVM.

   b. A_{x1} in decimal degrees from the Middle Gimbal CDU.

5. Using the slew switch, reposition the Middle Gimbal Angle CDU to zero within the accuracy of the thumbwheel.

JOB: X IRIG ALIGNMENT TEST

JDC 35.0020 Sheet 4 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 2. Measuring γ_{x_Y} by Rotation About X IRIG Output Axis

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002 are required before performing this job. JDC 35.0014 must also be performed.

B PROCEDURE (continued)

6. Repeat Step B1.
7. Repeat Step B2.
8. Use Middle Gimbal CDU slew switch to rotate the Middle Gimbal in a negative direction to A_{MG} equals -90° ±1°.

   NOTE: Do not use thumbwheel to set in an exact number for end of test.
   Take final reading upon stopping.

9. Within 60 seconds (time) of completing slew position command (Step B8), read and record on Data Sheet E-1230 DS-3:
   - a. e_{x12} in mv, shifting scales as necessary on the PAVM.
   - b. A_{x2} in decimal degrees from the Middle Gimbal CDU.
10. Repeat Steps B1 through B9. Read and record:
    - a. From Step B4: e_{x13} in mv
      A_{x3} in decimal degrees
    - b. From Step B9: e_{x14} in mv
      A_{x4} in decimal degrees
11. Repeat Steps B1 through B9. Read and record:
    - a. From Step B4: e_{x15} in mv
      A_{x5} in decimal degrees
    - b. From Step B9: e_{x16} in mv
      A_{x6} in decimal degrees

C. COMPUTATION OF γ_{x_Y}

1. Compute $R_{+avg.}$ and $R_{-avg.}$ on Data Sheet Form E-1230 DS-3:

$$R_{+avg.} = \frac{\frac{e_{x11}}{A_{x1}} + \frac{e_{x13}}{A_{x3}} + \frac{e_{x15}}{A_{x5}}}{3} \qquad R_{-avg.} = -\frac{\frac{e_{x12}}{A_{x2}} + \frac{e_{x14}}{A_{x4}} + \frac{e_{x16}}{A_{x6}}}{3}$$

2. Compute γ'_{x_Y} on Data Sheet Form E-1230 DS-3:

$$\gamma'_{x_Y} = \frac{R_{+avg.} - R_{-avg.}}{2} \times \frac{57.29577}{S} \text{ mr}$$

3. Compute γ_{x_Y} on Data Sheet Form E-1230 DS-3:

$$\gamma_{x_Y} = (\gamma'_{x_Y} + \epsilon_{IGR}) = \gamma'_{x_Y}$$ because the Inner Gimbal Resolver has been adjusted.

4. Measure and record on Data Sheet Form E-1230 DS-3:
   - a. Precision in 3200-cps excitation voltage in mv.
   - b. IRIG temperature deviation in °F.

JOB: X IRIG ALIGNMENT TEST

JDC 35.0020 Sheet 5 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 3. Measuring γ_{x_z} by Rotation About X IRIG Spin Reference Axis

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from Gyro Data Sheet Form ______ and JDC 35.0002 are required before performing this job.

A. PREPARATION

1. Test Table Orientations

   Set:

   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = (λ) Local Latitude

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{OGA}} \pm 180^\circ$

      Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

2. Gimbal Assembly

   Gimbal orientations by using CDU's in "Coarse Align" Mode and "Precision Zero Set" where indicated by asterisk (*).

   a. Outer Gimbal Angle (A_{OG}) = 0°*

   b. Middle Gimbal Angle (A_{MG}) = 0°*

   c. Inner Gimbal Angle (A_{IG}) = 0°

3. Ground Support Equipment Setup

   Place Inner Gimbal CDU in "Manual Align" Mode for operation by the slew switch.

B. PROCEDURE

1. Null X IRIG with manual pulses; shift PAVM scales as required.
2. Reset IRIG bias with two positive pulses; select PAVM 10-volt scale.
3. Using Inner Gimbal CDU slew switch, rotate the Inner Gimbal in a positive direction to A_{IG} equals 270° ±1°.
4. Within 60 seconds (time) of completing the slew position command (Step B3), read and record e_{x17} in mv on Data Sheet Form E-1230 DS-3, shifting scales as necessary on the PAVM.
5. Using the slew switch, reposition the Inner Gimbal Angle CDU to zero within accuracy of the thumbwheel.
6. Repeat Steps B1 through B5, reading and recording e_{x18} in mv on Data Sheet Form E-1230 DS-3.
7. Repeat Steps B1 through B5, reading and recording e_{x19} in mv on Data Sheet Form E-1230 DS-3.

JOB: X IRIG ALIGNMENT TEST	**JDC** 35.0020 Sheet 6 of 6
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Part 3. Measuring γ_{x_z} by Rotation About X IRIG Spin Reference Axis	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT: Results from Gyro Data Sheet Form ______ and JDC 35.0002 are required before performing this job.	

C. COMPUTATION OF γ_{x_z}

1. Compute $e_{avg.}$ on Data Sheet Form E-1230 DS-3.

$$e_{avg.} = \frac{e_{x17} + e_{x18} + e_{x19}}{3} \text{ mv}$$

2. Determine $\frac{H}{C}$ from Gyro Data Sheet Form ______, and record on Data Sheet Form E-1230 DS-3.

3. Compute γ_{x_z} on Data Sheet Form E-1230 DS-3.

$$\gamma_{x_z} = -\frac{e_{avg.}}{\frac{H}{C} S} \text{ mr}$$

4. Measure and record on Data Sheet Form E-1230 DS-3:
   a. Precision 3200-cps excitation voltage in mv.
   b. IRIG temperature deviation in °F.

JOB: Y IRIG ALIGNMENT TEST

JDC 35.0021 Sheet 1 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 1. Calibration of Input Angle to Preamp Voltage Output S_Y

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

A. PREPARATION

1. Test Table Orientations

   Set:

   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = (λ) Local Latitude

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

      Initial Rotary Angle (θ) = 0°

2. Gimbal Assembly

   Set:

   a. Outer Gimbal Angle (A_{OG}) = 270°

   b. Middle Gimbal Angle (A_{MG}) = Precision 0°

   c. Inner Gimbal Angle (A_{IG}) = Precision 0°

3. IRIG Preamp

   Route Y IRIG Preamp Out to PAVM.

B. PROCEDURE

1. Null Y IRIG with manual pulses; shift PAVM scales as required.
2. Reset IRIG bias with two positive pulses; select PAVM 10-volt scale.
3. Set in following Rotary Angles; read within 30 seconds (time) the PAVM outputs, and record results on Data Sheet Form E-1230 DS-3 in order given:

   Set θ = +15'00" Read and record e_{Y1} in (+) mv.
   Set θ = -15'00" Read and record e_{Y2} in (-) mv.

   Return to θ = 0° and renull.

   Set θ = +15'00" Read and record e_{Y3} in (+) mv.
   Set θ = -15'00" Read and record e_{Y4} in (-) mv.

   Return to θ = 0° and renull.

   Set θ = +15'00" Read and record e_{Y5} in (+) mv.
   Set θ = -15'00" Read and record e_{Y6} in (-) mv.

   Return to θ = 0°.

4. Compute $e_{+avg.}$ and $e_{-avg.}$ on Data Sheet Form E-1230 DS-3:

$$e_{+avg.} = \frac{e_{Y1} + e_{Y3} + e_{Y5}}{3} \text{ mv}$$

$$e_{-avg.} = \frac{e_{Y1} + e_{Y4} + e_{Y6}}{3} \text{ mv}$$

JOB: Y IRIG ALIGNMENT TEST

JDC 35.0021 Sheet 2 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 1. Calibration of Input Angle to Preamp Voltage Output S_Y

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

C. LINEARITY CHECK

1. Renull and set in following Rotary Angles; read the PAVM outputs, and record results on Data Sheet Form E-1230 DS-3 in order given:

   Set θ = +10'00" Read and record e_{Y7} in (+) mv.

   Set θ = -10'00" Read and record e_{Y8} in (-) mv.

   Return to θ = 0° and renull.

   Set θ = +5'00" Read and record e_{Y9} in (+) mv.

   Set θ = -5'00" Read and record e_{Y10} in (-) mv.

   Return to θ = 0°.

2. Compute on Data Sheet Form E-1230 DS-3:

   $$\frac{e_{Y7}}{e_{+avg.}} \quad \text{and} \quad -\frac{e_{Y8}}{e_{-avg.}}$$

   Plot results on Data Sheet Form E-1230 DS-3 Linearity Plot.

3. Determine that:

   $$\frac{\left(\frac{e_{Y7}}{e_{+avg.}}\right)}{\frac{2}{3}} = \frac{-\left(\frac{e_{Y8}}{e_{-avg.}}\right)}{-\frac{2}{3}} = 1.00 \pm 0.01$$

4. Compute on Data Sheet Form E-1230 DS-3:

   $$\frac{e_{Y9}}{e_{+avg.}} \quad \text{and} \quad -\frac{e_{Y10}}{e_{-avg.}}$$

   Plot results on Data Sheet Form E-1230 DS-3 Linearity Plot.

5. Determine that:

   $$\frac{\left(\frac{e_{Y9}}{e_{+avg.}}\right)}{\frac{1}{3}} = \frac{-\left(\frac{e_{Y10}}{e_{-avg.}}\right)}{-\frac{1}{3}} = 1.00 \pm 0.01$$

D. SENSITIVITY COMPUTATION

1. Use Data Sheet Form E-1230 DS-3 to compute Sensitivity.

   $$S_Y = \frac{e_{+avg.} - e_{-avg.}}{8.727} \quad \frac{mv}{mr}$$

2. Measure and record on Data Sheet Form E-1230 DS-3:

   a. Precision 3200-cps excitation voltage in mv.

   b. IRIG temperature deviation in °F.

JOB: Y IRIG ALIGNMENT TEST

JDC 35.0021 Sheet 3 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 2. Measuring γ_{Y_Z} by Rotation About Y IRIG Output Axis

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002 are required before performing this job. JDC 35.0011 must also be performed.

A. PREPARATION

1. Test Table Orientations

Set:

a. Initial Tilt Angle (Φ)

Desired Angle Designation = (λ) Local Latitude

NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

b. Initial Rotary Angle (θ)

Desired Angle Designation = $\theta_{H_{OGA}} - 90°$

Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

2. Gimbal Assembly

Gimbal orientation by using CDU's in "Coarse Align" Mode and "Precision Zero Set" where indicated by asterisk (*).

a. Outer Gimbal Angle (A_{OG}) = 0°

b. Middle Gimbal Angle (A_{MG}) = 0°*

c. Inner Gimbal Angle (A_{IG}) = 0°*

3. Ground Support Equipment Setup

Set Outer Gimbal CDU in "Manual Align" Mode for operation by slew switch.

B. PROCEDURE

1. Null Y IRIG with manual pulses; shift the PAVM scales as required.
2. Reset IRIG bias with two positive pulses; select PAVM 10-volt scale.
3. Use Outer Gimbal CDU slew switch to rotate the Outer Gimbal in a positive direction to A_{OG} equals 90° ±1°.

   NOTE: Do not use thumbwheel to set in an exact number for end of test.
   Take final reading upon stopping.

4. Within 60 seconds (time) of completing the slew position command (Step B3), read and record on Data Sheet Form E-1230 DS-3:

   a. e_{X11} in mv, shifting scales as necessary on the PAVM.

   b. A_{X1} in decimal degrees from the Outer Gimbal CDU.

5. Using the slew switch, reposition the Outer Gimbal Angle CDU to zero within the accuracy of the thumbwheel.

JOB: Y IRIG ALIGNMENT TEST	**JDC** 35.0021 Sheet 4 of 6
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Part 2. Measuring γ_{Y_Z} by Rotation About Y IRIG Output Axis	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT: Results from JDC 35.0002 are required before performing this job. JDC 35.0011 must also be performed.	

B. PROCEDURE (continued)

6. Repeat Step B1.
7. Repeat Step B2.
8. Use Outer Gimbal CDU slew switch to rotate the Outer Gimbal in a negative direction to A_{OG} equals -90° ±1°.

   NOTE: Do not use thumbwheel to set in an exact number for end of test.
   Take final reading upon stopping.

9. Within 60 seconds (time) of completing slew position command (Step B8), read and record on Data Sheet Form 1230 DS-3:
   a. e_{X12} in mv, shifting scales as necessary on the PAVM.
   b. A_{X2} in decimal degrees from the Outer Gimbal CDU.
10. Repeat Steps B1 through B9. Read and record:
    a. From Step B4: e_{Y13} in mv
       A_{Y3} in decimal degrees
    b. From Step B9: e_{Y14} in mv
       A_{Y4} in decimal degrees
11. Repeat Steps B1 through B9. Read and record:
    a. From Step B4: e_{Y15} in mv
       A_{Y5} in decimal degrees
    b. From Step B9: e_{Y16} in mv
       A_{Y6} in decimal degrees

C. COMPUTATION OF γ_{Y_Z}

1. Compute $R_{+avg.}$ and $R_{-avg.}$ on Data Sheet Form E-1230 DS-3:

$$R_{+avg.} = \frac{\frac{e_{Y11}}{A_{Y1}} + \frac{e_{Y13}}{A_{Y3}} + \frac{e_{Y15}}{A_{Y5}}}{3} \qquad R_{-avg.} = -\frac{\frac{e_{Y12}}{A_{Y2}} + \frac{e_{Y14}}{A_{Y4}} + \frac{e_{Y16}}{A_{Y6}}}{3}$$

2. Compute γ'_{Y_Z} on Data Sheet Form E-1230 DS-3:

$$\gamma'_{Y_Z} = \frac{R_{+avg.} - R_{-avg.}}{2} \times \frac{57.29577}{S} \text{ mr}$$

3. Compute γ_{Y_Z} on Data Sheet Form E-1230 DS-3:

   $\gamma_{Y_Z} = (\gamma'_{Y_Z} + \epsilon_{MGR})$ mr $= \gamma'_{Y_Z}$ because the Middle Gimbal Resolver has been adjusted.

4. Measure and record on Data Sheet Form E-1230 DS-3:
   a. Precision 3200-cps excitation voltage in mv.
   b. IRIG temperature deviation in °F.

JOB: Y IRIG ALIGNMENT TEST	**JDC** 35.0021 Sheet 5 of 6
SUBSYSTEM: INERTIAL MEASUREMENT UNIT	**SYSTEM:** AGE/
DESCRIPTION: Part 3. Measuring γ_{Y_X} by Rotation About Y IRIG Spin Reference Axis	**TYPE:** Alignment **INTERVAL:**
TOOLS AND MATERIAL:	**REFERENCES:**
IMPORTANT: Results from Gyro Data Sheet Form ______, JDC 35.0002 and JDC 35.0012 are required before performing this job.	

A. PREPARATION

1. Test Table Orientations

   Set:

   a. Initial Tilt Angle (Φ)

   Desired Angle Designation = (λ) Local Latitude

   NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

   b. Initial Rotary Angle (θ)

   Desired Angle Designation = $\theta_{H_{OGA}}$

   Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

   NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

2. Gimbal Assembly

   Gimbal orientations by using CDU's in "Coarse Align" Mode and "Precision Zero Set" where indicated by asterisk (*).

   a. Outer Gimbal Angle (A_{OG}) = 270°

   b. Middle Gimbal Angle (A_{MG}) = 0°

   c. Inner Gimbal Angle (A_{IG}) = 0°*

3. Ground Support Equipment Setup

   Place Middle Gimbal CDU in "Manual Align" Mode for operation by the slew switch.

B. PROCEDURE

1. Null Y IRIG with manual pulses; shift PAVM scales as required.
2. Reset IRIG bias with two positive pulses; select PAVM 10-volt scale.
3. Using Middle Gimbal CDU slew switch, rotate the Middle Gimbal in a positive direction to A_{MG} equals 270° ±1°.
4. Within 60 seconds (time) of completing the slew position command (Step B3), read and record e_{YI7} in mv on Data Sheet Form E-1230 DS-3, shifting scales as necessary on the PAVM.
5. Using the slew switch, reposition the Middle Gimbal Angle CDU to zero within accuracy of the thumbwheel.
6. Repeat Steps B1 through B5, reading and recording e_{YI8} in mv on Data Sheet Form E-1230 DS-3.
7. Repeat Steps B1 through B5, reading recording e_{YI9} in mv on Data Sheet Form E-1230 DS-3.

JOB: Y IRIG ALIGNMENT TEST

JDC 35.0021 Sheet 6 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 3. Measuring γ_{Y_X} by Rotation About Y IRIG Spin Reference Axis

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from Gyro Data Sheet Form ______, JDC 35.0002, and JDC 35.0012 are required before performing this job.

C. COMPUTATION OF γ_{Y_X}

1. Compute $e_{avg.}$ on Data Sheet Form E-1230 DS-3:

$$e_{avg.} = \frac{e_{Y17} + e_{Y18} + e_{Y19}}{3} \text{ mv}$$

2. Determine $\frac{H}{C}$ from Gyro Data Sheet Form ______, and record on Data Sheet Form E-1230 DS-3.
3. Compute γ'_{Y_X} on Data Sheet Form E-1230 DS-3:

$$\gamma'_{Y_X} = -\frac{e_{avg.}}{\frac{H}{C} S} \text{ mr}$$

4. Compute γ_{Y_X} on Data Sheet Form E-1230 DS-3.

$$\gamma_{Y_X} = (\gamma'_{Y_X} - \epsilon_{IGA}) \text{ mr}$$

5. Measure and record on Data Sheet Form E-1230 DS-3:
   a. Precision 3200-cps excitation voltage in mv.
   b. IRIG temperature deviation in °F.

JOB: Z IRIG ALIGNMENT TEST

JDC 35.0022 Sheet 1 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 1. Calibration of Input Angle to Preamp Voltage Output: S_z

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

A. PREPARATION

1. Test Table Orientations

Set:

a. Initial Tilt Angle (Φ)

Desired Angle Designation = (λ) Local Latitude

NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

Initial Rotary Angle (θ) = 0°

2. Gimbal Assembly

Set:

a. Outer Gimbal Angle (A_{OG}) = Precision 0°

b. Middle Gimbal Angle (A_{MG}) = Precision 0°

c. Inner Gimbal Angle (A_{IG}) = Precision 0°

3. IRIG Preamp

Route Z IRIG Preamp Output to PAVM.

B. PROCEDURE

1. Null Z IRIG with manual pulses; shift PAVM scales as required.
2. Reset IRIG bias with two positive pulses: select PAVM 10-volt scale.
3. Set in following Rotary Angles; read within 30 seconds (time) the PAVM outputs, and record results on Data Sheet Form E-1230 DS-3 in order given:

Set θ = +15'00" Read and record e_{z1} in (+) mv.

Set θ = -15'00" Read and record e_{z2} in (-) mv.

Return to θ = 0° and renull.

Set θ = +15'00" Read and record e_{z3} in (+) mv.

Set θ = -15'00" Read and record e_{z4} in (-) mv.

Return to θ = 0° and renull.

Set θ = +15'00" Read and record e_{z5} in (+) mv.

Set θ = -15'00" Read and record e_{z6} in (-) mv.

Return to θ = 0°.

4. Compute $e_{+avg.}$ and $e_{-avg.}$ on Data Sheet Form E-1230 DS-3:

$$e_{+avg.} = \frac{e_{z1} + e_{z3} + e_{z5}}{3} \text{ mv}$$

$$e_{-avg.} = \frac{e_{z2} + e_{z4} + e_{z6}}{3} \text{ mv}$$

JOB: Z IRIG ALIGNMENT TEST

JDC 35.0022 Sheet 2 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 1. Calibration of Input Angle to Preamp Voltage Output: S_z

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT:

C. LINEARITY CHECK

1. Renull and set in following Rotary Angles; read the PAVM outputs, and record results on Data Sheet Form E-1230 DS-3 in order given:

Set $\theta = +10'00''$ Read and record e_{z7} in (+) mv.

Set $\theta = -10'00''$ Read and record e_{z8} in (-) mv.

Return to $\theta = 0°$ and renull.

Set $\theta = +5'00''$ Read and record e_{z9} in (+) mv.

Set $\theta = -5'00''$ Read and record e_{z10} in (-) mv.

Return to $\theta = 0°$.

2. Compute on Data Sheet Form E-1230 DS-3:

$$\frac{e_{z7}}{e_{+avg.}} \text{ and } -\frac{e_{z8}}{e_{-avg.}}$$

Plot results on Data Sheet Form E-1230 DS-3 Linearity Plot.

3. Determine that:

$$\frac{\left(\frac{e_{z7}}{e_{+avg.}}\right)}{\frac{2}{3}} = \frac{-\left(\frac{e_{z8}}{e_{-avg.}}\right)}{-\frac{2}{3}} = 1.00 \pm 0.01$$

4. Compute on Data Sheet Form E-1230 DS-3:

$$\frac{e_{z9}}{e_{+avg.}} \text{ and } -\frac{e_{z10}}{e_{-avg.}}$$

Plot results on Data Sheet Form E-1230 DS-3 Linearity Plot.

5. Determine that:

$$\frac{\left(\frac{e_{z9}}{e_{+avg.}}\right)}{\frac{1}{3}} = \frac{-\left(\frac{e_{z10}}{e_{-avg.}}\right)}{-\frac{1}{3}} = 1.00 \pm 0.01$$

D. SENSITIVITY COMPUTATION

1. Use Data Sheet Form E-1230 DS-3 to compute Sensitivity.

$$S_z = \frac{e_{+avg.} - e_{-avg.}}{8.727} \frac{\text{mv}}{\text{mr}}$$

2. Measure and record on Data Sheet Form E-1230 DS-3:
   a. Precision 3200-cps excitation voltage in mv.
   b. IRIG temperature deviation in °F.

JOB: Z IRIG ALIGNMENT TEST

JDC 35.0022

Sheet 3 of 6

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 2. Measuring γ_{z_1} by Rotation About Z IRIG Output Axis

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002 and JDC 35.0009 are required before performing this job. JDC 35.0014 must also be performed.

A. PREPARATION

1. Test Table Orientations

   Set:

   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = (λ) Local Latitude

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{OGA}}$ -90°

      Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

2. Gimbal Assembly

   Gimbal orientation by using CDU's in "Coarse Align" Mode and "Precision Zero Set" where indicated by asterisk (*).

   a. Outer Gimbal Angle (A_{OG}) = 0°

   b. Middle Gimbal Angle (A_{MG}) = 0°*

   c. Inner Gimbal Angle (A_{IG}) = 0°*

3. Ground Support Equipment Setup

   Set Outer Gimbal CDU in "Manual Align" Mode for operation by slew switch.

B. PROCEDURE

1. Null Z IRIG with manual pulses; shift the PAVM scales as required.
2. Reset IRIG bias with two positive pulses; select PAVM 10-volt scale.
3. Use Outer Gimbal CDU slew switch to rotate the Outer Gimbal in a positive direction to A_{OG} equals 90° ±1°.

   NOTE: Do not use thumbwheel to set in an exact number for end of test.
   Take final reading upon stopping.

4. Within 60 seconds (time) of completing the slew position command (Step B3), read and record on Data Sheet Form E-1230 DS-3:

   a. e_{z11} in mv, shifting scales as necessary on the PAVM.

   b. A_{z1} in decimal degrees from the Outer Gimbal CDU.

5. Using the slew switch, reposition the Outer Gimbal Angle CDU to zero within the accuracy of the thumbwheel.

JOB: Z IRIG ALIGNMENT TEST

JDC 35.0022

SUBSYSTEM: INERTIAL MEASUREMENT UNIT

SYSTEM: AGE/

DESCRIPTION: Part 2. Measuring γ_{Z_Y} by Rotation About Z IRIG Output Axis

TYPE: Alignment

INTERVAL:

TOOLS AND MATERIAL:

REFERENCES:

IMPORTANT: Results from JDC 35.0002 and JDC 35.0009 are required before performing this job. JDC 35.0014 must also be performed.

B. PROCEDURE (continued)

6. Repeat Step B1.
7. Repeat Step B2.
8. Use Outer Gimbal CDU slew switch to rotate the Outer Gimbal in a negative direction to A_{OG} equals -90 ±1°.

   NOTE: Do not use thumbwheel to set in an exact number for end of test.
   Take final reading upon stopping.

9. Within 60 seconds (time) of completing slew position command (Step B8), read and record on Data Sheet Form E-1230 DS-3:
   a. e_{X12} in mv, shifting scales as necessary on the PAVM.
   b. A_{X2} in decimal degrees from the Outer Gimbal CDU.
10. Repeat Steps B1 through B9. Read and record:
    a. From Step B4: e_{Z13} in mv
       A_{Z3} in decimal degrees
    b. From Step B9: e_{Z14} in mv
       A_{Z4} in decimal degrees
11. Repeat Steps B1 through B9. Read and record:
    a. From Step B4: e_{Z15} in mv
       A_{Z5} in decimal degrees
    b. From Step B9: e_{Z16} in mv
       A_{Z6} in decimal degrees

C. COMPUTATION OF γ_{Z_Y}

1. Compute $R_{+avg.}$ and $R_{-avg.}$ on Data Sheet Form E-1230 DS-3:

$$R_{+avg.} = \frac{\frac{e_{Z11}}{A_{Z1}} + \frac{e_{Z13}}{A_{Z3}} + \frac{e_{Z15}}{A_{Z5}}}{3} \qquad R_{-avg.} = -\frac{\frac{e_{Z12}}{A_{Z2}} + \frac{e_{Z14}}{A_{Z4}} + \frac{e_{Z16}}{A_{Z6}}}{3}$$

2. Compute γ'_{Z_Y} on Data Sheet Form E-1230 DS-3:

$$\gamma'_{Z_Y} = \frac{R_{+avg.} - R_{-avg.}}{2} \times \frac{57.29577}{S} \text{ mr}$$

3. Compute γ_{Z_Y} on Data Sheet.

$$\gamma_{Z_Y} = (\gamma'_{Z_Y} + \epsilon_{IGR} - \epsilon_{MGA}) \text{ mr} = \gamma'_{Z_Y} - \epsilon_{MGA}$$ because the Inner Gimbal Resolver has been adjusted.

Value of ϵ_{MGA} is obtained from JDC 35.0009, Data Sheet Form E-1230 DS-1.

4. Measure and record on Data Sheet Form E-1230 DS-3:
   a. Precision 3200-cps excitation voltage in mv.
   b. IRIG temperature deviation in °F.

JOB:	Z IRIG ALIGNMENT TEST	**JDC** 35.0022	Sheet 5 of 6
SUBSYSTEM:	INERTIAL MEASUREMENT UNIT	**SYSTEM:**	AGE/
DESCRIPTION:	Part 3. Measuring γ_{z_x} by Rotation About Z IRIG Spin Reference Axis	**TYPE:** **INTERVAL:**	Alignment
TOOLS AND MATERIAL:		**REFERENCES:**	
IMPORTANT:	Results from Gyro Data Sheet Form ______ and JDC 35.0002 are required before performing this job.		

A. PREPARATION

1. Test Table Orientations

   Set:

   a. Initial Tilt Angle (Φ)

      Desired Angle Designation = (λ) Local Latitude

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

   b. Initial Rotary Angle (θ)

      Desired Angle Designation = $\theta_{H_{OGA}}$

      Value of $\theta_{H_{OGA}}$ obtained from JDC 35.0002 Data Sheet Form E-1230 DS-1.

      NOTE: Record Value, Calibration Error, and Angle Setting on Data Sheet Form E-1230 DS-3.

2. Gimbal Assembly

   Gimbal orientations by using CDU's in "Coarse Align" Mode and "Precision Zero Set" where indicated by asterisk (*).

   a. Outer Gimbal Angle (A_{OG}) = 0°*

   b. Middle Gimbal Angle (A_{MG}) = 0°*

   c. Inner Gimbal Angle (A_{IG}) = 0°

3. Ground Support Equipment Setup

   Place Inner Gimbal CDU in "Manual Align" Mode for operation by the slew switch.

B. PROCEDURE

1. Null Z IRIG with manual pulses; shift PAVM scales as required.
2. Reset IRIG bias with two positive pulses; select PAVM 10-volt scale.
3. Using Inner Gimbal CDU slew switch, rotate the Inner Gimbal in a negative direction to A_{IG} equals 270° ±1°.
4. Within 60 seconds (time) of completing the slew position command (Step B3), read and record e_{Z17} in mv on Data Sheet Form E-1230 DS-3 shifting scales as necessary on the PAVM.
5. Using the slew switch, reposition the Inner Gimbal Angle CDU to zero within accuracy of the thumbwheel.
6. Repeat Steps B1 through B5, reading and recording e_{Z18} in mv on Data Sheet Form E-1230 DS-3.
7. Repeat Steps B1 through B5, reading and recording e_{Z19} in mv on Data Sheet Form E-1230 DS-3.

JOB:	Z IRIG ALIGNMENT TEST	**JDC** 35.0022	Sheet 6 of 6
SUBSYSTEM:	INERTIAL MEASUREMENT UNIT	**SYSTEM:**	AGE/
DESCRIPTION:	Part 3. Measuring γ_{z_x} by Rotation About Z IRIG Spin Reference Axis	**TYPE:** **INTERVAL:**	Alignment
TOOLS AND MATERIAL:		**REFERENCES:**	
IMPORTANT:	Results from Gyro Data Sheet Form ______ and JDC 35.0002 are required before performing this job.		

C. COMPUTATION OF γ_{z_x}

1. Compute $e_{avg.}$ on Data Sheet Form E-1230 DS-3:

$$e_{avg.} = \frac{e_{z17} + e_{z18} + e_{z19}}{3} \text{ mv}$$

2. Determine $\frac{H}{C}$ from Gyro Data Sheet Form ______, and record on Data Sheet Form E-1230 DS-3.

3. Compute γ_{z_x} on Data Sheet Form E-1230 DS-3:

$$\gamma_{z_x} = - \frac{e_{avg.}}{\frac{H}{C} S} \text{ mr}$$

4. Measure and record on Data Sheet Form E-1230 DS-3:
   a. Precision 3200-cps excitation voltage in mv.
   b. IRIG temperature deviation in °F.

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SUBSYSTEM: IMU
SERIAL NO. ________
JDC ______________

PIPA ALIGNMENT TESTS DATA SHEET
FORM E-1230 DS-1

NOTE: This Data Sheet to be used with JDC 35.0001 through JDC 35.0006
JDC 35.0008 through JDC 35.0010
JDC 35.0012 and JDC 35.0013
JDC 35.0015 through JDC 35.0017

TEST STEP NO.	RECORD OR CALCULATE	TEST STEP NO.	RECORD OR CALCULATE
A.2.a.	Initial Tilt Angle	D.2.a	Initial Tilt Angle
	Desired Angle Designation =		Desired Angle Designation =
	Value ______° ______' ______"		Value ______° ______' ______"
	Indicator Error (-) ______"		Indicator Error (-) ______"
	Readout Angle ______° ______' ______"		Readout Angle ______° ______' ______"
A.2.b.	Initial Rotary Angle	D.2.b.	Initial Rotary Angle
	Desired Angle Designation =		Desired Angle Designation =
	Value ______° ______' ______"		Value ______° ______' ______"
	Indicator Error (-) ______"		Indicator Error (-) ______"
	Readout Angle ______° ______' ______"		Readout Angle ______° ______' ______"
C.1.	Final Tilt Angle Φ ___	F.1.	Final Tilt Angle Φ ___
	Readout Angle ______° ______' ______"		Readout Angle ______° ______' ______"
	Indicator Error (+) ______"		Indicator Error (+) ______"
	Desired Angle ______° ______' ______"		Desired Angle ______° ______' ______"
C.2.	Final Rotary Angle θ ___	F.2.	Final Rotary Angle θ ___
	Readout Angle ______° ______' ______"		Readout Angle ______° ______' ______"
	Indicator Error (+) ______"		Indicator Error (+) ______"
	Desired Angle ______° ______' ______"		Desired Angle ______° ______' ______"

PERFORM CALCULATIONS SHOWN IN TEST STEP G OF SHEET 2 OF JDC.

DATE OF TEST ______________
BY ____ CHECKED BY __________

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WHEN FILLED IN

SUBSYSTEM: IMU
SERIAL NO.________
JDC______________

PIPA ALIGNMENT TESTS
FINE RESOLVER ALIGNMENT TESTS DATA SHEET
FORM E-1230 DS-2

NOTE: This Data Sheet to be used with JDC 35.0007, JDC 35.0011, and JDC 35.0014.

TEST STEP NO.	RECORD OR CALCULATE	TEST STEP NO.	RECORD OR CALCULATE
	FIRST NULL MEASUREMENT		SECOND NULL MEASUREMENT
A. 2. a.	Initial Tilt Angle	C. 2. a.	Initial Tilt Angle
	Desired Angle Designation =		Desired Angle Designation =
	Value ______° ______' ______"		Value ______° ______' ______"
	Indicator Error (-) ______"		Indicator Error (-) ______"
	Readout Angle ______° ______' ______"		Readout Angle ______° ______' ______"
A. 2. b.	Initial Rotary Angle	C. 2. b.	Initial Rotary Angle
	Desired Angle Designation =		Desired Angle Designation =
	Value ______° ______' ______"		Value ______° ______' ______"
	Indicator Error (-) ______"		Indicator Error (-) ______"
	Readout Angle ______° ______' ______"		Readout Angle ______° ______' ______"
B. 1.	FINAL TILT ROTARY ANGLE	E.	FINAL TILT ROTARY ANGLE
	Desired Angle Designation =		
	Value ______° ______' ______"		Readout Angle ______° ______' ______"
	Indicator Error (-) ______"		Indicator Error (+) ______"
	Readout Angle ______° ______' ______"		Desired Angle ______° ______' ______"

PERFORM CALCULATIONS SHOWN IN TEST STEP F ON SHEET 2 OF JDC.

DATE OF TEST________________
BY____CHECKED BY____________

CONFIDENTIAL

WHEN FILLED IN

SUBSYSTEM: IMU
SERIAL NO.__________

IRIG ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-3 (sheet 1 of 5)
PART 1

NOTE: This Data Sheet to be used with JDC 35.0020 through JDC 35.0022

ROW NUMBER	TEST STEP NO.	RECORD OR CALCULATE	JDC 35.0020 X IRIG TEST COLUMN		JDC 35.0021 Y IRIG TEST COLUMN		JDC 35.0022 Z IRIG TEST COLUMN	
			+	-	+	-	+	-
1	A-1	Initial Tilt Angle (Φ) - Desired Designation	(λ) Loc.	Lat.	(λ) Loc	Lat.	(λ) Loc.	Lat.
—	—	Desired Angle Value	° ' "		° ' "		° ' "	
—	—	Calibration Error	"		"		"	
—	—	Angle Setting	° ' "		° ' "		° ' "	
1-a	B-3	e_1	mv		mv		mv	
2	B-3	e_2		mv		mv		mv
3	B-3	e_3	mv		mv		mv	
4	B-3	e_4		mv		mv		mv
5	B-3	e_5	mv		mv		mv	
6	B-3	e_6		mv		mv		mv
7	—	$e_1 + e_3 + e_5$ = Row 1-a + Row 3 + Row 5	mv		mv		mv	
8	—	$e_2 + e_4 + e_6$ = Row 2 + Row 4 + Row 6		mv		mv		mv
9	B-4	$e_{+avg} = e_1 + e_3 + e_5/3$ = Row 7/3	mv		mv		mv	
10	B-4	$e_{-avg} = e_2 + e_4 + e_6/3$ = Row 8/3		mv		mv		mv
11	—	$e_{+avg} - e_{-avg}$ = Row 9 - Row 10	mv		mv		mv	
12	C-1	e_7	mv		mv		mv	
13	C-1	e_8		mv		mv		mv
14	C-1	e_9	mv		mv		mv	
15	C-1	e_{10}		mv		mv		mv
16	C-2	e_7/e_{+avg} = Row 12/Row 9						
17	C-2	$-(e_8/e_{-avg})$ = -(Row 13/Row 10)						

DATE OF TEST (X IRIG)__________
BY____CHECKED BY__________

DATE OF TEST (Y IRIG)__________
BY____CHECKED BY__________

DATE OF TEST (Z IRIG)__________
BY____CHECKED BY__________

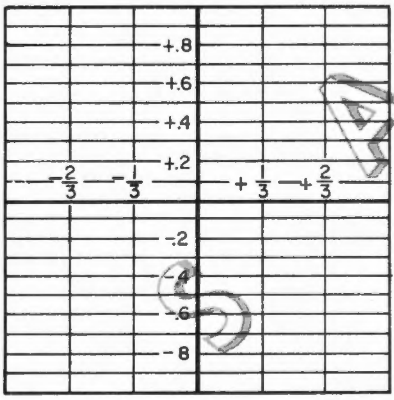
SUBSYSTEM: IMU
SERIAL NO.__________

IRIG ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-3 (sheet 2 of 5)
PART 1

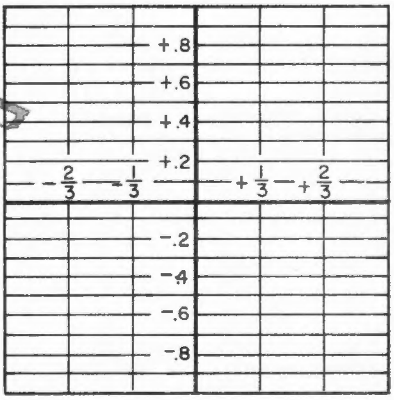
NOTE: This Data Sheet to be used with JDC 35.0020 through JDC 35.0022.

ROW NUMBER	TEST STEP NO.	RECORD OR CALCULATE	JDC 35.0010 X IRIG TEST COLUMN	JDC 35.0021 Y IRIG TEST COLUMN	JDC 35.0022 Z IRIG TEST COLUMN
18	C-2	Plot Row 16 values along $+\frac{2}{3}$ line and Row 17 values along $-\frac{2}{3}$ line on Linearity Plots.			
19	C-3	$e_7/e_{+avg}/2/3$ = Row 16/2/3			
20	C-3	$-(e_8/e_{-avg})/-2/3$ = Row 17/-2/3			
21	C-3	Row 19 = Row 20 = 1.00 ±0.01	YES NO*	YES NO*	YES NO*
22	C-4	e_9/e_{+avg} = Row 14/Row 9			
23	C-4	$-(e_{10}/e_{-avg})$ = -(Row 15/Row 10)			
24	C-4	Plot Row 22 values along $+\frac{1}{3}$ line and Row 23 values along $-\frac{1}{3}$ line on Linearity Plots.			
25	C-5	$e_9/e_{+avg}/1/3$ = Row 22/1/3			
26	C-5	$-(e_{10}/e_{-avg})/-1/3$ = Row 23/-1/3			
27	C-5	Row 25 = Row 26 = 1.00 ±0.01	YES NO*	YES NO*	YES NO*
28	D	$S = \frac{e_{+avg} - e_{-avg}}{8.727} = \frac{\text{Row 11}}{8.727}$	mv/mr	mv/mr	mv/mr
29	D.a.	Excitation Voltage	mv	mv	mv
30	D.b.	Temperature Deviation	°F	°F	°F

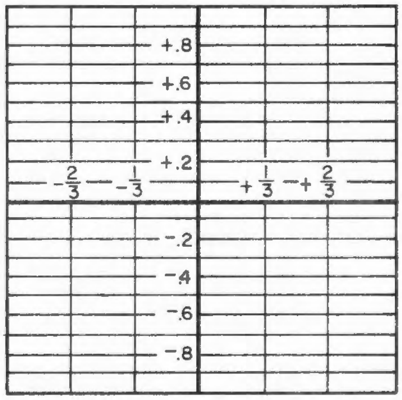
X IRIG LINEARITY PLOT



Y IRIG LINEARITY PLOT



Z IRIG LINEARITY PLOT



*Repeat test. If still "NO," notify responsible engineer.

DATE OF TEST (X IRIG)______________ DATE OF TEST (Y IRIG)______________ DATE OF TEST (Z IRIG)______________

BY____CHECKED BY______________ BY____CHECKED BY______________ BY____CHECKED BY______________

SUBSYSTEM: IMU
SERIAL NO. _______

IRIG ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-3 (sheet 3 of 5)
PART 2

NOTE: This Data Sheet to be used with JDC 35.0020 through JDC 35.0022.

ROW NUMBER	TEST STEP NO.	RECORD OR CALCULATE	JDC 35.0020 X IRIG TEST COLUMN	JDC 35.0021 Y IRIG TEST COLUMN	JDC 35.0022 Z IRIG TEST COLUMN
31	A-1	Initial Tilt Angle (Φ) - Desired Designation	(λ) Loc. Lat.	(λ) Loc. Lat.	(λ) Loc. Lat.
—	—	Desired Angle Value	° ' "	° ' "	° ' "
—	—	Calibration Error	"	"	"
—	—	Angle Setting	° ' "	° ' "	° ' "
32	A-1	Initial Rotary Angle (θ) - Desired Designation	$\theta_{H_{OGA}}$	$\theta_{H_{OGA}}$ - 90°	$\theta_{H_{OGA}}$ - 90°
—	—	Desired Angle Value	° ' "	° ' "	° ' "
—	—	Calibration Error	"	"	'
—	—	Angle Setting	° ' "	° ' "	° ' "
33	B-4	e_{11}	mv	mv	mv
34	B-4	A_1	deg	deg	deg
35	—	e_{11}/A_1 = Row 33/Row 34	mv/deg	mv/deg	mv/deg
36	B-9	e_{12}	mv	mv	mv
37	B-9	A_2	deg	deg	deg
38	—	e_{12}/A_2 = Row 36/Row 37	mv/deg	mv/deg	mv/deg
39	B-10	e_{13}	mv	mv	mv
40	B-10	A_3	deg	deg	deg
41	—	e_{13}/A_3 = Row 39/Row 40	mv/deg	mv/deg	mv/deg
42	B-10	e_{14}	mv	mv	mv
43	B-10	A_4	deg	deg	deg
44	—	e_{14}/A_4 = Row 42/Row 43	mv/deg	mv/deg	mv/deg
45	B-11	e_{15}	mv	mv	mv
46	B-11	A_5	deg	deg	deg
47	—	e_{15}/A_5 = Row 45/Row 46	mv/deg	mv/deg	mv/deg
48	B-11	e_{16}	mv	mv	mv
49	B-11	A_6	deg	deg	deg
50	—	e_{16}/A_6 = Row 48/Row 49	mv/deg	mv/deg	mv/deg

DATE OF TEST (X IRIG)____________ DATE OF TEST (Y IRIG)____________ DATE OF TEST (Z IRIG)____________

BY____CHECKED BY____________ BY____CHECKED BY____________ BY____CHECKED BY____________

SUBSYSTEM: IMU
SERIAL NO.________

IRIG ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-3 (sheet 4 of 5)
PART 2

NOTE: This Data Sheet to be used with JDC 35.0020 through JDC 35.0022

ROW NUMBER	TEST STEP NO.	RECORD OR CALCULATE	JDC 35.0020 X IRIG TEST COLUMN	JDC 35.0021 Y IRIG TEST COLUMN	JDC 35.0022 Z IRIG TEST COLUMN
51	---	Row 35 + Row 41 + Row 47	mv/deg	mv/deg	mv/deg
52	C-1	R_{+avg} = Row 51/3	mv/deg	mv/deg	mv/deg
53	---	Row 38 + Row 44 + Row 50	mv/deg	mv/deg	mv/deg
54	C-1	R_{-avg} = -Row 53/3	mv/deg	mv/deg	mv/deg
55	---	Row 52 - Row 54	mv/deg	mv/deg	mv/deg
56	---	57.29577/S = 57.29577/Row 28			
57	C-2(X)	γ'_{x_y} = (Row 55/2) Row 56	mr		
58	C-2(Y)	γ'_{y_z} = (Row 55/2) Row 56		mr	
59	C-2(Z)	γ'_{z_y} = (Row 55/2) Row 56			mr
60	C-3(X)	$\gamma_{x_y} = \gamma'_{x_y}$ = Row 57	mr		
61	C-3(Y)	$\gamma_{y_z} = \gamma'_{y_z}$ = Row 58		mr	
62	C-3(Z)	$\gamma_{z_y} = \gamma'_{z_y} - \epsilon_{MGA}$ = Row 59 - ϵ_{MGA}			mr
63	C-4	Excitation Voltage	mv	mv	mv
64	C-4	Temperature Deviation	°F	°F	°F

DATE OF TEST (X IRIG)____________ DATE OF TEST (Y IRIG)____________ DATE OF TEST (Z IRIG) ________
BY____CHECKED BY____________ BY____CHECKED BY______________ BY____CHECKED BY__________

SUBSYSTEM: IMU
SERIAL NO. ________

IRIG ALIGNMENT TEST DATA SHEET
FORM E-1230 DS-3 (sheet 5 of 5)
PART 3

NOTE: This Data Sheet to be used with JDC 35.0020 through JDC 35.0022.

ROW NUMBER	TEST STEP NO.	RECORD OR CALCULATE	JDC 35.0020 X IRIG TEST COLUMN	JDC 35.0021 Y IRIG TEST COLUMN	JDC 35.0022 Z IRIG TEST COLUMN
65	A-1	Initial Tilt Angle - Desired Designation	(λ) Loc. Lat.	(λ) Loc. Lat.	(λ) Loc. Lat.
—	—	Desired Angle Value	° ′ ″	° ′ ″	° ′ ″
—	—	Calibration Error	″	″	″
—	—	Angle Setting	° ′ ″	° ′ ″	° ′ ″
66	A-1	Initial Rotary Angle - Desired Designation	$\theta_{H_{OGA}} \pm 180°$	$\theta_{H_{OGA}}$	$\theta_{H_{OGA}}$
—	—	Desired Angle Value	° ′ ″	° ′ ″	° ′ ″
—	—	Calibration Error	″	″	″
—	—	Angle Setting	° ′ ″	° ′ ″	° ′ ″
67	B-4	e_{17}	mv	mv	mv
68	B-6	e_{18}	mv	mv	mv
69	B-7	e_{19}	mv	mv	mv
70	—	$e_{17} + e_{18} + e_{19}$ = Row 67 + Row 68 + Row 69	mv	mv	mv
71	C-1	$e_{avg.}$ = Row 70/3	mv	mv	mv
72	C-2	$\frac{H}{C}$			
73	—	$\frac{H}{C} \times S$ = Row 72 x Row 28	mv/mr	mv/mr	mv/mr
74	C-3(X)	γ_{x_z} = - (Row 71 / Row 73)	mr	▨	▨
75	C-3(Y)	γ'_{y_x} = - (Row 71 / Row 73)	▨	mr	▨
76	C-3(Z)	γ_{z_x} = - (Row 71 / Row 73)	▨	▨	mr
77	C-4(Y)	$\gamma_{y_x} = \gamma'_{y_x} - \epsilon_{IGA}$ = Row 75 - ϵ_{IGA}	▨	mr	▨
78	C-4(X)(Z)	Excitation Voltage	mv	▨	mv
79	C-5(Y)	Excitation Voltage	▨	mv	▨
80	C-4(X)(Z)	Temperature Deviation	°F	▨	°F
81	C-5(Y)	Temperature Deviation	▨	°F	▨

DATE OF TEST (X IRIG)______________
BY____CHECKED BY______________

DATE OF TEST (Y IRIG)______________
BY____CHECKED BY______________

DATE OF TEST (Z IRIG)______________
BY_____CHECKED BY______________

ERC TEST FACILITY

BRIEF SUMMARY
OF AUTOMATED TEST STATION

PRÉPARED
FOR
NASA/HOUSTON

UAC/HS

~~Planned~~
~~but~~
Not Exact copy
of apollo test station
used late in
program

HARDWARE THAT HSSC WILL PROVIDE

A Hewlett-Packard 2116B Computer with

- 32 K of memory
- up to 48 Input/Output Slots
- Direct Memory Access Option included

A Hewlett-Packard 3030G Magnetic Tape Unit

- with computer interface

A Sanders 720 CRT Display System and keyboard

- with computer interface

An HP-2754B Teleprinter (ASR-35)

- with computer interface

A Hewlett-Packard 2737A Hi-Speed Paper Tape Reader

- with computer interface

A Hewlett-Packard Multiplexer/Low Speed A-D Converter System consisting of

- an HP-3502A Digital Voltmeter
- An HP-2911B Guarded Crossbar Scanner
- An HP-2911A Scanner Control
- with computer interfaces

A Hewlett-Packard 5610A Hi-Speed A-D Converter

- with computer interface

A Calcomp 565 Plotter

- with computer interface

A Quan Tech 304 TDM Wave Analyzer

- with computer interface

A Hewlett-Packard 2059A Remote Switch Register

- with computer interface

HARDWARE THAT HSSC WILL PROVIDE (continued)

- Six Hewlett-Packard H40-5280A Reversible Counters with computer interface
- A Hewlett-Packard 5214L Preset Counter
- AC and DC Power Supplies as necessary to adequately satisfy NASA/Houston's requirements
- Special interface with your rate table where practical
- Special interfaces for controlling the power supplies, counters, and wave analyzer
- Patchboards for signal routing
- A 24-hour digital clock
- Stable crystal oscillators and countdown circuits
- Six X-Y Monitor Scopes
- Test Point Panels
- A Hewlett-Packard 6130B Programmable Power Source with computer interface
- 16 Bit Parrel Computer Interface (expandable to 32)
- Hewlett-Packard Extended Arithmetic Unit

SOFTWARE THAT HSSC WILL PROVIDE

- A Real-Time Executive (not DACE)
- CRT Display/Keyboard routines
- Calcomp Plotter routines
- Mag. Tape Unit read/write routines
- Teleprinter hard copy routines
- Program Loading routines (via Paper Tape reader)
- DVM/Scanner routines
- Test event routines, such as:
    - -- Connecting power supply outputs
    - -- Providing operator control of power supplies
    - -- Test article turn-on sequences
    - -- Test article turn-off sequences
    - -- Monitoring of safety parameters
    - -- High-speed accumulation of counter data (1 millisecond max.)
    - -- Hard copy printout of high speed counter data falling outside of preset means and deviations
    - -- Counter control and readout for longer totalizing periods (1 sec to 100 sec)
    - -- Hard copy of CRT display of counter data
    - -- Rate table control where applicable
    - -- Scanning and measuring of low speed analog data
    - -- Hard copy or CRT display of low speed analog data
    - -- Display of predetermined CRT messages
    - -- Frequency response control and data accumulation

SOFTWARE THAT HSSC WILL PROVIDE (continued)

-- Reduction of frequency response data to db and phase

-- Hard copy printout of reduced frequency response data

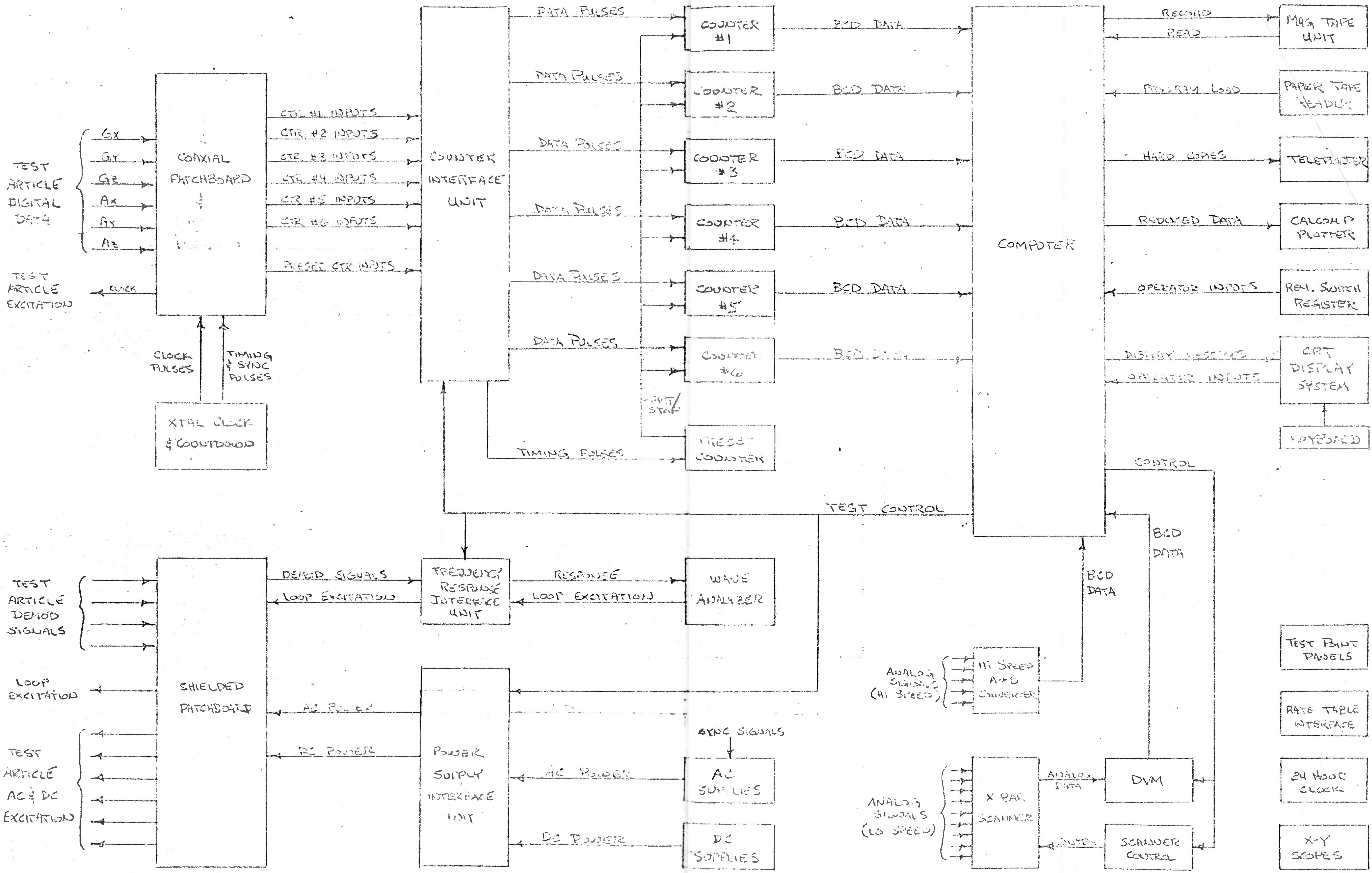
-- Plotting of reduced frequency response data

-- Computation of first order static error coefficients

-- Hard copy printout of reduced calibration data

-- Computation of scale factor linearity

-- Hard copy printout of reduced linearity data


TEST ARTICLE DIGITAL DATA
GX
GY
GZ
AX
AY
AZ
COAXIAL PATCHBOARD &
TEST ARTICLE EXCITATION
CLOCK
CLOCK PULSES
TIMING & SYNC PULSES
XTAL CLOCK & COUNTDOWN
CTR #1 INPUTS
CTR #2 INPUTS
CTR #3 INPUTS
CTR #4 INPUTS
CTR #5 INPUTS
CTR #6 INPUTS
PRESET CTR INPUTS
COUNTER INTERFACE UNIT
DATA PULSES
DATA PULSES
DATA PULSES
DATA PULSES
DATA PULSES
DATA PULSES
TIMING PULSES
START/STOP
COUNTER #1
COUNTER #2
COUNTER #3
COUNTER #4
COUNTER #5
COUNTER #6
PRESET COUNTER
BCD DATA
BCD DATA
BCD DATA
BCD DATA
BCD DATA
BCD DATA
COMPUTER
RECORD
READ
MAG TAPE UNIT
PROGRAM LOAD
PAPER TAPE READER
HARD COPIES
TELEPRINTER
REDUCED DATA
CALCOMP PLOTTER
OPERATOR INPUTS
REM. SWITCH REGISTER
DISPLAY MESSAGES
OPERATOR INPUTS
CRT DISPLAY SYSTEM
KEYBOARD
CONTROL
TEST CONTROL
BCD DATA
BCD DATA
TEST ARTICLE DEMOD SIGNALS
LOOP EXCITATION
TEST ARTICLE AC & DC EXCITATION
SHIELDED PATCHBOARD
DEMOD SIGNALS
LOOP EXCITATION
AC POWER
DC POWER
FREQUENCY RESPONSE INTERFACE UNIT
RESPONSE
LOOP EXCITATION
WAVE ANALYZER
POWER SUPPLY INTERFACE UNIT
AC POWER
DC POWER
SYNC SIGNALS
AC SUPPLIES
DC SUPPLIES
ANALOG SIGNALS (HI SPEED)
HI SPEED A→D CONVERTER
ANALOG SIGNALS (LO SPEED)
X BAR SCANNER
ANALOG DATA
SWITCH
DVM
SCANNER CONTROL
TEST POINT PANELS
RATE TABLE INTERFACE
24 HOUR CLOCK
X-Y SCOPES

Recommended Modifications to ERC SSCMS to Obtain Gimbal System Testing Capability

To convert to gimballed systems, the only major equipment addition would be to provide a means of torquing the gyros and/or the gimbal motors. HSSC suggests the following hardware implementation (Reference attached block diagram).

(a) DC Drive Systems: HSSC will furnish additional HP-6130B programmable power sources each capable of voltages to ±50 volts and currents of 1 amp. Resolution is 1 millivolt. Supply amplitude is under computer control.

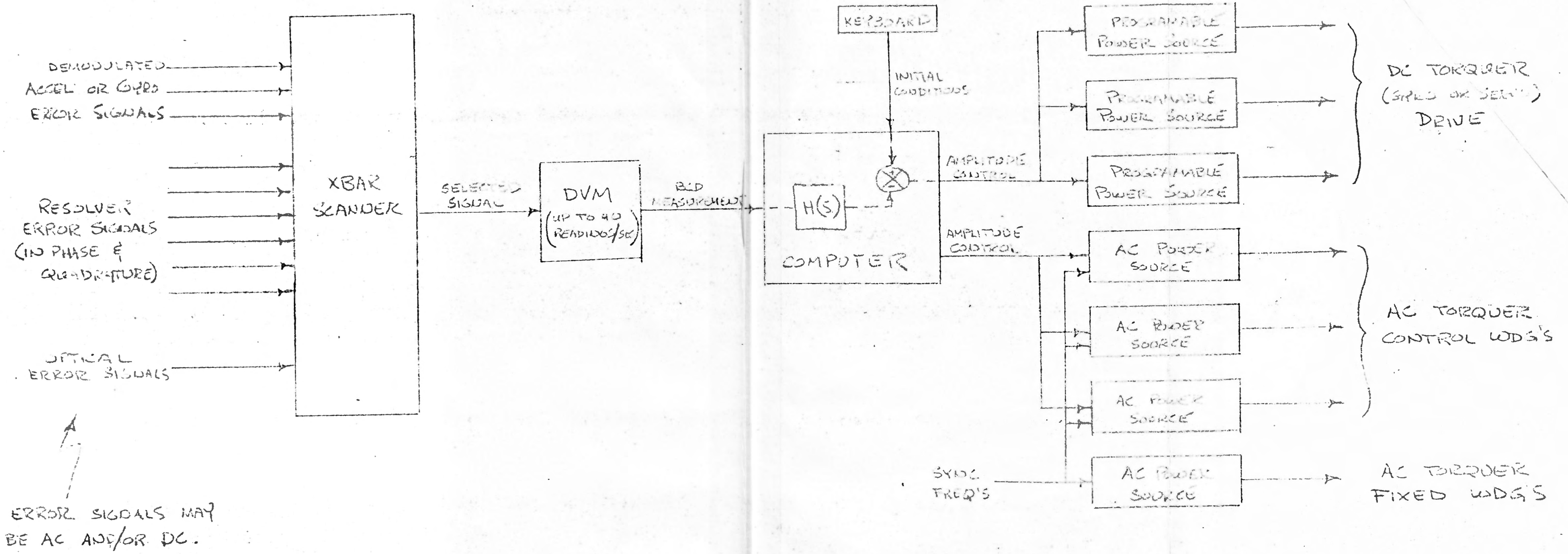
(b) AC Drive Systems: HSSC will furnish additional AC power supplies such as the microsyn supply described on succeeding pages. This supply is capable of 0 to 35 volts rms and currents of 1 amp. Resolution is 1 millivolt, and amplitude voltage and frequency is under computer control.

---OR---

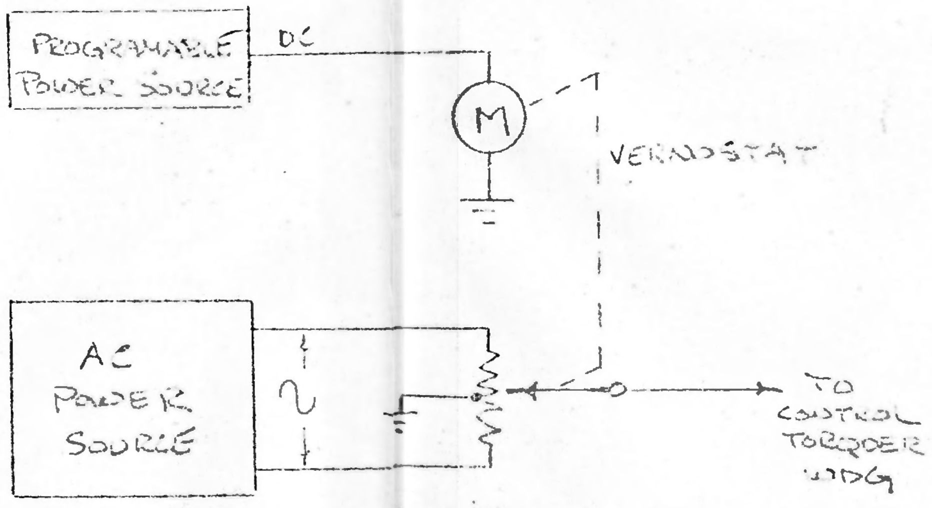
HSSC will furnish Vernostats (motor driven center tapped potentiometers) driven by the HP-6130 Programmable Power Sources.

Measurement of the error signal, wiether it be the gyro output or the gimbal resolvers, will be accomplished using the DVM and Crossbar Scanner provided. The computer then becomes the feedback element, and the software permits any response desired. Having measured the error signals, the computer then readjusts the signal (torquer or servo motor) amplitude to increase or decrease the driving force. It is expected that resolutions of 5 samples/second can be obtained.

All signal monitoring equipment would remain as described. The counters would not be required in this mode and would remain idle.



BLOCK DIAGRAM OF GYRO/SERVO CLOSED LOOP CONTROL
(GIMBAL TYPE SYSTEMS)



ALTERNATE TO AC DRIVE ABOVE

BRIEF DISCUSSION OF EQUIPMENT OPERATION

FIRST Program is loaded into non-volitile memory. Approximately 20 minutes required to complete.

SECOND Operator defines background TASK's (Non-Real Time) from his choices of test events using keyboard and/or paper reader as his input device. Such a TASK might look like:

TASK: Connect power to test article

COMPOSED OF: Events 79, 99, 98, 90, 77, 69

WHERE: Event #79 applies heater power and holds off other events until test article is up to heat.

Event #99 samples DC Voltage #1 and applies it to test article only if it is within acceptable limits

Event #98 samples DC Voltage #2 and applies it to test article only if it is within acceptable limits

Event #90 samples AC Voltage #1 and applies it to test article only if it is within acceptable limits

Event #77 applies spin motor excitation holding off further events until such time as wheels are up to speed

Event #69 samples all AC and DC voltages, wheel and microsyn frequencies, and temperature of test article and outputs results to teleprinter

NOTE: Event limits are alterable through keyboard.

THIRD Operator defines Foreground Tasks (Real Time) from his choiced of test events using keyboard or paper tape reader as his input device. Such a task might look like:

BRIEF DISCUSSION OF EQUIPMENT OPERATION (continued)

TASK: Safety check temperature and wheel current

COMPOSED OF: Events 63, 65

INTERVAL TIME: 10 seconds

WHERE: Event #63 measures wheel current, compares measurement against two sets of limits, alerts operator if inner set of limits is exceeded and shuts test article down if outer set of limits is exceeded

Event #65 measures temperature of test article, compares measurement against two sets of limits, alerts operator if inner set of limits is exceeded, and shuts down test article if outer set of limits is exceeded

NOTE: Event limits and interval times are alterable through the keyboard.

LAST Operator may remain in the Initialization Mode (Non-Real Time) and execute any or all Background Tasks and/or individual events in any order and at any time desired. Execution of these tasks and events is accomplished simply by typing the task name or event number on keyboard.

OR Operator may enter Run Mode (Real Time Operation) in which all Foreground Tasks will automatically commence. While in this mode, the operator can also execute any background task or event desired in a similar manner as before.

ADVANTAGES

1. HSSC has the experience, and NASA/Houston would benefit through proven design & existing software, such as:
   - (a) HSSC wrote our own real time executive encompassing foreground and background priorities and tasks. Foreground denotes real time operation, and background is non-real time. Foreground tasks are performed on a time interval basis; whereas, background tasks are performed under operator initiated action. Foreground always has priority over background. NOTE: The Hewlett-Packard DACE executive was unacceptable as it could not operate in both foreground and background simultaneously.
   - (b) HSSC wrote our own CRT interface software as none was existant. It should also be noted that our application was the first such interface of any CRT display with a Hewlett-Packard computer.
   - (c) HSSC has existing a library of user event software, much of which can be applied to NASA/Houston's applications. Note subsequent user event descriptions.
2. By being able to operate in foreground and background simultaneously, the Automated Test Equipment will be capable of performing extensive safety checking (foreground tasks) while performing the testing sequence (background tasks). Safety checking can be expanded to cover any parameter that can be measured and/or controlled.
3. Because of the computer's ability for ordered action, self-check programs can be written to essentially calibrate itself. This is done in a fashion in many of the user event routines, such as:
   - (a) Measuring the voltage and comparing against preset limits before applying to test article.

(b) Advising the operator if the counters do not output.

(c) Advising the operator when safety parameters fall beyond safe limits.

4. The hardware provided gives an extensive capability for future implementation, for example:

   (a) The high speed A/D converter can be used for vibration analysis because of its capability of sampling 16 channels of information at a 100 KHz rate.

   (b) The Wave Analyzer can be used to perform dynamic bias tests by using its output (1 Hz to 5 KHz) to drive a rate table, or it can also drive a vibration table.

   (c) Patchboards give rapid changeover when modifications or system changes direct.

   (d) Programmable Power Supplies can be used to generate controlled transients or ripple on power lines for noise susceptability tests.

   (e) The Calcomp Plotter can be used for X-Y plots, or even real time stability plots.

   (f) Interface units are designed to make maximum use of the support equipment. Special circuitry in these HSSC designed interface units permit remote control via the HP computer of these devices. Interface Unit citcuitry would typically:

      (1) Connect/disconnect power supply outputs to the load under computer command.

      (2) Start/stop counters under computer command.

      (3) Route counter input signals under computer command.

      (4) Provide counter input sensitivity adjustments.

      (5) Control Wave Analyzer input signal as well as meter scale.

      (6) Provide isolation for data pulse trains from test article.

5. With the addition of a small amount of circuitry, it may be possible to use this Automated Test Equipment to test gimballed guidance systems as well. Computer controlled power supplies such as the HP-6130B can be used for torquing and gimbal slewing. The low speed A to D converter existing in the station is more than capable of monitoring the resolver outputs; and where drift plots are required, the Calcomp plotter fits in nicely. Spin motor and pick-off excitation supplies are already included and can be used with thise gimballed systems as well.

USES OF EQUIPMENT

The prime use of this automated test station is to provide excitation to the test article, accumulate and process data received from the test article, provide a high degree of safety monitoring of critical parameters, and finally test control under the operator's supervision.

The equipment and the software required to accomplish this is described in the succeeding pages along with a discussion of the operation of the computer and operator communications. It should be noted that HSSC has completed a similar test equipment complex for NASA/ERC, and much of the discussion here reflects upon this equipment. The hardware/software approach recommended for this automated test station will be identical with that of NASA/ERC and will embody the proven concepts and valuable experience obtained through our past performance.

The hardware/software combination which HSSC proposes will provide NASA/Houston with extreme flexibility and a ready capability of performing the following more common tests:

(a) Electrical Frequency Response

(b) Static Error Coefficient Calibration

(c) Gyro Scale Factor Linearity

(d) Accelerometer Scale Factor Linearity

(e) Pulse Moding

By ready capability is meant, the hardware necessary to perform the test (less special devices, viz., collimators, rate table, and coolant equipment), the software necessary to perform the mechanics of the test, the software necessary to reduce the data obtained, and the hardware and software required to display or output the reduced data.

Other tests which can be performed with the addition of software ~~by NASA~~/ for NASA/ Houston include:

(a) Saturation Tests

(b) Vibration Analysis

(c) Dynamic Error Coefficient Tests

(d) Mechanical Frequency Response

(e) Voltage Sensitivity Tests

(f) Gyro Motor Performance Tests

(g) Environmental Tests

~~Further, additional hardware and software can be added at a later date so as to be capable of performing these additional tests:~~

(i) Navigation

(j) Gyro Component Tests

(k) Gyro Tumble Tests

Uses of HP-5601A Hi-Speed A/D Converter

1. Since the HP Hi-Speed A/D Converter has a capability of 16 input channels and 100,000 samples/second, it can be used as follows:
   - (a) Vibration table accelerometers can be monitored; thus, the true vibration profile can be obtained.
   - (b) Sensor or gimbal response to a step function can be observed and damping characteristics determined.
   - (c) Loop behavior can be observed in the presence of a disturbing function such as vibrations or rotations with knowledge obtained such as loop saturation points.
   - (d) AC and DC voltages can be monitored for intermittant conditions.
   - (e) AC signals can be recorded for later waveshape analysis.

PERFORMANCE CHARACTERISTICS OF EQUIPMENT

2.1 Digital Control Unit Capabilities

Measurement System is comprised of:

DCU
Analog Data Scanner
Analog-to-Digital Converter (DVM)
Teleprinter

Capability (DCU)

32 K Memory
48 Input/Output Channels
1.6 Microsecond Cycle Time
16 Bit Word Size
Direct Memory Access
ASA Basic Fortran Programming

Capability (Analog Measurements)

Up to 40 readings per second
0.01% DC Accuracy Typical
0.06% AC Accuracy Typical at 100 Hz - 10 KHz
0.013% Resistance Accuracy Typical at 1 K to 1 Meg
HI, LO, Guard for each measurement individually switched

2.2 Magnetic Tape Unit Capabilities

Provides a high speed recording media for digital data.

Utilizes 9 channel tape.

75 IPS tape speed.

Can be used as a high speed program loader.

Intermediate storage of raw data.

2.3 Data Display Capabilities

Provides visual information to the operator on the test being performed.

Alphanumeric only, 40 ASCII character set.

Controlled by the DCU.

Provision for connecting a slave unit with duplicate display.

2.4 Multiplexer - A/D Converter (Hi-Speed) Capabilities

Provides high speed measurement capability for analog signals.

16 Input Channesl

Sample rates to 100 KHz.

50 nanoseconds aperture time.

Input ranges of ±1 volt.

Accuracy - 0.03% of input typical ± LSB.

2.5 X-Y Plotter Capabilities

Graphically displays the processed data.

Interfaces with the DCU.

Generates alphanumeric symbols.

Positioning resolution of 0.01 inches.

Plot size of 11" x 17".

2.7 Programmable Power Source Capabilities

Provides programmable DC voltage to rate table to control its rate.

Provide programmable voltage as a function of time for special test; e.g., transient tests.

Controlled by the DCU.

Two voltage ranges:

0 to ±10 V DC
0 to ±50 V DC

1 amp driving capability.

10 KHz frequency limit.

2.8 Preset Counter Capabilities

Provides synchronization for sensor data counters.

Frequency range - 2 Hz to 100 KHz.

Sensitivity - 0.1 rms sine wave.

Input Impedance - 2 channels - 1 megohm, 50 Pf.

Accuracy - ±1 count ± time base accuracy ± trigger error.

Measures:

Normalized rate
Ratio
Normalized ratio
Time for N events to occur

N can be remotely programmed.

Gate control to counters as a function of N events.

2.10 Sensor Data Counter Capabilities

Measures inertial sensor outputs.

Two inputs - X & Y

Input sensitivity - 100 mv, all channels.

Frequency - 2 MHz, all channels.

Continuous sampling without loss of data between sampling (Read on the Fly).

2.11 Wave Analyzer Capabilities

Acts as a signal generator to excite the test article:

- Sine wave output
- Frequency range 1 to 5000 Hz
- Manually or automatically controller via DCU (Amplifier, Freq, and Scale)
- Sweep capabilities

Acts as a tuned voltmeter to measure the test article disturbance:

- Sensitivity 30 microvolts to 300 volts
- Input impedance 1 megohm
- Recorder outputs

Measures phase shift from input to output.

Measures voltage amplitude.

Measures noise (amp'l and Freq) content of input signals.

2.12 Monitor Oscilloscope Capabilities

Displays X-Y Lissijous patterns of sensor loops.

Seven (7) scope provided:

- 6 X-Y
- 1 Sweep

Isolated floating inputs.

1 inch x 3 inch viewing area.

Sensitivity - 0.1 volt to 10 V rms/inch

1 megohm input impedance.

2.13 Precision Power Supply Capabilities

Provide an ultra stable voltage for test article usage.

Voltage range - 0 to 36 volts

Current range - 0 to 10 amps.

Accuracy - ±0.05%

Stability - ±0.002% for eight hours.

Load Regulation - 0.001% for no-load to full-load.

Line Regulation - 0.0002% for 10% change.

Temperature Coefficient - ±0.001 per °C.

Over-Load Protection.

Over-Temperature Protection

Remote Sensing.

2.14 Bulk Power Supply Capabilities

Provide DC power to test article.

Voltage Range - 0-40 V.

Current Output - 0-30 A.

Remote sensing capability.

Overload Protection.

Load Regulation:

Constant Voltage - 0.01% + 200 uV
Constant Current - 0.02% + 3 MA

Line Regulation:

Constant Voltage - 0.01% + 200 uV
Constant Current - 0.02% + 3 MA

2.15 DC Power Supply (0-160 V) Capabilities

Provide DC power to test article.

Voltage Range - 0-160 V.

Current Output - 0-0.2 A

Remote sensing capability.

Overload Protection.

Load Regulation:

Constant Voltage - 0.02% + 2 MV
Constant Current - 200 microamps

Line Regulation:

Constant Voltage - 0.02% + 2 MV
Constant Current - 200 microamps

2.16 DC Power Supply (Dual) Capabilities

Provide DC power to test article.

Dual Range - 0-30 V, 0-60 V

Current Output - 0-1 A, 0-0.5 A

Remove Programming - 300 ohms/volt

Overload Protection

Load Regulation - 0.01% + 4 MV

Line Regulation - 0.01% + 4 MV

Remote sensing capability.

2.17 DC Power Supply (0-7.5 V) Capabilities

Provide DC power to test article.

Current Output - 0-3 A

Voltage Output - 0-7.5 V

Remote Programming

Constant Current - 500 ohms/amp

Constant Voltage - 200 ohms/volt

Overload Protection.

Remote sensing capability.

Load Regulation - 5 MV

Line Regulation - 3 MV

2.18 DC Power Supply/Amplifier Capabilities

Provide DC excitation to the test article.

Output voltage range - -50 V DC to +50 V DC at 1 amp

Remote programming at 500 ohms/volt

Load Regulation - 0.02% + 5 MV

Line Regulation - 0.02% + 5 MV

Time stability of 0.075%/8 hours

Temperature stability of 0.015% + 1 MV/°C

Can be used as an amplifier:

- 50 watt output
- DC to 20 KC bandwidth
- Gain of 0-10

2.19 Microsyn Supply Capabilities

Provides AC excitation for gyros and accelerometers.

Remote programmable (amplitude and frequency)

Output Characteristics:

- Sine wave
- 1 volt to 35 volts rms
- 400 Hz to 30 KHz (4 preselected discrete frequencies)
- 0.03% time stability/per week
- Single Phase
- Floating
- Overload protection

Auxiliary output for demod reference circuits.

2.20 Wheel Supply Capabilities

Provide wheel excitation to the gyros.

2 Phase or 3 Phase operation.

200 Hz to 5 KHz frequency operation.

Output voltages - 5 to 125 rms.

Stability of 0.03%/week.

2.21 Oscilloscope Capabilities

Provides the operator with display capabilities for signals via the test point panel.

Located on Operator's Console.

Features:

35 nanosecond rise time
1 megohm input impedance
two identical input channels
10 millivolts/division sensitivity
Signal delay permits viewing leading edge of signal
50 nanosecond/division sweep rate maximum
External horizontal input 0.2 V/division to 5 V/division
Single sweep operation

2.22 Test Point Panel Capabilities

Provides the operator with access to sensor data and other signals.

Provides a convenient means of routing these signals to the monitoring device(s).

Provides a total of 144 three-wire jacks.

48 output
96 input

Auxiliary panels in each console.

2.23 Power Supply Control Unit Capabilities

Provides voltage programming for the DC power supplies:

Fixed
Variable

Connects supply outputs to load:

AC supplies
DC supplies

Provides safety circuitry for over-voltage protection (DC supplies only)

Provides sine and square wave demod reference signals for the test article (from microsyn supplies)

2.24 Frequency Response Control Unit Capabilities (Driver and Relay Circuits)

Provides interface between wave analyzer and the test article.

Provides 20 MA driving capability.

Connects any of 12 test article outputs to the wave analyzer input (via DCU).

Capable of external input such as step function to the test article.

2.25 Crystal Clock and Countdown Capabilities

Provides clock and signal frequencies required by the SSCMS:

1.152 MHz
28.8 KHz
19.2 KHz
8.0 KHz
3.6 KHz
800 Hz
Plus many, many more

Temperature Stability:

3×10^{-7} from 0° to 50°C

Time Stability:

1×10^{-8} per day at 25°C

2.26 Counter Interface Unit Capabilities

Provide the necessary control and interface circuits required by the inertial counters.

Routes appropriate signals to counter inputs.

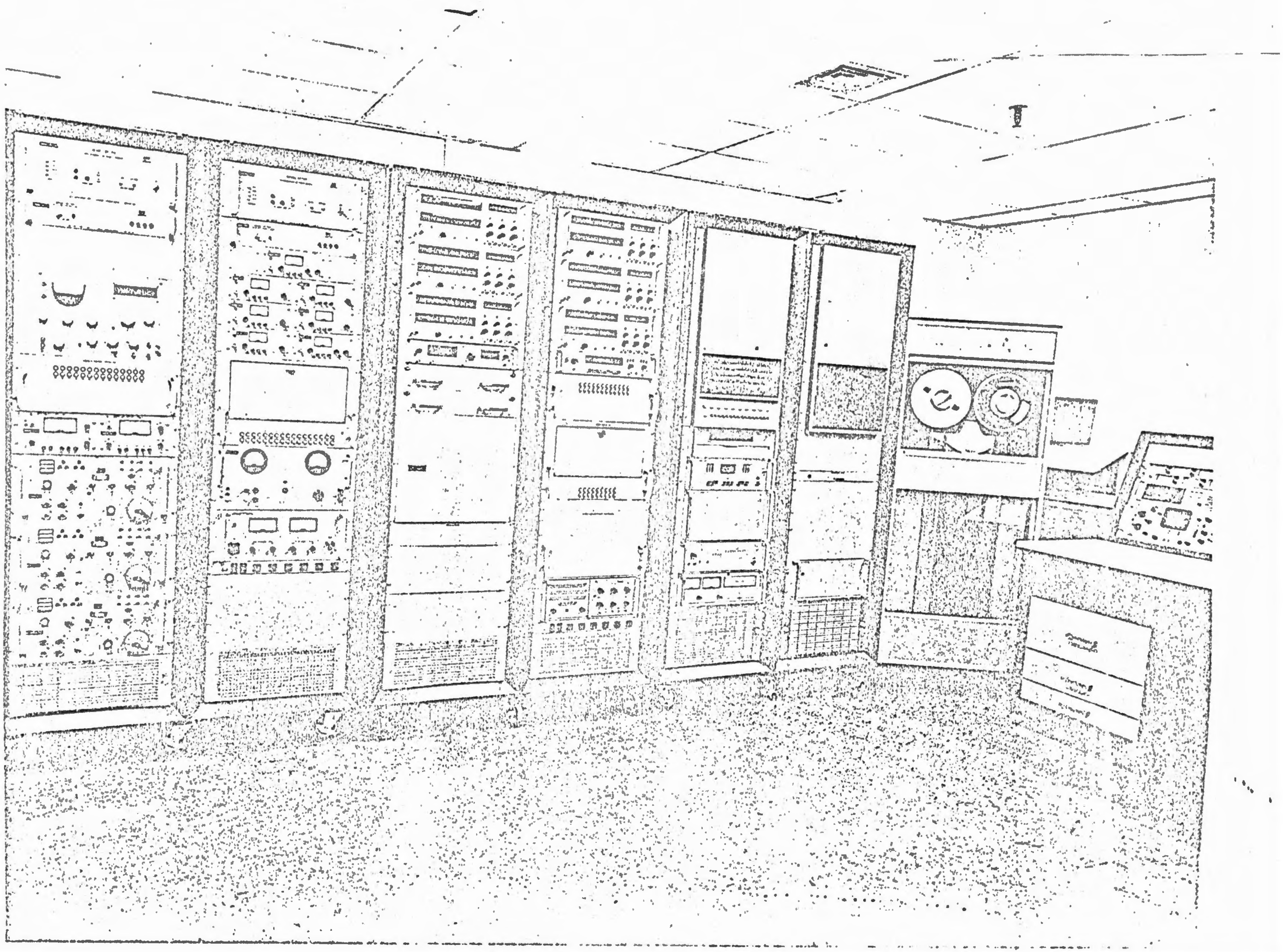
Provides amplitude sensitivity adjustments for input signals.

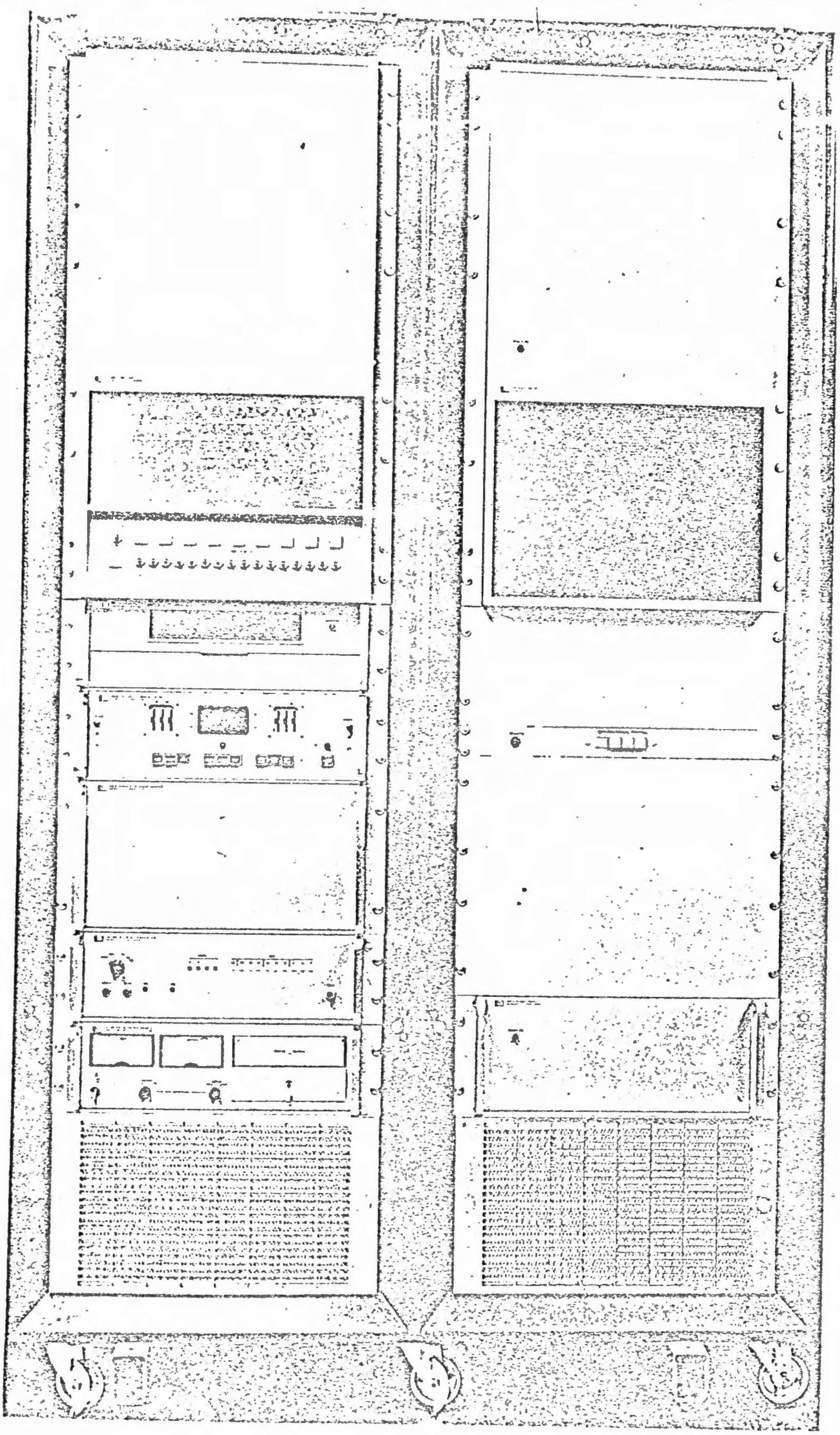
Provides single count capability.

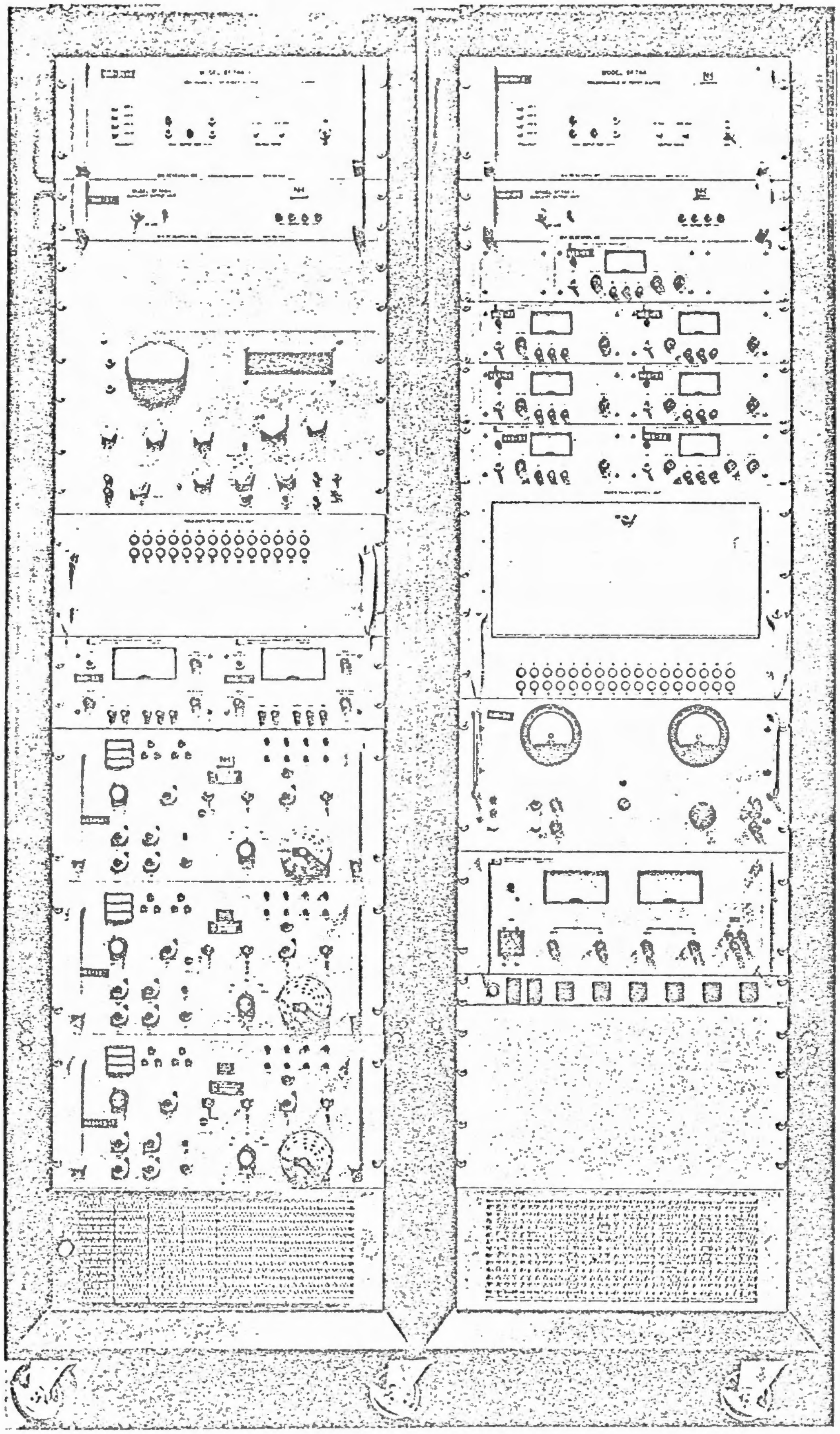
Provides logic circuits to synchronize gate opening and closing to system timing signals.

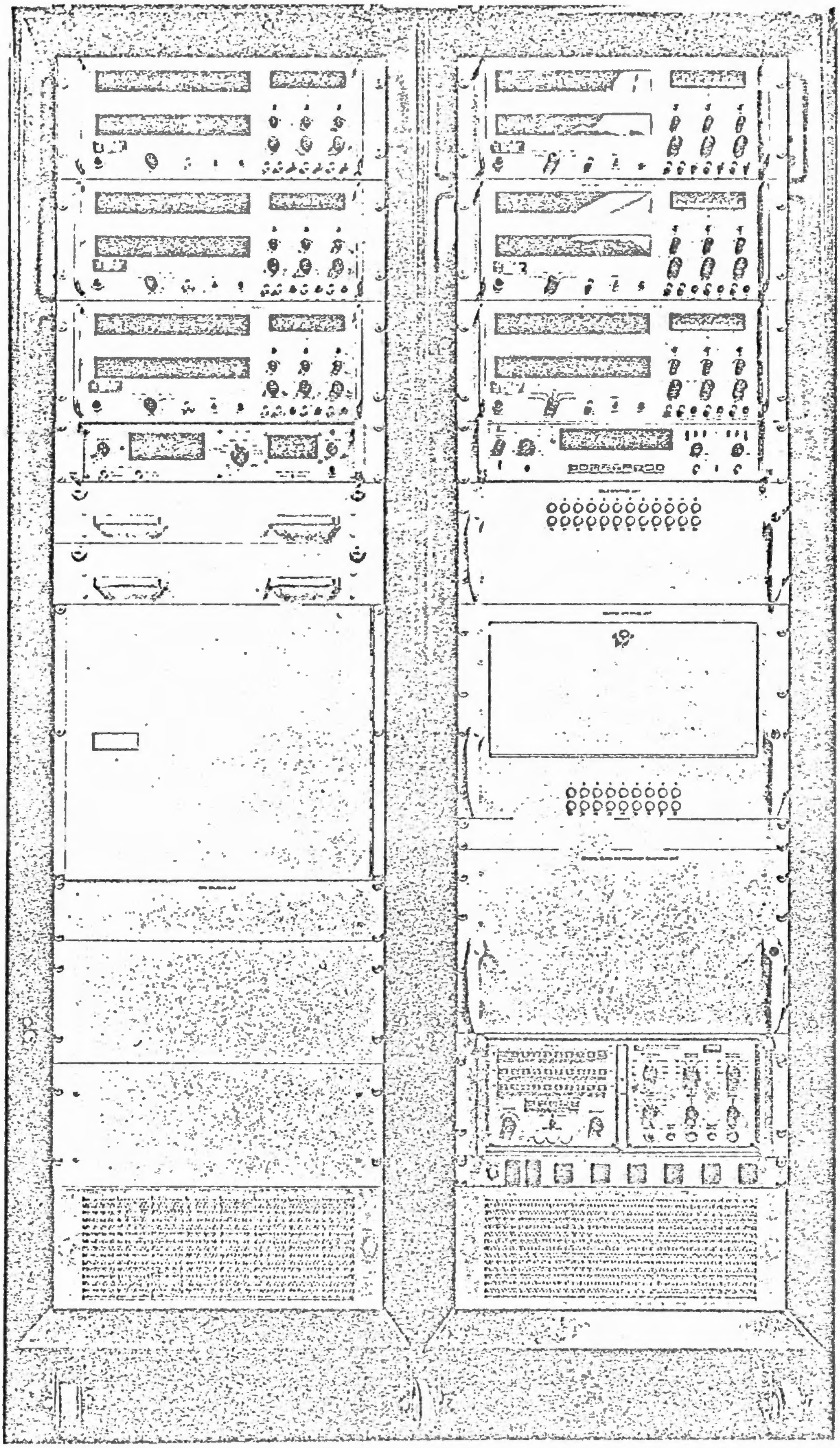
STRAPDOWN SYSTEM CONTROL
AND MONITOR STATION

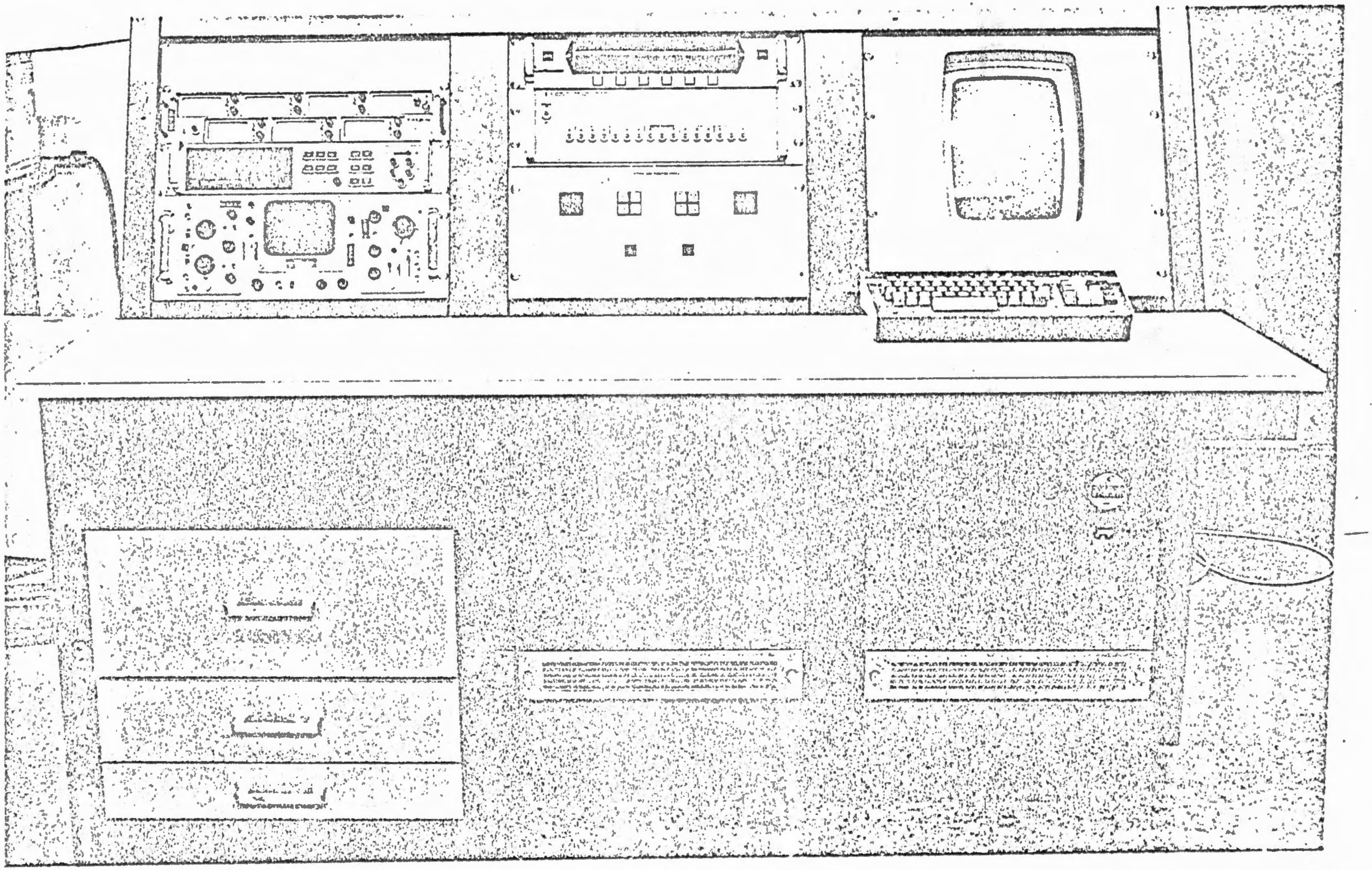
DESIGNED AND BUILT
FOR
NASA/ERC











DETAILED DISCUSSION OF OPERATOR CONTROLS AND COMMUNICATION WITH COMPUTER

3. EXECUTIVE PROGRAM OPERATION

The SSCMS Bimodal Real-Time Executive (BREX) program interfaces the user with the SSCMS event programs. It supplies the user with options for event data modification, manual event execution, construction of executable event sequences (tasks), and manual or time-base scheduled execution of tasks. Events may also be assigned to handle system interrupts.

3.1 Operational Modes

(a) Initialization Mode - Initialization mode provides the user with complete manual control of the system. Foreground and background tasks are constructed in this mode, time of day is set, and interrupt servicing events are assigned. Single events may be executed, and background tasks may be initiated. Event data and task times may be assigned. In this mode, each preassigned remote register switch corresponds to a single function (except while executing a background task).

(b) Run Mode - Run mode provides a multiprogramming environment for automatic execution of foreground tasks on a preassigned time interval basis while performing background tasks or single events on a manually scheduled basis. System control functions include event data modification, task time assignment, and return to Initialization mode. Background tasks may be initiated, continued (after a period of suspension), or killed. In this mode, all functions and user events are accessed through a single remote register switch (the "COMMAND" switch).

3.2 **Operator Communication** - The primary communication device for the BREX program and user events is the Sanders 720 CRT and keyboard part of the monitor control panel. The operator should normally watch the CRT screen for directives or messages from the system.

(a) **CRT Screen Format** - The standard BREX CRT screen format with the permanent titles is illustrated in Figure 1. The top line displays the date as MO/DA/YR (MO = month, DA = day, YR = year, all two digit numbers); time as HR:MN (HR = hours, MN = minutes, both two digit numbers); and system lag in seconds at the last turn of a minute as XXXX (a four digit number).

The remainder of the screen is divided into the four areas separated by the dotted lines and corresponding labels. The areas labeled "FOREGROUND", "BACKGROUND", and "EXECUTIVE" are output areas where messages, data, and directives are displayed. The "FOREGROUND" area (5 lines by 30 characters per line maximum) is primarily used by events which are designed to be executed as part of a foreground task while in run mode. The "BACKGROUND" area (5 lines by 30 characters ber line maximum) is primarily used by events and background tasks executed in initialization mode or as background programs in run mode. The "EXECUTIVE" area is used only by the BREX program for displaying executive messages and querying the operator for information necessary to an executive function such as modifying event data. The fourth CRT area is labeled "OPERATOR RESPONSE" and handles data preparation for input from the keyboard to the computer.

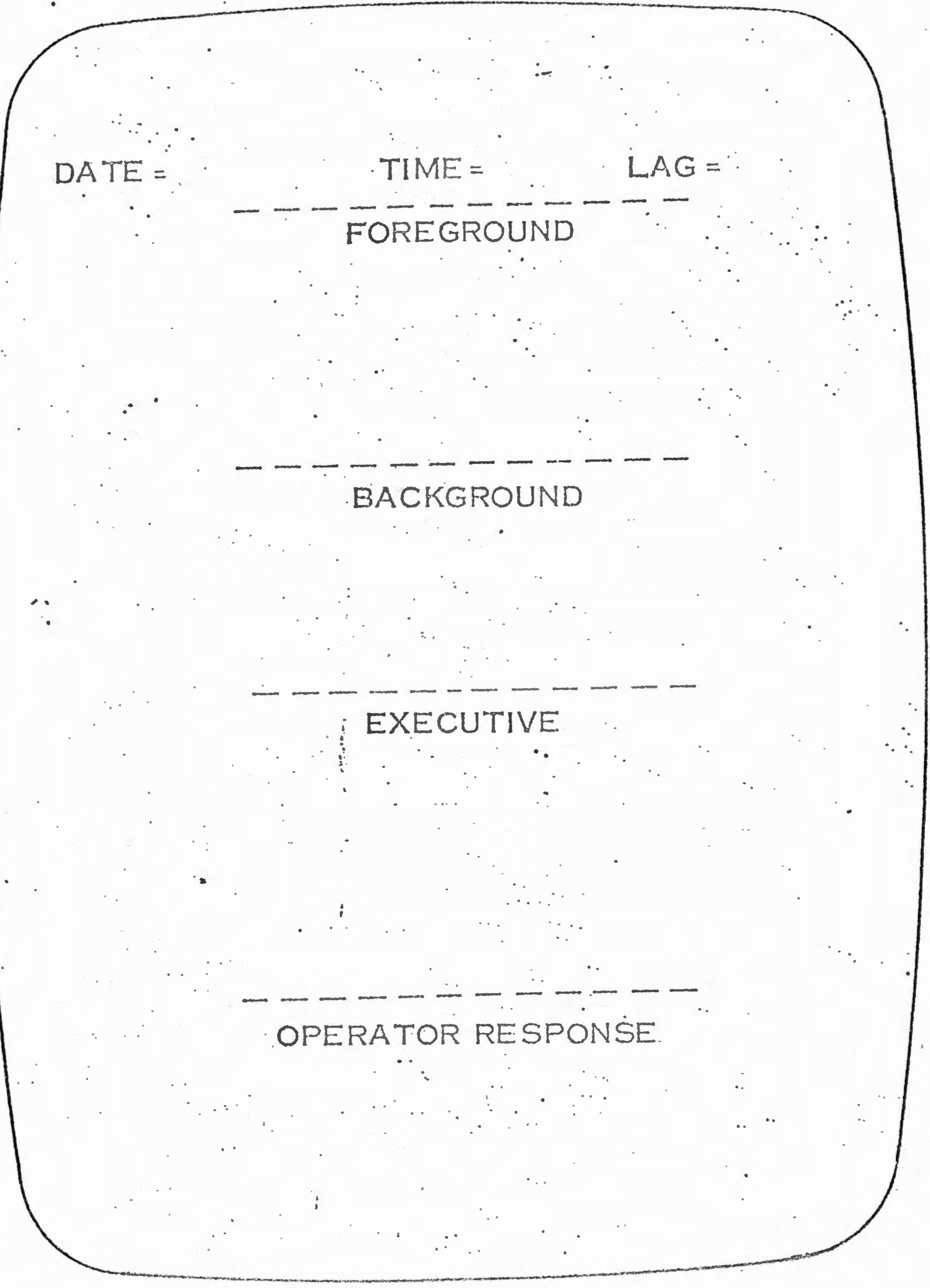


Fig. 1 - Standard BREX CRT Screen Format

(b) Keyboard - CRT Input Operation - Responses to system and user requests as displayed on the CRT screen are usually made with the Sanders keyboard on the monitor console. The cursor (blinking underline) on the CRT screen is positioned by the computer to the beginning of the area labeled "OPERATOR RESPONSE".

The operator now types in the appropriate information using the CRT keyboard like a typewriter keyboard, with each character pressed being displayed in consecutive locations in the input area. Up to 100 characters can be entered at one input operation.

Any mistakes in entering the information that are made may be corrected by pressing the "SHIFT" key with the "SPACE" key as many times as necessary to backspace the cursor to the beginning of the error. From that point, the operator may resume typing the input in a correct manner. Having finished typing the necessary information, the operator should check it for mistakes then, if verified, press the "SEND BLOCK" key to transmit the information to the computer and terminate the input operation.

3.3 Remote Switch Register Functions - Operator control of the BREX program is implemented through the remote switch register on the monitor console. The switches are used to invoke the various executive functions as labeled on the register for each of the two modes of operation. A function is invoked only when a single switch is set (execpt when using PAPER TAPE INPUT option switch).

(a) Initialization Mode - The following are the switch assignments for operation in Initialization Mode. The desired function is executed when the corresponding switch is set (placed in the "UP" position) after having been in the off ("DOWN") position.

SWITCH	FUNCTION
15	COMMAND OPTION TO EXECUTIVE EVENT - suspends background task processing to execute command or user events
14	SYSTEM ABORT - stop all event and task executions and restart system
13	available to user events
12	available to user events
11	ENTER RUN MODE - start automatic execution of Foreground tasks
10	SET TIME OF DAY - initializes system clock
9	ASSIGN TASK TIMES - controls modification of Foreground task phase and interval times
8	DELETE FOREGROUND TASK - deletes the last assigned Foreground task sequence
7	DELETE BACKGROUND TASK - deletes the last assigned Background task sequence
6	EXECUTE BACKGROUND TASK - initiates execution of a specified Background task sequence
5	EXECUTE EVENT - initiates execution of a specified event
4	ASSIGN INTERRUPT SERVICE EVENT - handles linking of a user event to a system interrupt
3	ASSIGN FOREGROUND TASK - allows the user to specify sequences of events to be executed automatically in run mode
2	ASSIGN BACKGROUND TASK - allows user to specify sequences of events to be executed manually
1	ASSIGN EVENT CONSTANTS - allows the user to modify event data
0	PAPER TAPE INPUT - allows the user to input on paper tape parameters requested by the executive functions or display remaining tasks after task deletion

(b) Run Mode - The switch assignments for Run Mode follow; again, the desired function is executed when the corresponding switch is set.

SWITCH	FUNCTION
15	COMMAND OPTION TO EXECUTE EVENT - suspends background task processing to execute command or user events
14	SYSTEM ABORT - stop all event and task executing and restart system
13	available to user events
12	available to user events
11-0	reserved for SSCMS applications

3.4 Response Format[1] - Response made to the BREX program requests for numeric data from the CRT keyboard or paper tape reader are in free field format. Certain symbols are field delimiters, eliminating the need for fixed data field bounds. Special symbol usage is:

space or ,	Data item delimiters
/	Record terminator (list continuation) (DO NOT USE WITH CRT KEYBOARD)
+ -	Sign of item
. E + -	Floating point number
@	Octal integer

All other non-numeric characters are treated as spaces. Two or more consecutive spaces are treated as one space. Two consecutive commas indicate no new data are supplied for the corresponding item.

The following Teletype and CRT keyboard key symbols are used in illustrative examples:

CR	carriage return (Paper Tape Only)
LF	line feed (Paper Tape Only)
SB	send block (CRT keyboard only)

(a) Example - The following replies to the Executive request are all equivalent:

ENTER TIME (HRS:MIN:SEC)	Executive request
12:05:00 SB	possible responses
12,05,00 SB	
12 HOURS, 5 MINUTES, 0 SECONDS	

3.5 Command Option To Executive Event - This switch provides manual control in Run Mode or while executing a background task in Initilization Mode. At the end of the currently executing event of the background task (if any), the background task is suspended and control directed to the operator to execute an event. The following message is displayed:

COMMAND

EXECUTE EVENT

ENTER ----

EVENT NUMBER

The operator responds with a desired event number (an-integer 1-105). An event number outside the allowable limits will cause the additional line

ILLEGAL ENTRY - PHASE TERMINATED

to be displayed and control returned to the BREX program with the background task still suspended. Any of the 99 user events may be executed, or one of the following system command events may be chosen

EVENT NUMBER	FUNCTION
100	ASSIGN EVENT CONSTANTS
101	EXECUTE BACKGROUND TASK
102	CONTINUE BACKGROUND TASK
103	KILL BACKGROUND TASK
104	ABORT JOB STEP - RETURN TO INITILIZATION
105	ASSIGN TASK TIMES

The background task that was in operation when the COMMAND option was invoked remains suspended after the manual execution of an event; command event 102 must be used to continue execution of the background task.

(a) Command Event Descriptions

ASSIGN EVENT CONSTANTS - See 3.17

EXECUTE BACKGROUND TASK - See 3.12

CONTINUE BACKGROUND TASK - This command event removes the hold-off on the current background task.

KILL BACKGROUND TASK - This command event deactivates the currently executing background task.

ABORT JOB STEP - This command event terminates all background and foreground (if in Run Mode) tasks and returns control to Initialization Mode (if not already in Initialization Mode).

ASSIGN TASK TIMES - See 3.9

(b) Example - Assume a background task is executing and it is desired to execute event number 35. The COMMAND switch is set (up) until the following message appears on the CRT (EXECUTIVE area):

COMMAND

EXECUTE EVENT

ENTER ----

EVENT NUMBER

Now the COMMAND switch is put in the off (down) position and the user responds via the CRT keyboard with:

35 SB

Event 35 is then executed by the computer and when finished with it, the line

EVENT DONE

is appended to the preceeding CRT message. To continue executing the background task, the COMMAND switch is set,

COMMAND

EXECUTE EVENT

ENTER ----

EVENT NUMBER

appears on the CRT screen and the user responds with

102 SB

and the completion message

EVENT DONE

is displayed after the preceeding message. The background task is then resumed.

Note that instead of executing command event 102 to continue the background task, the user may have elected to execute another user event or other system command events. There are no restrictions on the number of times the COMMAND option can be exercized, or when, if ever, a background task is continued.

This switch and the SYSTEM ABORT switch are the only Executive control switches available in Run Mode.

3.6 System Abort - An event may be in the process of execution (either as a single event or part of a foreground or background task) when it is desired to prematurely exit from it. Moving the SYSTEM ABORT switch to the up position immediately terminates any event in progress, kills any pending background or foreground tasks, resets system lag to zero, and restarts the system with control passed to the SET TIME OF DAY processor (see 3.8) in Initialization Mode. The switch should immediately be moved to the down position to avoid repeated aborts.

3.7 Enter Run Mode - When the user has finished constructing foreground tasks and is ready to place them in automatic execution, the ENTER RUN MODE switch is used to process the transition from Initialization Mode to Run Mode. On setting this switch up, the following message appears on the CRT:

```
SET COMMAND SWITCH, TYPE IN "GO"
DOWN = RUN
UP = RETURN TO INITIALIZATION
```

At this point, the user may decide to return to Initialization Mode. This option is selected by setting the COMMAND switch up and responding via the CRT keyboard with

```
GO SB
```

The new message that appears is simply

```
INITIALIZATION MODE
```

to indicate the current mode of operation.

Any response other than "GO" to the Executive query causes the message

RETRY

to be appended to the request and the operator then may enter the correct response.

NOTE: Once in Run Mode, the only methods of return to Initialization Mode are either the system command event no. 104 (ABORT JOB STEP) or the SYSTEM ABORT switch.

3.8 Set Time of Day - This switch initializes the system clock. Moving the SET TIME OF DAY switch to the up position causes the following message to be displayed on the CRT screen:

```
ENTER DATE (MONTH, DAY, YEAR)
```

The response to this request is the numeric month, day, and year such as:

```
8, 27, 69   SB
```

The system then displays the request for time-of-day:

```
ENTER TIME (HRS:MIN:SEC)
```

In response, the operator types in the time in hours, minutes, and seconds a few seconds in the future and then waits for the actual time to arrive before pressing SB to start the clock and synchronize it with the actual time:

```
10:31:45 SB
```

The SB was pressed at 10:31:45.

3.9 Assign Task Times - Every foreground task has a phase time and an interval time (both in seconds) assigned to it at time of construction. Upon entering Run Mode, each foreground task is executed initially after a delay equal to its phase time, and thereafter executed at a frequency equal it its interval time. The ASSIGN TASK TIMES function, invoked as a switch register function or a system command event, allows modification of the phase and interval times for any foreground task.

When invoked, the function displays this message identifying it and requesting the task name:

ASSIGN TASK TIMES
ENTER ----
TASK NAME

The operator responds with the task name and a SB (if using CRT keyboard). If the foreground task as named does not exist, the error message

ILLEGAL ENTRY - PHASE TERMINATED

is appended to the preceeding message and control returned to the system. Upon entering the task name, the message is changed to request the task times:

ASSIGN TASK TIMES
ENTER ----
PHASE & INTERVAL TIMES

The operator responds with the two times which may be in the range 1 to 32768. An out-of-range value causes the error message

ILLEGAL ENTRY - PHASE TERMINATED

to be appended to the display and control returned to the system.

(a) Example - Assume a foreground task exists with the name of "CAL" and the task times to be assigned are a phase time of 20 seconds and an interval time of 45 seconds. Upon invoking the function, the following is displayed:

ASSIGN TASK TIMES

ENTER ----

TASK NAME

The operator response is:

CAL SB

The display becomes:

ASSIGN TASK TIMES

ENTER ----

PHASE & INTERVAL TIMES

The operator response is:

20, 45 SB

The Executive CRT display is either appended by the message

EVENT DONE

if the function was run as a command event or is cleared and displays

INITIALIZATION MODE

if run as a switch function.

3.10 Delete Foreground Task - This switch function deletes the most recently constructed foreground tasks. When the switch is set, the following message is displayed:

PREVIOUS FGRD TASK DELETED

indicating that the task has been deleted. When there are no foreground tasks defined, the message that is displayed is:

PREVIOUS FGRD TASK DELETED

NO ENTRIES REMAIN

The remaining foreground task entries will be displayed by name when the PAPER TAPE INPUT switch is set to the up position while the DELETE FOREGROUND TASK switch is used.

(a) Example - Assume there are four foreground tasks defined in the order given:

TASK NAME

CAL

TEST

TRY1

LAST

To delete the most recently assigned foreground task (the one named "LAST") and receive a display of the remaining foreground task names, the operator does the following:

1. Set PAPER TAPE INPUT switch up.
2. Set DELETE FOREGROUND TASK switch up.

The following display is issued:

```
PREVIOUS FGRD TASK DELETED
CAL
TEST
TRY1
```

The operator then sets both the PAPER TAPE INPUT and DELETE FOREGROUND TASK switches to the down position and control is returned to Initialization Mode.

3.11 Delete Background Task - This function deletes the most recently constructed background task. The method of execution is the same as for DELETE FOREGROUND TASK. The PAPER TAPE INPUT switch is used to obtain a list of remaining tasks.

(a) Example - Assume there are three background tasks defined in the order given:

TASK NAME

BACK

CTR

RLAY

To delete the most recently assigned background task (named "RLAY") without a display of those remaining, the operator just sets the DELETE BACKGROUND TASK switch up. The following message confirms the task deletion:

PREVIOUS BGRD TASK DELETED

The operator sets the switch down and control is returned to Initialization Mode. Now the most recently assigned background task is "CTR". To delete this task and obtain a display of those remaining, the PAPER TAPE INPUT switch is set to the up position. Then the DELETE BACKGROUND TASK switch is set causing the task deletion and the following message:

PREVIOUS BGRD TASK DELETED

BACK

When this last task is deleted (with or without the PAPER TAPE INPUT switch set) the message displayed is:

PREVIOUS BGRD TASK DELETED

NO ENTRIES REMAIN

3.12 Execute Background Task - This function is available either as system command event no. 101 or under switch control. It is the means for initiating execution of an assigned background sequence. Upon invoking this function, a message identifying it and requesting the name of the task to be executed is displayed:

EXECUTE BACKGROUND TASK

ENTER ----

TASK NAME

The operator responds with the desired background task name. If a task name is entered that has not been defined, or if there is already a background task in execution, the following error message is appended to the display and control returned to the system:

ILLEGAL ENTRY - PHASE TERMINATED

NOTE: When the EXECUTE BACKGROUND TASK function is selected via the switch register in Initialization Mode, operator control for the duration of the background task execution must be directed through the COMMAND switch; Initialization Mode operation is temporarily suspended until the background task is finished and the message

INITIALIZATION MODE

is displayed to notify the operator of the task completion.

When invoked in the Run Mode, after entering the desired task name, the message

EVENT DONE

is appended to the display. When the background task is finished, this completion message is appended to the CRT display:

DONE

In either mode of operation, use of the COMMAND switch is the only system control the operator may exercise (except, of course, the ABORT switch). Use of the COMMAND switch will suspend the background task until the operator takes action to alter the suspension (by a system command event to continue or kill the background task).

3.13 Execute Event - This switch allows the user to manually initiate execution of a specified event. When the EXECUTE EVENT switch is moved to the up position, the following message appears on the CRT identifying the function and requesting the event number:

EXECUTE EVENT
ENTER ----
EVENT NUMBER

The operator responds with the integer number of the event it is desired to execute. If the response is not within the allowable range for event numbers (1-105), the following error message is appended to the preceeding message and control returned to Initialization Mode:

ILLEGAL ENTRY - PHASE TERMINATED

When the event number is entered and the SB key pressed, execution of the desired event is initiated. At completion of the event, the EXECUTIVE CRT area is cleared and this mode identification message is displayed:

INITIALIZATION MODE

This signifies that the BREX program is ready to accept further switch commands in Initialization Mode.

3.14 ASSIGN INTERRUPT SERVICE EVENT

For certain computer interrupts it is necessary for the user to supply special handling routines depending on the circumstances under which the interrupt occurs. The ASSIGN INTERRUPT SERVICE EVENT function allows the user to link up a specially written interrupt service event (see 2.2) on line to handle the interrupt on a specified channel. Upon setting this switch up, the following message is displayed identifying the function and requesting the service event number:

```
ASSIGN INTERRUPT SERVICE
ENTER--
INTERRUPT SERVICE EVENT NO.
```

The operator responds with the proper user event number. If the response is not in the range 1-99, this standard error message is appended to the display and control returned to Initialization Mode:

```
ILLEGAL ENTRY - PHASE TERMINATED
```

Upon responding with the service event number, the CRT displays the request for the channel number:

```
ASSIGN INTERRUPT SERVICE
ENTER--
SERVICE CHANNEL NO.
```

The operator responds with the channel number, usually in octal. If this response is not within the range 5_8-77_8 , this error message is appended to the display and control returned to Initialization Mode:

```
ILLEGAL ENTRY - PHASE TERMINATED
```

A legal response to the request for the service channel numbers will cause the BREX program to establish the linkage necessary for control to pass to the specified event when an interrupt occurs on the specified channel. The message area is cleared and the mode identifying line

INITIALIZATION MODE

is displayed.

Example: Assume it is desired to assign event number 5 to service interrupts coming in on channel number 10_8 . The ASSIGN INTERRUPT SERVICE switch is set up, then down. The CRT displays:

ASSIGN INTERRUPT SERVICE

ENTER--

INTERRUPT SERVICE EVENT NO.

The operator responds with

5 SB

The CRT displays:

ASSIGN INTERRUPT SERVICE

ENTER--

SERVICE CHANNEL NO.

The operator responds with

@10 SB

and the CRT displays

INITIALIZATION MODE

NOTE: Do not assign to interrupt service an event that has not been specifically prepared for interrupt service (see 2.2 for event construction method).

3.15 ASSIGN FOREGROUND TASK

This function allows the user to construct a logical sequence of events under a single symbolic name to be executed automatically, on a specified schedule, upon entering Run Mode. Upon setting the ASSIGN FGRD TASK switch up and down, the CRT displays this message identifying the function and requesting the symbolic task name:

```
ASSIGN FOREGROUND TASK SEQUENCE
  ENTER--
TASK NAME
```

The operator responds with an alphanumeric name up to four characters long. If the name is greater than four characters, only the first four are used. If the name is already defined as a foreground task (background task names may be duplicated) the message is displayed and control returned to Initialization Mode:

```
ILLEGAL ENTRY - PHASE TERMINATED
```

After the task name is entered, the CRT display requests the number of events in the task sequence:

```
ASSIGN FOREGROUND TASK SEQUENCE
ENTER--
EVENT COUNT
```

The response is the number of events to be used in the task sequence (1-50); if an event is used more than once it is counted at the number of times it is used. The CRT display then requests the list of events:

```
ASSIGN FOREGROUND TASK SEQUENCE
ENTER--
SEQUENCE EVENTS
```

The event numbers are entered in the order in which they are to be executed. An out of range event number causes the standard error-on-entry message to be displayed. If there is no room left in the task table the following error message is displayed and control returned to Initialization Mode:

TASK TABLE OVERFLOW

Finally the Executive displays the request for the phase and inteval time in seconds. Upon entering Run Mode, the tasks will be executed the first time after a delay equal to the phase time and thereafter at a frequency equal to the interval time.

ASSIGN FOREGROUND TASK SEQUENCE

ENTER

PHASE & INTERVAL TIMES

If either of the two times are not in the rang 1 - 32767, the following error message is displayed and control returned to Initialization Mode:

ILLEGAL ENTRY - PHASE TERMINATED

Upon receiving correct phase and interval times, the BREX program stores the task information in a table for use in calling it up when needed. The function then clears the CRT display area and recycles to define another task by requesting another task name (note that after the first task definition the heading line is omitted):

ENTER--

TASK NAME

The operator may construct another task sequence and continue to cycle in this function until all desired task definitions have been completed.To terminate this function, the operator responds with a task name of "0" which will return control to Initialization Mode.

Example: Suppose a foreground task is to be constructed with the name of "CHEK". When in Run Mode, it is to sequence through the five events in the order given starting at 10 seconds and then every 35 seconds:

Event No.

3

2

10

25

2

The ASSIGN FGRD TASK switch is set up then down, and the CRT displays:

ASSIGN FOREGROUND TASK SEQUENCE

ENTER--

TASK NAME

The operator response is:

CHEK (SB)

The display becomes

ASSIGN FOREGROUND TASK SEQUENCE

ENTER--

EVENT COUNT

The response is

5 (SB)

Then the CRT displays

ASSIGN FOREGROUND TASK SEQUENCE

ENTER--

SEQUENCE EVENTS

The response is

3,2,10,25,2 (SB)

The CRT then displays

ASSIGN FOREGROUND TASK SEQUENCE

ENTER--

PHASE & INTERVAL TIMES

The operator response is

10,35 (SB)

Now the task "CHEK" is completely defined and stored, so the function starts processing for another task:

ENTER--

TASK NAME

To terminate the function the operator response is

0 (SB)

The CRT display becomes

INITIALIZATION MODE

Upon entering Run Mode the foreground task "CHEK" will go into automatic execution.

3.16 ASSIGN BACKGROUND TASK

This function enables the construction of logical sequences of events under symbolic names that may be called up for manual execution in either Initialization Mode or Run Mode. The procedure for construction a background task is exactly the same as for constructing a foreground task (see 3.15) with the exception that there are no phase and interval times for a background task so these are not requested.

Example: Assume a background task is to be created and named "CAL." It is to consist of four events in the order given:

Event No.
20
6
6
69

The ASSIGN BKGRD TASK switch is set up then down, and the CRT displays

```
ASSIGN BACKGROUND TASK SEQUENCE

ENTER--

TASK NAME
```

The operator response is

CAL (SB)

The display becomes

```
ASSIGN BACKGROUND TASK SEQUENCE

ENTER--

EVENT COUNT
```

The operator response is

4 (SB)

Then the display is

```
ASSIGN BACKGROUND TASK SEQUENCE

ENTER--

SEQUENCE EVENTS
```

The response is

20,6,6,69 (SB)

Now the background task "CAL" has been entered into the task table and the functions recycles, ready to define another background task:

```
ENTER

TASK NAME
```

The function is terminated with a zero task name:

0 (SB)

The display becomes

INITIALIZATION MODE

The background task named "CAL" may be called up by the EXECUTE BACKGROUND TASK function as a switch command or as a system command event.

3.17 ASSIGN EVENT CONSTANTS

This function allows the uses to modify data in events which have been declared as accessable in the call to EVENT (see 2.3 for specification of accessable data elements for events). It may be invoked either by switch command or as a system command event. For either method, the CRT keyboard is the standard processing device, but for the switch command only, a special paper tape input procedure is available.

Under CRT keyboard operation, data items to be modified must be uniquely specified. Upon invoking the function for CRT operation, the following message is displayed identifying the function and requesting the event number, which array (real or integer), and which element of the array:

ASSIGN EVENT CONSTANTS

ENTER--

EVENT, ARRAY, ELEMENT NUMBERS

The response is 3 integers, for the event number (1-99), the array number (0=real array, any nonzero number = integer array), and the element number (bound by event definition). If the event number is out of bounds (excepting 0) or an array or element number specified which is not declared as accessable in the event, the following error message is displayed and control returned to the Executive:

ILLEGAL ENTRY - PHASE TERMINATED

Having received the event, array, and element numbers, the BREX function then requests either the real or integer constant as specified in the array type number:

ASSIGN EVENT CONSTANTS

ENTER

REAL CONSTANT

OR

ASSIGN EVENT CONSTANTS

ENTER--

INTEGER CONSTANT

The operator responds with the desired data item, and the function recycle to the beginning to enable modification of another constant:

ASSIGN EVENT CONSTANTS

ENTER--

EVENT, ARRAY, ELEMENT NUMBERS

The process is repeated until an event number of "0" is entered to properly terminate the function.

Example: Suppose the third element of the accessable real data array and the fifth element of the accessable integer data array of event number 53 are to be given the values of 49.75 and 202 respectively. Invoking the ASSIGN EVENT CONSTANTS function brings the following message to the CRT screen:

ASSIGN EVENT CONSTANTS

ENTER--

EVENT, ARRAY, ELEMENT NUMBERS

The operator response is:

53,0,3 (SB)

The CRT display becomes

ASSIGN EVENT CONSTANTS

ENTER--

REAL CONSTANT

The reply is

49.75 (SB)

The display again becomes

ASSIGN EVENT CONSTANTS

ENTER--

EVENT, ARRAY, ELEMENT NUMBERS

The response is

53, 1, 5 (SB)

The CRT then displays

ASSIGN EVENT CONSTANTS

ENTER--

INTEGER CONSTANT

The operator responds with

202 (SB)

Again the display becomes

ASSIGN EVENT CONSTANTS

ENTER--

EVENT, ARRAY, ELEMENT NUMBERS

The response is

0 (SB)

The function is terminated and control returned to whichever mode of operation that is in effect.

Values for entire data arrays may be prepared off line on punched paper tape for use with the paper tape input option of ASSIGN EVENT CONSTANTS. When invoked via the switch command in Initialization Mode with the PAPER TAPE INPUT switch in the up position, the CRT displays:

ASSIGN EVENT CONSTANTS
P.T. INPUT - TYPE "GO" TO PROCEED

The prepared paper tape is then placed in the reader with the first character within ten feed frames of the read station. The reply of "GO (SB)" is made on the CRT keyboard and the function reads the paper tape, filling the arrays of the specified events with the supplied constants.

The format of the paper tape is as follows:

Logical input record 1: event number
Logical input record 2: all real elements 1-n *
Logical input record 3: all integer elements 1-n *
Logical input record 4: event number
Logical input record 5: all real elements

and so forth until all desired event arrays are supplied. The paper tape is terminated by an event number of "0".

*<u>NOTE</u>: If an event does not have a given array (real or integer) specified as accessable, there must be no input record for that array. That is, if event 65 only had an integer array of four elements accessable, the portion of the input tape for event 65 might look like this:

•
•
•

65 (CR) (LF)	event 65 arrays coming up
1,2,3,4, (CR) (LF)	integer array only (real omitted)
72 (CR) (LF)	event 72 is next

•
•

Example: Suppose there are three events for which it is neccssary to assign data to all elements in their accessable arrays. The events, arrays, and data items are to be as follows:

Event No.	Real Array Values	Integer Array Values
29	3.2	5
	4.2	4
	5.2	3
		2
		1
48	none more accessable	4084 (octal) 4344 (octal)
16	360.0	4
	4.14	0
		2

The paper tape is then punched like this:

```
leader
  .
  .
 29 (CR) (LF)
 3.2, 4.2, 5.2 (CR)(LF)
 5,4,3,2,1 (CR)(LF)
 48 (CR)(LF)
 @4084, @4344 (CR)(LF)
 16 (CR) (LF)
 360., 3.14 (CR) (LF)
 4,0,2 (CR)(LF)
 0 (CR) (LF)
  .
  .
  .
 Trailer
```

To use this tape, the Executive is in Initialization Mode, the PAPER TAPE INPUT switch is set to the up position, then the ASSIGN EVENT CONSTANTS SWITCH is placed in the up position. The CRT displays

ASSIGN EVENT CONSTANTS
P.T INPUT - TYPE "GO" TO PROCEED

The operator properly places the tape in the photoreader (first character within ten feed frames of read station) and responds at the CRT keyboard with

GO SB

The function reads the tape, assigns the supplied data items to their respective arrays then upon reading the "0" for the event number returns to Initialization Mode.

3.18 PAPER TAPE INPUT

This switch command is used only with other functions. It allows the user to supply a punched paper tape of prepared responses to bypass use of the CRT keyboard. The punched responses are the same in order and content as the responses via the keyboard, except that the logical record terminator for punched tape is CR LF instead of SB. This option may be used by setting the switch up before invoking one of these applicable functions:

SET TIME OF DAY
ASSIGN TASK TIMES
EXECUTE BACKGROUND TASK
EXECUTE EVENT
ASSIGN INTERRUPT SERVICE EVENT
ASSIGN FOREGROUND TASK
ASSIGN BACKGROUND TASK

Special paper tape input processing is available for ASSIGN EVENT CONSTANTS (see 3.17). The PAPER TAPE INPUT option is usually exercized only with event constant modification (3.17) and task definition (3.15 and 3.16).

Example: Assume it is desired to assign via paper tape the foreground task named "CHEK" which was used as an example for ASSIGN FOREGROUND TASK (3.16). The task is to have the following event sequence:

3
2
10
25
2

The phase time and interval time are 10 seconds and 35 seconds respectively. The paper tape is prepared off-line in the following format:

leader
CHEK (CR)(LF)
5 (CR)(LF)
3,2,10,25,2 (CR)(LF)
10, 35 (CR)(LF)
0 (CR)(LF)
trailer

To use this tape, the operator places the tape in the photoreader with the first character within ten feed frames of the read station. Then the PAPER TAPE INPUT switch is set to the up position, and the function ASSIGN FOREGROUND TASK is selected by placing its switch up. The paper tape is read in and the function completed. The PAPER TAPE INPUT switch is set to the down position immediately upon completing the function and returning to Initialization Mode.

The rules to remember when selecting the PAPER TAPE INPUT option for functions other than ASSIGN EVENT CONSTANTS are:

1. Prepare the tape with responses in the order and content of response made if keyboard entry was to be made for the function. Use CR LF in place of SB (there is no SB on the TTY keyboard).
2. Place the tape in the photoreader <u>before</u> invoking the function. Set the first character of the paper tape within ten feed frames of the read station.
3. Set the PAPER TAPE INPUT switch up <u>before</u> setting the switch for the function.

4. LOADING PROCEDURE

There are complete SSCMS software system configurations available for the following applications:

- CALIBRATION
- FREQUENCY RESPONSE
- MILLISECOND COUNTER DATA
- FREQUENCY RESPONSE PLOT

The first three applications follow loading procedure no. 1. Due to 16K memory limitations, FREQUENCY RESPONSE PLOT requires its own loading procedures, no.2.

4.1 LOADING PROCEDURE NO.1

4.1.1 Load the BCS using the Basic Binary Loader

a. Set 37700 (0-011-111-111-000-000) into computer switch register.

b. Place BCS tape in reader.

c. Press LOAD ADDRESS.

d. Set LOADER to ENABLED

e. Press PRESET

f. Press RUN

The computer will read the tape and halt.

g. Set LOADER to PROTECTED.

h. Rewind the BCS tape.

4.1.2 Initialize the Relocating Loader.

a. Set 2 (0-000-000-000-000-010) into computer switch register.

b. Press LOAD ADDRESS.

c. Set switch 15 up and all others down (1-000-000-000-000-000)

4.1.3 Load BREX relocatable tape

a. Place BREX tape in photoreader

b. Press RUN

The computer will read the tape, print *LOAD on the teletype, and halt.

c. Rewind the BREX tape.

4.1.4 Load BREX SYSTEM relocatable tape.

a. Place BREX SYSTEM tape in photoreader

b. Press RUN.

The computer will read the tape, print *LOAD on the teletype, and halt.

c. Rewind the BREX SYSTEM tape.

4.1.5 Load applications tape.

a. Select applications tape from among FUNCTION MODULES (i.e. CALIBRATION, FREQUENCY RESPONSE, or MILSEC. CTR.) and place in photoreader.

b. Press RUN

The computer should read the tape, type *LOAD on the Teletype, and halt.

c. Rewind the tape.

4.1.6 Load the BREX SUBROUTINE LIBRARY.

a. Set 100004 (1-000-000-000-000-100) in the computer switch register.

b. Place the BREX SUBROUTINE LIBRARY tape in the photoreader.

c. Press RUN

The computer should read the whole tape, type out a list of needed routines on the teletype, then type *LOAD on the teletype, and halt.

d. Rewind the BREX SUBROUTINE LIBRARY tape.

4.1.7 Load the FORTRAN-ALGOL LIBRARY.

a. Place the FORTRAN-ALGOL LIBRARY tape in the photoreader.

b. Press RUN.

The computer should read as much of the tape as necessary to find all needed routines, type *LST on the teletype, and halt.

4.1.8 Obtain Loader Symbol Table tape (omit this step if a Loader Symbol Tape for the Configuration as loaded already exists).

a. Set teletype right knob to LOCAL

b. Turn teletype left knob to "T" (vertical)

c. Generate six or more inches of leader.

d. Turn teletype right knob to ON-LINE.

e. Set 4 (0-000-000-000-000-100) in computer switch register.

f. Press PRESET

g. Press RUN

The computer should type and punch the Loader Symbol Table on the Teletype, then print *RUN.

h. Set teletype right knob to LOCAL

i. Generate six or more inches of leader.

j. Turn teletype left knob to "KT"

k. Turn teletype right knob to ON-LINE

l. Tear off, identify, and save the punched tape.

4.1.9 Enter Initialization Mode

a. Press PRESET

b. Press RUN (if 4.1.8 skipped, press RUN again)

The computer should type on the teletype:

```
ENTER LOADER SYMBOL TAPE

REPLY "GO" WHEN READY
```

c. Place the Loader Symbol tape for the configured system in the photoreader, with the first character within ten feed frames of read station.

d. Type in the following on the Teletype keyboard:

```
 GO  CR  LF
```

The computer should read the tape and type out on the teletype a list of event names and associated event numbers followed by the message "LINKAGE COMPLETE". An example of this is:

```
*EVENT  NO.

NAVD .... 25

EV09 ....  9

PLOTX .... 27


LINKAGE COMPLETE
```

The BREX program is now in Initialization Mode, and operator communication is now directed to the remote switch register and CRT screen and keyboard. The CRT screen should be displaying a request for the date as part of the SET TIME OF DAY function invoked upon system start and restart.

4.2 LOADING PROCEDURE NO.2

4.2.1 Load the BCS tape using the Basic Binary Loader. (see 4.1.1)

4.2.2 Initialize the Relocating Loader (see 4.1.2)

4.2.3 Load BREX Relocatable tape (see 4.1.3)

4.2.4 Load the BREX LIBRARY (not BREX SUBROUTINE LIBRARY) tape.

a. Place BREX LIBRARY tape in photoreader.

b. Press RUN

The computer should read the tape, print *LOAD on the teletype, and halt.

c. Rewind the BREX LIBRARY tape.

4.2.5 Load the procedure module RELAY AND CTR SERVICE.

a. Place RELAY AND CTR SERVICE tape in photoreader

b. Press RUN

The computer should read the tape, print *LOAD on the Teletype, and halt.

c. Rewind the RELAY AND CTR SERVICE tape.

4.2.6 Load the procedure module SAFETY CHECK.

a. Place SAFETY CHECK tape in photoreader.

b. Press RUN.

The computer should read the tape, print *LOAD on the teletype, and halt.

c. Rewind the SAFETY CHECK tape.

4.2.7 Load the function module FREQ. RESP. PLOT

a. Place FREQ. RESP. PLOT tape in photoreader

b. Press RUN

The computer should read the tape, print *LOAD on the teletype, and halt.

c. Rewind the FREQ. RESP. PLOT tape

4.2.8 Load the BREX SUBROUTINE LIBRARY (see 4.1.6)

4.2.9 Load the PLOTTER LIBRARY

a. Place PLOTTER LIBRARY tape in photoreader.

b. Press RUN

The computer should read the whole tape, print out a list of needed routines on the teletype, then type *LOAD on the Teletype, and halt.

c. Rewind the PLOTTER LIBRARY tape.

4.2.10 Load the FORTRAN-ALGOL LIBRARY (see 4.1.7)

4.2.11 Obtain Loader Symbol Tape if needed (see 4.1.8)

4.2.12 Enter Initialization Mode (See 4.1.9)

4.3 System Operation

The SSCMS software system for the chosen configuration is now loaded and running in Initialization Mode. Refer to Section 3 for Executive program operation.

DESCRIPTIONS OF TYPICAL USER EVENTS

Name: EV99

Event #: 99

Purpose: To connect power supply #1 to the test article if the reading on scanner channel 000 is within certain limits. Connection is made by closing relay A1.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal values:

Low Limit : 4.85 volts
High Limit : 5.15 volts
Channel # : 000
Program Word : 4244 (Octal)
Relay to be closed: 1 (A1)

Name: EV98

Event # 98

Purpose: To connect power supply #2 to the test article if the reading on channel 100 is within certain limits. Connection is made by closing relay A2.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values:

Low Limit : 14.55 volts
High Limit : 15.45 volts
Channel # : 100
Program Word : 4245 (Octal)
Relay to be closed: 2 (A2)

Name: EV97

Event #: 97

Purpose: To connect power supply #3 to the test article if the reading on scanner channel 001 is within certain limits. Connection is made by closing relay A3.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values:

Low Limit : 14.55 volts
High Limit : 15.45 volts
Channel # : 001
Program Word: : 4245 (Octal)
Relay to be closed: 3 (A3)

Name: EV96

Event #: 96

Purpose: To connect power supply #4 to the test article if the reading on scanner channel 101 is within certain limits. Connection is made by closing relay A4.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values:

Low Limit : 27.645 volts
High Limit : 29.355 volts
Channel # : 101
Program Word : 4245 (Octal)
Relay to be closed: 4 (A4)

Name: EV95

Event # 95

Purpose: To connect power supply #5 to the test article if the reading on scanner channel 002 is within certain limits. Connection is made by closing relay A5.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values:

Low Limit : 14.55 volts

High Limit : 15.45 volts

Channel # : 002

Program Word : 4245 (Octal)

Relay to be closed: 5 (A5)

Name: EV94

Event #: 94

Purpose: To connect power supply #6 to the test article if the reading on scanner channel 102 is within certain limits. Connection is made by closing relay A6.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values

Low Limit : 0.0 volts

High Limit : 0.0 volts

Channel # : 102

Program Word : 0000

Relay to be closed: 6 (A6)

Name: EV93

Event #: 93

Purpose: To connect power supply #7 to the test article if the reading on scanner channel 003 is within certain limits. Connection is made by closing relay A7.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values

Low Limit : 48.5 volts

High Limit : 51.5 volts

Channel # : 003

Program Word : 4245 (Octal)

Relay to be closed: 7 (A7)

Name: EV92

Event #: 92

Purpose: To connect power supply #8 to the test article if the reading on scanner channel 103 is within certain limits. Connection is made by closing relay A8.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values:

Low Limit : 0.0 volts

High Limit : 0.0 volts

Channel # : 103

Program Word : 0000

Relay to be closed: 8 (A8)

Name: EV91

Event #: 91

Purpose: To connect power supply #11 to the test article if the reading on scanner channel 005 is within certain limits. Connection is made by closing relay A9.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values:

Low Limit : 0.0 volts
High Limit : 0.0 volts
Channel # : 005
Program Word : 0000
Relay to be closed: 9 (A9)

Name: EV90

Event #: 90

Purpose: To connect microsyn supply #1 to the test article if the reading on channel 123 is within certain limits. Connection is made by closing relay A10.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values:

Low Limit : 4.85 volts
High Limit : 5.15 volts
Channel # : 123
Program Word : 7004 (Octal)
Relay to be closed: 10 (A10)

Name: EV89

Event #: 89

Purpose: To connect microsyn supply #2 to the test article if the reading on scanner channel 024 is within certain limits. Connection is made by closing relay A11.

Input: A 2 element real array

1. Low Limit
2. High Limit

Nominal Values

Low Limit : 0.0 volts
High Limit : 0.0 volts
Channel # : 024
Program Word : 0000
Relay to be closed: 11 (A11)

Name: EV88

Event #: 88

Purpose: To provide operator control of power supply #1. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B1 and connection is made to the test article by closing relay A1.

Input: None

Nominal Values:

Channel # : 000
Test article relay: 1 (A1)
Operator Control relay: 17 (B1)

Name: EV87

Event #: 87

Purpose: To provide operator control of power supply #2. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B2 and connection is made to the test article by closing relay A2.

Input: None

Nominal Values:

Channel # : 100

Test article relay: 2 (A2)

Operator Control relay: 18 (B2)

Name: EV86

Event #: 86

Purpose: To provide operator control of power supply #2. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B3 and connection is made to the test article by closing relay A3.

Input: None

Nominal Values:

Channel # : 001

Test article relay: 3 (A3)

Operator Control relay: 19 (B3)

Name: EV85

Event #: 85

Purpose: To provide operator control of power supply #4. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B4 and connection is made to the test article by closing relay A4.

Input: None

Nominal Values:

Channel # : 101
Test article relay: 4 (A4)
Operator Control relay: 20 (B4)

Name: EV84

Event#: 84

Purpose: To provide operator control of power supply #5. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B5 and connection is made to the test article by closing relay A5.

Input: None

Nominal Values:

Channel # : 002
Test article relay: 5 (A5)
Operator Control relay: 21 (B5)

Name: EV83

Event #: 83

Purpose: To provide operator control of power supply #6. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B6 and connection is made to the test article by closing relay A6.

Input: None

<u>Nominal Values:</u>

Channel # : 102

Test article relay: 6 (A6)

Operator Control relay: 22 (B6)

Name: EV82

Event #: 82

Purpose: To provide operator control of power supply #7. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B7 and connection is made to the test article by closing relay A7.

Input: None

<u>Nominal Values:</u>

Channel # : 003

Test article relay: 7 (A7)

Operator Control relay: 23 (B7)

Name: EV81

Event #: 81

Purpose: To provide operator control of power supply #8. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B8 and connection is made to the test article by closing relay A8.

Input: None

Nominal Values:

Channel # : 103
Test article relay: 8 (A8)
Operator Control relay: 24 (B8)

Name: EV80

Event #: 80

Purpose: To provide operator control of power supply #11. Connection to the test article is made on operator command. Control is provided to the operator by closing relay B10 and connection is made to the test article by closing relay A11.

Input: None

Nominal Values:

Channel # : 005
Test article relay: 11 (A11)
Operator Control relay: 26 (B10)

Name: EV79

Event #: 79

Purpose: To apply AC power to Bulk Power Supply (#9) by closing relay A12. To sample scanner channel 116 and determine if the voltage is within certain limits. The channel is continuously sampled until the voltage is within limits. This event is used during ISUS turn on procedure.

Input: A 2 element real array

1. Low Limit
2. High Limit

<u>Nominal Values</u>

Low Limit : 0.000 volts
High Limit : 0.001 volts
Channel # : 116
Program Word : 4242 (Octal)

Name: EV78

Event #: 78

Purpose: To select choice #1 for microsyn supply programming by closing relay C4 and to connect the crystal clock output by closing relay F8. A delay of 310 milliseconds occurs after the relays are closed. This event is used during ISUS turn on procedure.

Input: None

<u>Nominal Values:</u>

Delay time : 310 milliseconds

Name: EV77

Event #: 77

Purpose: To apply AC power to precision power supply (#10), place spin motor Supply #1 on, connect spin #1 supply output, place spin motor supply #1 in start, place spin motor supply #1 in Run, place spin motor supply in Remote sense. The preceding is done by closing relay A13, closing relay B11, closing relay A14, closing relay B12, opening relay B12, closing relay B13 respectfully. Delays are also associated with each step. This event is used during ISUS turn on procedure.

Input: None

Nominal Values:

Delay #1: 310 milliseconds

Delay #2: 40 milliseconds

Delay #3: 180.0 seconds

Name: EV76

Event #: 76

Purpose: To apply AC power to precision power supply (#10);place spin motor supply #1, #2, and #3 on; Connect output of spin motor supply #1, #2, and #3; Place spin motor Supply #1, #2, and #3 in start; Place spin motor supply #1, #2, and #3 in run, place spin motor Supply #1, #2, and #3 in remote sense. The preceding is done by closing relay A13, closing relays B11, B14, and C1; closing relays A14, A15, and A16; closing relays B12, B15, and C2; opening relays B12, B12 and C2; closing relays B13, B16, and C3 respectively. Delays are also associated with each step.

Input: None

Nominal Values:

Delay #1: 310 milliseconds

Delay #2: 40 milliseconds

Delay #3: 180.0 seconds

Name: EV75

Event #: 75

Purpose: To shutdown ISUS. The shutdown is done by opening relays B13, B16, A14, A15, A16, B11, B14, C1, A1-A12. Delays are included within the sequence.

Input: None

Nominal Values

Delay #1: 180 seconds

Delay #2: 310 milliseconds

Name: EV74

Event #: 74

Purpose: To set up the counters to take one set of 5 second numbers. If the counter interrupt does not occur within 6 seconds the operator is notified.

Input: None

Nominal Values

Delay #1: 300 milliseconds

Delay #2: 6 seconds

Name: EV73

Event #: 73

Purpose: To set up the counters to take one set of 300 second numbers. If the counter interrupt does not occur within 310 seconds the operator is notified.

Input: None

Nominal Values

Delay #1: 300 milliseconds

Delay #2: 310 seconds

Name: EV72

Event #: 72

Purpose: To reset the power supplies. The shutdown sequence follows: Relay G14 is closed, Relays A1-A16 are opened, relays B11-B16 are opened, Relays C1-C3 are opened, relays H2 and H7 are opened, relay G14 is opened, relay G12 is closed, relay G12 is opened.

Input: None

Nominal Values:

Delay #1 : 40 milliseconds

Name: EV71

Event #: 71

Purpose: To position the Rotary axis of the Rate Table to a specified position.

Input: A single element real array specifying the desired position in degrees.

Nominal Values:

Rate table position : 0.0 degrees

Name: EV70

Event #: 70

Purpose: To rotate the rate table counterclockwise at 20 deg/sec for one revolution. The table is positioned at 180 deg ± .1 deg. at the start of the rotation. The IRA counters are conditioned to count between 0 and 360 degrees. The table is stopped rotating after 35 seconds. This time period allows 180 degrees to get up to speed, 360 degrees of rotation during which the counters are operating and the remaining time allows the table to be stopped at approximately 180 degrees.

Input: None

Nominal Values

Table position: 180.0 degrees

Delay #1 : 40 milliseconds

Delay #2 : 5 seconds

Delay #3 : 35 seconds

HP6130 outputs: 4.4444444 volts (20 deg/sec)

Name: EV69

Event #: 69

Purpose: To scan all pertinent scanner channels and output these values to the teletype. There is a 1 second delay between each line sent to the teletype. This delay assures that the system does not become I/O bound and gives the system time to do any necessary foreground processing. The time of day is also output on the teletype.

Input: A 52 element integer array, elements 1-26 define the channel numbers, 27-52 define the program words in octal.

Nominal Values

Channels to be scanned: 0, 100, 1, 101, 2, 3, 4, 104, 105, 6, 112, 13, 113, 14, 114, 115 116 17, 123, 124, 25, 29, 44, 60, 61, 74

Channel Program Words: 4244, 4245, 4245, 4245, 4245, 4245, 4245, 4245, 7003 7003, 4242, 4242, 4242, 4242, 4242, 4242, 4242, 4242, 7004, 7005, 7005, 4246, 4246, 4246, 4244, 4245

Delay #1: 4 seconds

Name: EV68

Event #: 68

Purpose: To output messages on the CRT in the background area. These messages describe to the operator the orientation in which the test article must be placed while conducting the ISUS calibration test. The operator must respond via the remote switch register when he has completed the particular orientation procedure.

Input: A single element integer array which points to the message to be displayed. This input should be 1 less than the desired message. If message #1 is desired the value should be zero. This pointer is incremented each time event 68 is executed. When the pointer reaches a value of 15 it is reset to zero.

Nominal Values:

Message Counter: 0

MS1 : Rotary axis horiz., X north
MS2 : X axis south
MS3 : Y axis north
MS4 : Y axis south
MS5 : Z axis north
MS6 : Z axis south
MS7 : Rotary axis vert., X axis up
MS8 : X axis down
MS9 : Y axis up
MS10: Y axis down
MS11: Z axis up
MS12: Z axis down
MS13: X, Y 45 WRT Vert., Z horiz.
MS14: X, Z 45 WRT Vert., Y horiz.
MS15: Y, Z 45 WRT Vert., X horiz.

Name: EV67

Event #: 67

Purpose: To open or close an individual Relay. If the Relay setting is nonzero, the corresponding relay is closed. If the Relay setting is zero, the corresponding relay is opened. If the relay number is zero, all relays are opened. The relays are numbered 1-160. Relay #1 points to relay A1, Relay #17 points to relay B1. Relay #160 points to relay J16.

Input: The operator is requested via the CRT to enter the setting and relay # when the event is executed.

<u>Nominal Values:</u>

Relay setting : 0

Relay number : 0

Name: EV66

Event #: 66

Purpose: To position the rate table at zero deg. ± .1 deg. The event will stay in a loop until the correct position is obtained.

Input: None

<u>Nominal Values:</u>

Delay #1: 5 seconds

Name: EV65

Event #: 65

Purpose: To determine if the value read from scanner channel #105 is within certain limits.

Input: A 4 element real array.

1. Low inner limit.
2. Low outer limit.
3. High inner limit.
4. High outer limit.

A 2 element integer array

1. Channel #
2. Program word (octal)

<u>Nominal Values</u>

Low inner limit : .165 volts

Low outer limit : .145 volts

High inner limit : .205 volts

High outer limit : .225 volts

Channel # : 105

Program word : 4003 (octal)

Name: EV64

Event #: 64

Purpose: To determine if the value read from scanner channel #006 is within certain limits.

Input: A 4 element real array.

1. Low inner limit.
2. Low outer limit.
3. High inner limit
4. High outer limit.

A 2 element integer array.

1. Channel #
2. Program word (Octal)

Nominal Values

Low inner limit : .165 volts
Low outer limit : .145 volts
High inner limit : .205 volts
High outer limit : .225 volts
Channel # : 006
Program Word : 4003 (octal)

Name: EV63

Event #: 63

Purpose: To determine if the value read from scanner channel #061 is within certain limits.

Input: A 4 element real array.

1. Low inner limit.
2. Low outer limit.
3. High inner limit.
4. High outer limit.

A 2 element integer array.

1. Channel #
2. Program Word (Octal)

<u>Nominal Values:</u>

Low inner limit : 5.82 volts

Low outer limit : 5.40 volts

High inner limit : 6.18 volts

High outer limit : 6.60 volts

Name: EV62

Event #: 62

Purpose: To rotate the rate table counterclockwise at a specified input rate.

Input: A positive real number specifying the rate at which the table is to be rotated. The rate should not exceed 200 deg/sec.

Nominal Values:

Input Rate: 10.0 degrees/second.

Name: EV61

Event #: 61

Purpose: To rotate the rate table clockwise at a specified input rate.

Input: A positive real number specifying the rate at which the table is to be rotated. The rate should not exceed 200 deg/sec.

Nominal Values:

Input Rate: 10.0 degrees/second

Name: EV60

Event #: 60

Purpose: To check the system lag against an input value. If the lag exceeds this value the lag alarm light on the console is illuminated and the following message is sent to the CRT foreground area.

XXX SEC LAG VIOLATION

Input: A single integer defining the lag limit in seconds.

Name: EV44

Event #: 44

Purpose: To conduct a full frequency response on a passive circuit. The phase, gain and frequency is calculated. The data are placed in COMMON for use with other events if desired.

Input: A 14 element real array defining the RMS voltage input and the corresponding voltage necessary to define a particular frequency. The order is as follows:

Element	Input
1	V1 RMS
2	V1 FREQ
.	.
.	.
.	.
13	V7 RMS
14	V7 FREQ

Nominal Values:

Voltage Inputs: .8, .1 (10 Hz) .8, .2 (20 Hz) .8, .5 (50 Hz) .8,
(14 elements) 1.0 (100 Hz), .8, 2.0 (200 Hz) .8, 4.0 (400 Hz), .8,
10.0 (1 K Hz)

Name: EV42

Event #: 42

Purpose: To safety check table rate. If the measured rate is too large when compared with the desired rate the alarm is activated and the table is turned off.

Input: A 2 element array specifying the low and high scale factor used in calculating the limits. The desired rate times the scale factor determines the tolerable limits.

1. Low limit scale factor.
2. High limit scale factor.

A 4 element integer array specifying the scanner channels and associated program words that provide the desired rates and actual rates.

1. Desired rate scanner channel.
2. Actual rate scanner channel.
3. Desired rate program word.
4. Actual rate program word.

<u>Nominal Values</u>:

Desired rate channel : 131
Actual rate channel : 32
Desired rate program word : 4144 (Octal)
Actual rate program word : 4126 (Octal)
Low Limit scale factor : 1.05
High Limit scale factor : 1.10

Name: EV40

Event #: 40

Purpose: To safety check SSCMS cabinet temperature. The power supply rack, Data Rack, Operator Console, and DCU RACK scanner channel values are compared against input limits.

Input: A 1 element real array defining the absolute limit in ohms.

A 8 element integer array defining the scanner channels and corresponding program words.

1. Power supply rack scanner channel.
2. Data Rack scanner channel.
3. Operator console scanner channel
4. DCU rack scanner channel.
5. Power Supply channel program word.
6. Data Rack channel program word.
7. Operator Console channel program word.
8. DCU rack channel program word.

Nominal Values

Limit : 780.0 ohms

P. S. Channel # : 029

Data Rack Channel # : 044

Oper. Console Channel # : 074

DCU Rack Channel # : 060

P. S. Program Word : 6156 (Octal)

Data Rack Program Word : 6156 (Octal)

Oper. Console Program Word: 6156 (Octal)

DCU Rack Program Word : 6156 (Octal)

Name: EV27

Event #: 27

Purpose: To plot the results of a frequency response on the CALCOMP plotter. The numbers plotted are read from paper tape or are read from the COMMON area used by event 44. This option is defined by the input parameter. The phase and gain for each of the 3 loops are plotted versus frequency. Frequency (X-axis) is plotted on a log scale. The gains for each loop appear on one graph and the phases for each loop appear on a second graph.

Input: A single element integer array.

= 0 data is read from the COMMON area

= 1 data is read from paper tape (3E20.8)

Nominal Values:

Data source flag: = 0 (data resides in COMMON)

Name: EV26

Event #: 26

Purpose: To type on the teleprinter or to type and punch the results of a frequency response test. The punch option is defined by an input parameter. Frequency phase and gain for each of 3 loops are output.

Input: A single element integer array

- = 0 print and punch
- ≠ 0 print only

ID	
4	Row 1 of T_B^I matrix; .xxxxxx
5	Row 2 of T_B^I matrix; .xxxxxx
6	Row 3 of T_B^I matrix; .xxxxxx
7	X, Y, Z position components, xxxx.xx FT
8	X, Y, Z velocity components, xxxx.xx FT/SEC
9	Latitude, Longitude, Altitude, xx[illegible]x DEG, DEG, FT

Name: NAVD

Event #: 25

Purpose: To display navigation data What values are displayed are controlled by the remote switch register switches. The data to be displayed must reside in the first 10 locations of COMMON. The first 9 words contain 2 digits each in 8-4-2-1 code right justified. A total of 6 digits is considered a number, there are 3 numbers represented by the first 9 words. Word #10 contains a 4 bit 8-4-2-1 identification code and 3 bits which contain the sign of the 3 numbers. These 7 bits are right justified. The following describes the format the data must be in and defines the I. D.'s.

Word	
1	digits 1,2 of first number
2	digits 3,4 of first number
3	digits 5,6 of first number
4	digits 1,2 of second number
5	digits 3,4 of second number
6	digits 5,6 of second number
7	digits 1,2 of third number
8	digits 3,4 of third number
9	digits 5,6 of third number
10	Last 7 bits give 4 bit I. D. and 3 signs

ID	
1	Row 1 of T_B^N matrix; .xxxxxx
2	Row 2 of T_B^N matrix; .xxxxxx
3	Row 3 of T_B^N matrix; .xxxxxx

Name: EV22

Event #: 22

Purpose: To select one of three choices for N for the counters as defined by the input parameter.

Input: A single element integer array

=1, select choice #1 for N

=2, select choice #2 for N

=3, select choice #3 for N

0,>3 - EXIT

Name: EV21

Event #: 21

Purpose: To place the counters in the X-Y/NZ mode or the USEC/NZ mode as defined by the input parameter.

Input: A single element integer array

=1, place counters in X-Y/NZ mode

=2, place counters in USEC/NZ mode

0,>2 - EXIT

Name: EV20

Event #: 20

Purpose: To place the counters in one of four signal routing modes as defined by the input parameter.

Input: A single element integer array.

=1, place counters in signal routing mode 1
=2, place counters in signal routing mode 2
=3, place counters in signal routing mode 3
=4, place counters in signal routing mode 4
0,>4 - EXIT

Name: EV19

Event #: 19

Purpose: To delay tens of milliseconds as defined by the input.

Input: A single element integer array. This integer times .010 seconds represents the delay which will occur when event 19 is executed. If the input value = 100 a delay of 1 second will occur.

Nominal Values:

Delay value: 0 (no delay)

Name: TSCNR

Event #: 15

Purpose: To scan from 1-10 of the scanner channels and output the values to the CRT display or to the teletype.

Input: A 24 element integer array

1. # of channels to be scanned (1-10)
2. = 0 CRT display, = 2 teletype
3. Delay #1 --a delay that represents .01 sec times the entered value. If the entered value = 100 a delay of 1 sec is defined.
4. Delay #2 -- Delay #1 times delay #2 represents the time period between which, values will be output to the screen or teletype. If delay #1 = 100, Delay #2 = 1 the scanned values will be output every second.

5-14. The scanner channel numbers that are to be read.

15-24. The program words corresponding to the scanner channels (OCTAL)

Name: DSET

Event #: 10

Purpose: This event is a diagnostic or demonstration type event. When executed the remote switch register is read and depending of the setting of switches 0 - 8 corresponding "canned" data is moved to an area in common storage reserved for storing the outputs of a nagivation test. When event 25 is executed these values will be displayed on the CRT. Therefore event 10 is merely a setup event to test event 25. Event 10 would not be used if actual data were being sent from the DDP-124. The following "canned" data is moved to the COMMON area.

SWITCH 0 UP, Row 1 of T_B^N matrix

-.999999 .666666 -.333333

I.D. = 1

SWITCH 1 UP, Row 2 of T_B^N matrix

.888888 -.555555 -.222222

I.D. = 2

SWITCH 2 UP, Row 3 of T_B^N matrix

-.777777 .444444 -.111111

I.D. = 3

SWITCH 3 UP, Row 1 of T_B^I matrix

.111111 -.444444 .777777

I.D. = 4

SWITCH 4 UP, Row 2 of T_B^I matrix

-.222222 .555555 -.888888

I.D. = 5

SWITCH 5 UP, Row 3 of T_B^I matrix

.333333 -.666666 .999999

I.D. = 6

SWITCH 6 UP, X, Y, Z position

-9999.99 8888.88 -7777.77

I.D. = 7

SWITCH 7 UP, X, Y, Z velocity

6666.66 -5555.55 4444.44

I.D. = 8

SWITCH 8 UP, Latitude, longitude, attitude

359.99 -359.99 25.52

I.D. = 9

Input: None

Name: EV09

Event #: 9

Purpose: This event is meant to be only a diagnostic type event. When executed it displays one of the following messages either in the foreground or background area of the CRT depending on the value of the input flag.

MES 1: EVENT 9 USING BACKGROUND AREA
MES 2: EVENT 9 USING FOREGROUND AREA

Input: A single element integer array

= 0, display MES 2 in foreground area
= non-zero, display MES 1 in background area

Nominal Values:

Input Flag: = 0

Name: EV08

Event #: 8

Purpose: To read a magnetic tape containing recorded counter data and check the data for validity. This process will be terminated when switch 12 on the remote switch panel is set. Each counter is compared against a nominal input value ± an input tolerance value. If the recorded value does not fall within these constraints the record number, the data set, the counter number, the monimal value, the counter value and the tolerance are printed on the teletype. The nominal values which are input must be input in octal representing the expected value of each counter in 8-4-2-1 BCD. The tolerance associated with each counter should be input in decimal and should be a number from 0 - 9.

Input: An eighteen element integer array, the first 12 elements representing the nominal BCD values of the 6 counters and the last 6 define the decimal tolerance for each counter.

Name: EV07

Event #: 7

Purpose: This event is an interrupt service event and must be assigned at run time. The event is set up to be assigned to I/O slot 30 (octal). When an interrupt occurs on I/O card 30 7 BCD (8-4-2-1) digits are read and placed in common storage, and a complete flag is set. This event is designed to read rate table position on interrupt and table position cables are connected to slot 30. The interrupt is generated by closing a contact, this contact is closed in a number of other events.

Name: EV06

Event #: 6

Purpose: To condition any I/O card. The card is conditioned in one of six ways as defined by the input.

Input: A 2 element integer array

1. I/O slot # (OCTAL)
2. Option number
    - =1 Clear control on slot #
    - =2 Clear control, clear flag on slot #
    - =3 Set control on slot #
    - =4 Set control, clear flag on slot #
    - =5 Clear flag on slot #
    - =6 Set flag on slot #

Nominal Values:

Slot # : 35 (OCTAL)

Option # : 1 (CLC)

The first record written on the tape is a dummy record of 480 words. This record should be ignored when read.

Input: A single element integer array.

= 0, execute the initiator portion

= 1, go directly to the continuator portion (this value must be 0 when starting, if the recording is stopped and it is desired that another sample is to be recorded, this flag must be reset to zero)

Nominal Values:

Initiator flag: = 0

Name: EV05

Event #: 5

Purpose: To read and record counter data on magnetic tape. This event will record the 6 counters on magnetic tape for any counter summing period down to 1 millisecond. The only constraint being that all counters issue their interrupts simultaneously. This event actually recognizes only the interrupt assigned to I/O slot 10 (octal). A workable counter should always be connected to slot 10. This event reads 32 bits of data from each counter for a total of 12 words per interrupt. Each tape record contains 40 sets of data for a total of 480 words per record. The data for each counter is 8 BCD digits plus sign. (8-4-2-1BCD). Note the following example of a counter output.

WORD 1: 1111 1001 1001 1001 BITS 15 - 0
WORD 2: 1001 1001 1001 1001 BITS 16 - 31

If bit 15 is set the number is positive, if bit 15 is not set the number is negative. The value represented by this example is +79999999.

This event has two parts--an initiator and a continuator. The event must first be assigned as an interrupt service event associated with slot 10 (octal), the event must then be executed like a normal event. This will initialize the interrupt (continuator) portion. The interrupts will be allowed to occur at this point and recording will continue until the operator sets switch 13 on the remote switch panel. The tape will be end filed and rewound and execution of event 5 will be terminated.

A related sequence of events to select the correct mode and to start the counters is necessary but the counter interrupts will not be recognized until event 5 is executed.

Name: STCNT

Event #: 4

Purpose: To set control and clear the interrupt flag on each of the 6 counters. This will allow the computer to be interrupted when each of the counters dump.

Input: None

Name: EV03

Event #: 3

Purpose: To route the counter data to various devices depending on the setting of an input flag.

Input: A single element integer array

= 0, exit

= 1, display counter data on CRT only

= 2, type on TTY and display on CRT counter data

= 3, send to DDP-124 and display on CRT counter data

= 4, sent to DDP, TTY type and CRT display counter data

<u>Nominal Values:</u>

Routing Flag: = 1

Name: EV02

Event #: 2

Purpose: To display the setting of each of the ten relay registers. The octal representation of each register is displayed in the background are of the CRT, the registers are labeled sequentially from A to J

Input: A single element integer array

= non-zero display the values of the relay registers

= 0, do not display, exit

Nominal Values:

Display flag: = 1

Name: EV01

Event #: 1

Purpose: To reset and start the 6 counters. This is done by closing contact E15 delaying 300 milliseconds and opening contact E15.

Input: None

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MC 25-846
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Declassified per NASA Letter
AP3-R-66-913-6, 1022
Date: Oct. 26, 1966 Signed:

Command Angle Torque Test Procedure

(Unclassified Title)

Date	Revision Letter	TDRR No.	Pages Revised	Approval MIT	Approval NASA
3/9/65	B	17642	1, 2, 5	WK.	BM
5/21/65	C	19837	1, 2, 3, 4, 5	WK.	BM
8/24/65	D	21787		WK.	AM
9-21-65	E	22585	4, 5, 6, 7.	MGM	N/R
11/9/65	F	23846	2, 3 (ALL)	WK	A. C. METZGER

~~DOWNGRADED AT 12 YEAR~~
~~INTERVALS; NOT AUTOMATICALLY~~
~~DECLASSIFIED DOD DIR 5200.10~~

TP#11937

This MC specification consists of page i to ____ and 1 to 7 inclusive.

TDRR 15323 JAN 6 1965

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CAMBRIDGE, MASS.

PREPARED BY: J. Feldman
DATE: 17 February 1964

MC 25-846

SHEET 1
OF 7

COMMAND ANGLE TORQUE TEST PROCEDURE

The following procedure will be used to normalize Apollo II pulse torquing gyro scale factors.

1. Orient the gyro with its input axis vertically up on the turntable.
2. Preset the counter to 60 (10 degrees).
3. Set the photocell amplifier switch into the (+) position.
4. Set the switches on the gyro control panel into the following positions:

Switch	Position
Master-Production	Master
ON	ON
Gyro-Dummy	Gyro
Inertial-Caged	Inertial
[Block II	[Block II
TM+ TM-]	TM+]

5. Use a fixed resistor of 70.588 (14.1666 MMHOS) as the scale factor resistor.
6. Push the "START" button on the gyro control panel.
7. Allow the table to torque through 100 degrees.
8. Record:
    a. The voltage across the current sampling resistor using the current source monitor.
    b. The voltage across the scale factor resistor using the current source monitor.
    c. The average number of pulses to move the table ten degrees.

The number of counts to command the table 10° for positive and negative torquing is given by:

$$N \pm = \frac{174.533 \text{ mr}}{SF \pm \frac{W_{IE_V}}{3200}}$$

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where SF is the pulse torque scale factor (Mr/pulse). The required system scale factor is $2.99605 \times 10^{-3} \frac{M_r}{\text{pulse}}$.

9. Repeat steps 4 to 8 with the $\begin{bmatrix}\text{Block II}\\ \text{TM+ TM-}\end{bmatrix}$ switch in the $\begin{bmatrix}\text{Block II}\\ \text{TM-}\end{bmatrix}$ position and the photocell amplifier in the (-) position to obtain N- (the pulses to negative torquer to command the table 10 degrees CCW).

10. From the values of counts obtained for plus and minus torquing select padding resistors from Table I. Connect these resistors across the torquer secondary windings.

F 11. The pulse torquing scale factor shall be within the requirements of [illegible] PS-2021500 Par. 3.2.3.3.6. Par. 2. [illegible]

12. Solder these resistors across the appropriate torquer windings.

B 13. For all subsequent tests using the normalized torquer, and the fixed scale factor resistor perform the pulse torquing tests in the following way:

   a) Measure the counts to command the table 10 degrees.
   b) Allow 5 prints for the data to settle, the next 5 prints shall be the submitted data.
   c) Measure the voltage across the current sampling resistor and the voltage across the scale factor resistor using the current source monitor.

FB 14. All pulse torquing tests on the normalized torquer including the test to verify the selection of the torquer padding resistor shall meet the specification of PS-2021500 Par. 3.2.3.3.6. Par. 2, Par. 3, Par. 4, Par. 5.

   a) Side loading shall cause a scale factor change of less than 800 ppm.
   b) The five points of submitted data shall have a peak to peak spread of 500ppm
   c) The four averages of the five print data shall have a maximum peak to peak spread of 1000 ppm.
   d) The average of the five print data for torquer padding verification shall be within 500 ppm of the specified scale factor. All subsequent tests shall be within 1000 ppm of specified scale factor.

[redacted]

15. Suspension side loading shall be verified in the following way:

a) The test can be run in an orientation that minimizes the effect of an external magnetic field or a shield can be placed around the gyro unit.

b) Record the radial and axial voltages before pulse torquing.

c) Preset the counter to 6 (1°) set counter reset to N2 and N2 set at 10^3.

d) Pulse the gyro until the radial and axial voltages settle. Record the settled radial and axial voltages.

e) Disregard the first data point. Determine the following sums

S_1 = sum of 2nd to 11th data point.

S_2 = sum of 3rd to 12th data point.

until

S_n = sum of the $(n-9)^{th}$ to n^{th} data point.

where n is the data point obtained which the radial and axial voltages have settled.

F f) The amplitude of a curve through the data S_1 to S_n shall be less than the requirements specified in PS-2021500 Par. 4.2.3.6.

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16. Magnetic shielding of the gyro unit during pulse torquing by only one of the following is permitted:

a. Mumetal shroud end cover

b. Mumetal test stand cover

[redacted]

TABLE I
Shunt Resistors Required To Adjust Pulse Torquing Scale Factor

Shunt Resistor	Pulses to Command the Table 10°	
	N^+	N^-
754.8	51690	52163
759.4	51723	52197
764.0	51757	52231
768.8	51792	52267
773.5	51825	52301
778.3	51859	52335
783.2	51893	52370
788.1	51927	52404
793.1	51961	52439
798.2	51995	52474
803.2	52029	52508
808.4	52063	52543
813.6	52097	52577
818.9	52131	52612
824.2	52165	52647
829.6	52199	52681
835.1	52233	52716
840.6	52267	52750
846.2	52301	52785
851.9	52335	52820
857.6	52368	52854
863.4	52402	52889
869.3	52437	52923
875.2	52470	52958
881.2	52504	52992
887.3	52538	53027
893.5	52572	53062
899.8	52606	53097
906.1	52640	53131
912.5	52674	53165
919.0	52708	53200
925.6	52742	53235
932.2	52776	53269
939.0	52810	53304
945.8	52844	53338
952.8	52878	53373
959.8	52912	53408
966.9	52946	53442
974.1	52980	53477
981.4	53013	53511
988.8	53047	53546
996.4	53082	53581
1004.0	53115	53615
1011.7	53149	53650
1019.6	53183	53684
1027.5	53217	53719

Shunt Resistor	Pulses to Command the Table 10^o	
Ω	N+	N-
1,035.6	53,251	53,753
1,043.8	53,285	53,788
1,052.1	53,319	53,823
1,060.5	53,353	53,857
1,069	53,386.4	53,892.6
1,078	53,421.6	53,928.5
1,087	53,456.2	53,963.8
1,096	53,490.3	53,998.5
1,105	53,523.9	54,032.8
1,114	53,557.0	54,066.5
1,124	53,593.2	54,103.4
1,134	53,628.8	54,139.7
1,144	53,663.9	54,175.4
1,154	53,698.3	54,210.5
1,164	53,732.3	54,245.1
1,174	53,765.6	54,279.1
1,185	53,801.8	54,315.9
1,196	53,837.3	54,352.1
1,207	53,872.2	54,387.7
1,218	53,906.5	54,422.7
1,229	53,940.2	54.457.1
1,240	53,973.4	54,490.9
1,252	54,009.0	54,527.2
1,264	54,044.0	54,562.8
1,276	54,078.3	54,597.8
1,289	54,114.8	54,635.0
1,301	54,147.9	54,668,8
1,314	54,183.2	54,704.7
1,327	54,217.8	54,740.0
1,341	54,254.3	54,777.2
1,354	54,287.6	54,811.2
1,368	54,322.8	54,847.1
1,382	54,357.4	54,882.3
1,396	54,391.2	54,916.8
1,411	54,426.8	54,953.1
1,426	54,461.7	54,988.7
1,441	54,496.0	55,023.6
1,457	54,531.7	55,060.0
1,473	54,566.8	55,095.7
1,489	54,601.1	55,130.7
1,506	54,636.8	55,167.1
1,523	54,671.8	55,202.8
1,540	54,706.0	55,237.7
1,558	54,741.5	55,273.9
1,576	54,776.2	55.309.3

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CAMBRIDGE, MASS.

PREPARED BY: J. Feldman
DATE: 17 February 1964

MC 25-846

SHEET 6
OF 7

Shunt Resistor	Pulses to Command the Table 10°	
Ω	N+	N-
1,594	54,810.2	55,343.9
1,613	54,845.3	55,379.7
1,633	54,881.3	55,416.5
1,653	54,916.6	55,452.4
1,673	54,941.1	55,487.6
1,693	54,984.8	55,521.9
1,715	55,021.0	55,558.8
1,737	55,056.3	55,594.9
1,759	55,090.8	55,630.0
1,782	55,126.0	55,665.9
1,806	55,161.8	55,702.4
1,830	55,196.7	55,738.0
1,854	55,230.8	55,772.8
1,879	55,265.4	55,808.0
1,906	55,301.8	55,845.1
1,932	55,335.9	55,879.9
1,960	55,371.7	55,916.4
1,988	55,406.5	55,951.9
2,017	55,441.6	55,987.7
2,047	55,476.9	56,023.7
2,078	55,512.3	56,059.9
2,109	55,546.8	56,095.0
2,142	55,582.4	56,131.3
2,175	55,617.0	56,166.6
2,210	55,652.5	56,202.9
2,246	55,688.0	56,239.1
2,282	55,722.5	56,274.2
2,320	55,757.7	56,310.1
2,359	55,792.7	56,345.8
2,400	55,828.3	56,382.2
2,442	55,863.6	56,418.2
2,485	55,898.6	56,453.8
2,530	55,933.9	56,489.8
2,576	55,968.8	56,525.4
2,624	56,003.9	56,561.3
2,675	56,040.0	56,598.0
2,727	56,075.3	56,634.1
2,780	56,110.1	56,669.5
2,836	56,145.4	56,705.6
2,894	56,180.6	56,741.5
2,955	56,216.2	56,777.8
3,018	56,251.5	56,813.8
3,084	56,286.9	56,850.0
3,152	56,322.0	56,885.7
3,224	56,357.5	56,921.9
3,299	56,392.9	56,958.0
3,378	56,428.5	56,994.4
3,460	56,463.8	57,030.4
3,545	56,498.7	57,066.0
3,636	56,534.3	57,102.3

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CAMBRIDGE, MASS.

PREPARED BY: J. Feldman

DATE: 17 Feburary 1964

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SHEET 7

OF 7

Shunt Resistor Ω	Pulses to Command the Table 10° N+	N-
3,731	56,569.7	57,138.4
3,831	56,605.1	57,174.5
3,936	56,640.3	57,210.5
4,048	56,676.0	57,246.8
4,166	56,711.5	57,283.1
4,290	56,746.7	57,319.1
4,422	56,782.2	57,355.2
4,563	56,817.8	57,391.5
4,712	56,853.1	57,427.6
4,872	56,888.7	57,463.9
5,042	56,924.1	57,500.0
5,225	56,959.7	57,536.3
5,422	56,995.3	57,572.7
5,633	57,030.8	57,608.9
5,861	57,066.3	57,645.1
6,108	57,101.8	57,681.3
6,376	57,137.3	57,717.5
6,670	57,172.9	57,573.9
6,991	57,208.5	57,790.2
7,344	57,244.0	57,826.5
7,734	57,279.6	57,862.7
8,168	57,315.2	57,899.1
8,653	57,350.8	57,935.5
9,198	57,386.4	57,971.8
9,816	57,422.0	58,008.1
10,520	57,457.6	58,044.4
11,340	57,493.4	58,081.0
12,300	57,529.4	58,117.7
13,400	57,564.3	58,153.3
14,760	57,600.3	58,190.0
16,410	57,636.0	58,226.5
18,470	57,671.7	58.262.9
21,100	57,707.2	58,299.1
24,600	57,742.6	58,335.3
29,600	57,778.8	58,372.2
37,000	57,814.5	58,408.6
49,470	57,850.5	58,445.4
74,100	57,886.0	58,481.6
148,200	57,921.7	58,518.1
No Resistor	57,957.3	58,554.4

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APOLLO II IRIG Specification
MC 25-847
Release Date 24 Feb 1965
Release Revision A
Class A Release
TDRR 16760

Prealigned Gyro Assembly Procedure

Date	Revision Letter	TDRR No.	Pages Revised	Approval MIT	Approval NASA
2/12/65	A	16760	Initial Release		
4/5/65	B	18103	1	WK.	
6/8/65	C	20015	1, 2	WK.	
5-23-66	D	30014	REVISED & REWRITTEN		L. C. METZGER

TP#11938

This MC specification consists of page i to____ and 1 to 3 inclusive.

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CAMBRIDGE, MASS.

PREPARED BY: J. Feldman SHEET 1

DATE: 23 May 1966 MC 25-847 OF 3

Prealigned Gyro Assembly Procedure

I. The circuit Board Assembly (2021743) is fabricated by the following procedure:

1. Thoroughly clean the printed circuit board (2021746) in trichloroethylene or perchlorethylene with an acid brush. Rinse in freon.
2. Fasten four terminals (1012516-002) to the printed circuit board with the turret on the printed circuit side.
3. Clean the printed circuit board as in step 1 above.

II. The Mounting Plate Assembly (2021788) shall be fabricated by the following procedure:

1. Stake the terminals (1010846-006); Test Jacks (1010919-1) and clinch nut (1011766-6) to the mounting plate.
2. Seat the connector (1010852-26) on the mounting plate. Pin A shall be orientated as per 2021788. The female guide pin is to be located on the connector end where the upper case letters start.
3. Install the circuit board assembly (2021743) to the mounting plate. The connector may have to be moved slightly to align the connector pins with the printed circuit board holes.
4. Assemble connector washer and nut and tighten to torque specified on 2021788.

III. The mounting plate and harness assembly (2021790) shall be fabricated by the following procedure:

1. Place a fillet of LCA-9 cement around the 10 terminals (1010846-006) as specified on 2021790.
2. Place a mating connector on 1010852-26. This mating connector shall be in place during all connector soldering.
3. Install a dummy pre-amp module, dummy capacitor module and a clamping ring to the mounting plate. Torque the five screws to the torque requirements of 2021500.

4. Solder E-13, E-14, E-18 and the 9 connector pins to the circuit board.

5. Install and solder the 4 jumper wires as specified in Table I on 2021790.

6. Install and solder the "A" harness ass'y (2021791).

7. Remove dummy hardware and clamping ring. Clean entire assembly by submerging in perchlorethylene and scrub joints with an acid brush to remove soldering flux. Rinse in freon.

The Prealigned Gyro Assembly (2021500) shall be fabricated by the following procedure:

1. Feed the harness wires through the heater and end mount ass'y (2021501).

2. Solder the harness leads to the S. G. and T. G. ends of the gyro.

3. Install a wire retaining sleeve (2021777) over the gyro wire harness. Center the sleeve on the gyro length. Be sure all wires are in their proper place. Heat the sleeve uniformly to 200-225°F to shrink it into position. Care should be taken not to exceed this temperature and not to raise the internal temperature of the gyro above 150°F during the heat shrinking operation.

4. Coat the mating surfaces of the gyro and heater and end mount assembly with a thermal interface grease per 1006879. Push the mount down on the gyro trunion and uniformly tighten both screws.

5. Determine the length of the heater leads and solder these to the connector per 2021500. Spot tie the heater leads to the harness trunk as necessary to hold leads in position.

6. Install a jumper wire from terminals E-13 to E-14 and solder terminal E-14 only.

7. Install a preamp module (2021785), capacitor (2021503) and a clamping ring to the mounting plate. Torque the 5 screws using the torque requirements of 2021500.

8. Solder the preamp and capacitor pins to the circuit board. Solder the 2 leads to pins 11 & 12 of the capacitor module. Solder 2021803 wire to E-2 of printed circuit board.

9. From the polarity of uncompensated bias determined in previous testing, select the bias winding connection polarity.

A. To compensate for a positive bias drift (+ BD) connect BC_1 to E24 and BC_2 to J1-Y.

B. To compensate for a negative bias drift (-BD) connect BC_1 to J1-Y and BC_2 to E24.

Solder resistor R1 (2021504-27) to the appropriate terminals on the mounting plate.

11. Solder resistor R3 (2021594 selected per MC 25-845) to the appropriate mounting plate terminals.

12. Remove clamping ring and the temporary screws.

13. Clean all solder connections per ND 1002071.

14. Apply cement fillets between the capacitor module and the 6 test jacks as specified on 2021500.

15. Assemble the wire cover (2021789). Place ground lug of 2021803 preamp mounting screw and torque the 5 screws to the requirements of 2021500.

16. Fasten the mounting plate assembly to the heater mount using temporary screws.

17. The unit is now ready to be tested per requirements of PS 2021500. After tests have been performed and components R2, R4, R5, and R6 have been selected, solder these resistors to the appropriate mounting terminals. Solder the loose end of the jumper wire to E-13.

18. Remove the wire cover and screws. Clean the resistor solder connections and inspect all solder connections per ND 1002071. Any noted discrepancies must be corrected, prior to proceeding.

19. Replace the wire cover and torque the screws to the requirements of 2021500.

20. Complete testing per PS 2021500.

21. Perform resistance, continuity, and insulation resistance checks per PS 2021500.

22. Install the nameplate on the top of the capacitor module per 2021500.

23. Follow the notes for unit storage and shipping per 2021500.

APOLLO II IRIG Specification
MC 25-849
Release Date Feb. 2. 1965
Release Revision A
Class A **Release**
TDRR 15909

Declassified per NASA Letter
AP3-R-66-913-6, 1022
Date: Oct. 26, 1966 Signed

Test Data Book

Inspection Data & Calculations

Date	Revision Letter	TDRR No.	Pages Revised	Approval MIT	Approval NASA
9-15-65	D	22586	Replaces Rev C with changes	WK.	NOT REQUIRED PER LETTE NASA P[illegible]7-65-612
5-9-66	E	29313	3, 5, 6, 7, 8, 9 13, 14, 15, 16, 19	WK	A. C. METZGER

TP# 11938

This MC specification consists of page i to ____ and 1 to 20 inclusive.

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CAMBRIDGE, MASS

MC25-849

25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS
SERVO SUMMARY

PREPARED BY P. Kerrigan

DATE 2/2/65

SHEET 1

OF 20

UNIT NO. ____________

PART NO. NA-2021500

		STUD VALUES							
Date	Run No.	+IA Up	+SRA Up	+SRA Down	NBD	ADIA	ADSRA	CD	ID
		SPEC: MERU MAX.			MERU MAX.	MERU MAX.	MERU MAX.		MERU MAX.

Date	RD	SPEC: MERU MAX.

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CAMBRIDGE, MASS.

MC25-849

25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS
PREALIGNED GYRO

PREPARED BY P. Kerrigan
DATE: 2/2/65

SHEET 2
OF 20

Date __________
Station __________

Unit No. __________
Part No. NA2021500

TORQUE COMMAND RATE IA UP 10° at 3200 PPS
CONDUCTANCE 14.1666 MMHOS

	TM+ (Positive Pulse)	TM- (Negative Pulse)	SPEC		OOS	OPER
	AVERAGE COUNT					
Verification	__________	__________	TM+ TM-			
A Servo B Servo C Servo	__________ __________ __________	__________ __________ __________	TM+ TM-			
	AVERAGE COUNT REPEATABILITY					
Verification To A To B To C Servos	__________	__________	Counts Max.			
	COUNT SPREAD					
Verification A Servo B Servo C Servo	 __________ __________ __________	 __________ __________ __________	Counts Max.			
	TORQUE CURRENT					
Verification A Servo B Servo C Servo	 __________ __________ __________	 __________ __________ __________	☒	☒	☒	
	SFR VOLTAGE					
Verification A Servo B Servo C Servo	 __________ __________ __________	 __________ __________ __________	☒	☒	☒	

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CAMBRIDGE, MASS.

PREPARED BY: P. Kerrigan
DATE: 2/2/65

MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

SHEET 3
OF 20

Operator ________________
Date ________________

Unit No. ________________
Part No. NA 2021602

(4.2.2.1) THERMISTOR CALIBRATION MC 25-800

Bath Temp. 135°F Current 2 MA

Bath No.

Signal		Torque	
E	R CAL	E	R CAL

Time In

Time Out

TOTAL CALCULATED RESISTANCE ____ OHMS

Checked By : __________ Approved By: __________ Witnessed By: __________

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MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

SHEET 4
OF 20

Date ____________ Vibration
Operator ____________ Test Record

Unit No. ____________
Part No. NA 2021611

DATA FROM GYRO TEST AREA

(1) 135° Thermistor Resistance ________ Ohms

(2) Radial Suspension Capacitance SG ________ MFD
TG ________ MFD

(3) WHEEL DATA AT SYNCH:

	PHASE A	PHASE B
Wheel Voltages	________ V	________ V
Wheel Currents	________ MA	________ MA
WHEEL HOURS FROM TEST AREA	_ _ _ _ _ _	________ HRS.

(4) SG Null (Wheel On) _ _ _ _ _ _ _ _ _ _ _ _

VIBRATION TEST (4.2.2.9)

OPERATOR ____________ DATE ____________

(1) 135° Thermistor Resistance Used ________ OHMS

(2) Radial Suspension Capacitance Used SG ________ MFD
TG ________ MFD

(3) Check Float Suspension (Wheel Off) ________ RESULT

(4) SG Null Before Vibration (Wheel On 0.3 HR. MIN.) ________ MV

(5)

Wheel was on ___ hrs. during this test.

WHEEL DATA DURING TEST

Wheel On 0.3 Hr. Min.	Phase	Voltage	Phase	Current
(Synch.) Wheel Date	A		A	
	B		B	
Wheel Data After Vibration	A		A	
	B		B	

(6) SG Null (Wheel On) after Vibration Test ________ MV

(7) Maximum Magnitude of Vibration Frequency ________

(8) Is Radial Suspension O.K. After Vibration? ________

(9) Has Gyro Passed the Vibration Test Successfully? ________

REMARKS:

Checked By: ________ Approved By: ________ Witnessed By: ________

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PREPARED BY: P. Kerrigan
DATE: 2/2/65

MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

Date________________
Bench________________

Unit No.________________
Part No. NA 2021602

RESISTANCE, CONTINUITY & MEGGER CHECK

RESISTANCE AND CONTINUITY CHECK (4.2.2.2)

Cir.	No.	Terminals	Resist	SPEC (ohms)	IS	OOS	OPER
SG SUSP		MS(6-7) - SG MS COMM.					
		MS(1-8) - SG MS COMM.					
		MS(2-3) - SG MS COMM.					
		MS(4-5) - SG MS COMM.					
SG PRIM		PH - PL					
SG SEC.		SH - SL					
SG THERM		TH - TH					
TG SUSP		MS(6-7) - TG MS COMM.					
		MS(1-8) - TG MS COMM.					
		MS(2-3) - TG MS COMM.					
		MS(4-5) - TG MS COMM.					
TORQUE COIL		T+ - TY					
		T- - TY					
		T COMM. - TY					
RESET		RH - RL					
BIAS		BC1 - BC2					
TG THER		TH - TH					
MOTOR		A+ - A-					
		B+ - B-					

INSULATION RESISTANCE (4.2.2.2)

Cir.	No.	Terminals	Resist	SPEC	IS	OOS	OPER
SG		PH - SH					
		PH - CASE					
		SH - CASE					
		MS COMM - CASE					
TG		T COMM - CASE					
		MS COMM - CASE					
		RH - CASE					
		BC1 - CASE					
		RH - T COMM					
		BC1 - T COMM					
		RH - BC1					
MOTOR		A - CASE					
		B - CASE					
		A - B					

Checked By:__________ Approved By:__________ Witnessed By:__________

PREPARED BY: P. Kerrigan
DATE: 2/2/65

MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

Date ______________

Station ______________

Unit No. ______________

Part No. NA 2021602

MICROSYN SUSPENSION EXCITATION & PHASING (4.2.2.4)

Microsyn Excitation		Values	SPEC LIMITS	IS	OOS	OPER
4.0 Volts	SG Current (Susp.)	MA				
	TG Current (Susp.)	MA				
	SG Phase Angle (Susp.)	°				
	TG Phase Angle (Susp.)	°				
	SG Capac. Setting	MFD				
	TG Capac. Setting	MFD				

MAGNETIC SUSPENSION (4.2.2.4)

SG Capac. Value ______________

TG Capac. Value ______________

Swamping Resistor Value ____________ 50 ohm

Suspension Current ______________ 50 ± 5 MA

Reset Coil Current ______________ MA

Selected for phase of $70^\circ \pm 2^\circ$ with 50 ohm swamping resistor and 50 ± 5 MA.

MAGNETIC SUSPENSION (4.2.2.4)
4.0 VOLTS - MS EXCITATION ONLY

SG	E MAX	PHASE	E REST	PHASE	CENTERING VALUE	RATIO	SPEC LIMITS	IS	OOS	OPER
(X) 1-8										
(X) 4-5										
(Y) 2-3										
(Y) 6-7										
TG										
(X) 1-8										
(X) 4-5										
(Y) 2-3										
(Y) 6-7										

CALCULATE ALGEBRAICALLY

CENTERING FORMULA EXAMPLE

1 TG 1-8 E MAX - TG 1-8 E REST = TG 1-8 Centering Value

2 Larger Centering Value + Smaller Centering Value = Ratio.

AXIAL FREEDOM			SPEC	IS	OOS	OPER
TG	Rest Current (I_R) ________ MA	I_R + 10% ________	☒	☒	☒	
	Current After Short Removed ____________ MA					
SG	Rest Current (I_R) ________ MA	I_R + 10% ________	☒	☒	☒	
	Current After Short Removed ____________ MA					

Checked By: ______________ Approved By: ______________ Witnessed By: ______________

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PREPARED BY: P. Kerrigan
DATE: 2/2/65

MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

SHEET 7
OF 20

Date ____________________

Station ____________________

Unit No. ____________________

Part No. NA 2021602

WHEEL CHECK (4.2.2.5)

	Phase A		Phase B	
Starting				
Voltage	________	Volts	________	Volts
Current	________	MA	________	MA

Using 28. 0 V Starting Voltage
Wheel Synched in ______ Sec.

SPEC	IS	OOS	OPER

Null Voltage (4.2.2.9)

SG Null ________ MV

Checked By: ____________ Approved By: ____________ Witnessed By: ____________

PREPARED BY: P. Kerrigan
DATE: 2/2/65

MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

SHEET 8
OF 20

Date ______________
Station ______________
Unit No. ______________
Part No. NA 2021611

(WHEEL ON) **FLOTATION TEMPERATURE (4.2.2.3)**

Date ______________ Station ______________

	SG X	SG Y	TG X	TG Y
Radial Nulls				

Series	Panel Therm. Resist. & Gyro Temp.	Gyro Position	RADIAL VOLTAGES				SPEC	IS	OOS	OPER
			SG X	SG Y	TG X	TG Y				
1 app. 137°F	Res. ______ Temp. °F	SRA Up					NOTE: Transter individual voltage differences, of each radial axis, to flotation temperature graph. Plot intersection point by drawing lines that connect the points of each axis. Resulting point of intersection of the 4 lines will indicate thermistor resistance at flotation.			
		SRA Dn								
	Radial Volt. Difference									
2 app. 133°F	Res. ______ Temp. °F	SRA Up								
		SRA Dn								
	Radial Volt. Difference									
3	Res. ______ Temp. °F	SRA Up								
		SRA Dn								
	Radial Volt. Difference									

FLOT. THERM. RESIST.		______			
FLOTATION TEMP.					

Checked By: ______________ Approved By: ______________ Witnessed By: ______________

PREPARED BY: P. Kerrigan
DATE: 2/2/65

MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

SHEET 9
OF 20

Date ________________
Station ________________

Unit No. ________________
Part No. NA 2021602

MICROSYN POLARITY (4.2.2.7)

	Phase Angle	Scope Phase	SPEC	IS	OOS	OPER
Wheel On, + IA Up Rotate Table CCW At the + Stop						
(CCW Table Rot.) + Stop Value MV						
(CW Table Rot.) - Stop Value MV						

Date ________________
Station ________________

ROTATIONAL ANGULAR LIMITS (4.2.2.6 & 4.2.2.8)

	Stop Voltages	Values	SPEC	IS	OOS	OPER
CCW Rotation for 2.9089	MV	MV MV				
CW Rotation For 2.9089 MR	MV	MV MV				
Average →		MV				
$TF = \frac{\text{Average}}{2.9089\ MR}$						
$\frac{\text{Stop Volt}}{TF \times 17.4533}$ = Angular Motion About IA		+ ° - °				

Checked By: __________ Approved By: __________ Witnessed By: __________

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MC25-849

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DATE 2/2/65

25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

SHEET 10
OF 20

Date ____________________

Station ____________________

Float Freedom
(4.2.3.2)

Unit No. ____________________

Part No. NA2021611

OA Vertical

A. Sweep from + 50 mv to - 50 mv

Average Torque 2 min. after start __________ meru
Average Torque 8 min. after start __________ meru

B. Sweep from - 50 mv to + 50 mv

Average Torque 2 min. after start __________ meru
Average Torque 8 min. after start __________ meru

C. Sweep from + 50 mv to - 50 mv

Average Torque 2 min. after start __________ meru
Average Torque 8 min. after start __________ meru

D. Sweep from - 50 mv to + 50 mv

Average Torque 2 min. after start __________ meru
Average Torque 8 min. after start __________ meru

E. Maximum Deviation (Spike) Amplitude:

A________ B________ C________ D________

F. Sum of Deviations (Spikes) Greater than meru

A________ B________ C________ D________

	A	B	C	D
	Max. Meru	Max. Meru	Max. Meru	Max. Meru
Sum				

G. Average Slope of Reference Lines __________ meru/mr

SPEC	IS	OOS	OPER
meru			
meru/sweep			
meru/mr			

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CAMBRIDGE. MASS

MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

PREPARED BY P. Kerrigan
DATE 2/2/65
SHEET 11
OF 20

Date ____________
Station ____________

FLOAT FREEDOM

(4.2.3.2)

Unit No. ____________
Part No. NA 2021611

OA HORIZONTAL

A. Sweep From + 50 mv to - 50 mv
Average Torque 2 min. after start ________ meru
Average Torque 8 min. after start ________ meru

B. Sweep From - 50 mv to + 50 mv
Average Torque 2 min. after start ________ meru
Average Torque 8 min. after start ________ meru

C. Sweep From + 50 mv to - 50 mv
Average Torque 2 min. after start ________ meru
Average Torque 8 min. after start ________ meru

D. Sweep From - 50 mv to + 50 mv
Average Torque 2 min. after start ________ meru
Average Torque 8 min. after start ________ meru

E. Maximum Deviation (Spike) Amplitude:
A. ____________ B. ____________

F. Sum of Deviations (Spikes) Greater than meru
A. ____________ B. ____________

	A	B	C	C
	Max. Meru	Max. Meru	Max. Meru	Max. Meru
Sum				

G. Average Slope of Reference Lines ________ meru/mr

SPEC	IS	OOS	OPER
meru			
meru sweep			
meru mr			

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~~(when filled in)~~

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MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

PREPARED BY P. Kerrigan
DATE 2/2/65

SHEET 12
OF 20

Date ____________
Station ____________

Unit No. ____________
Part No. NA 2021500

TEMPERATURE SENSITIVITY (4.2.3.1)

C Y C L E	THERMISTOR CIRCUIT RESISTANCE 135° ________ 138° ________ 132° ________					
	+ OA DOWN	+ OA UP	SPEC	IS	OOS	OPER
1	132° Value ______ meru 138° Value ______ meru Diff. ______ meru Temp. Change 6.0°F	132° Value ______ meru 138° Value ______ meru Diff. ______ meru Temp. Change 6.0°F	meru max. chg. per 1°F			
	$\frac{\text{Diff.}}{\text{Temp. Change}} = \frac{\text{meru}}{^\circ\text{F}}$	$\frac{\text{Diff.}}{\text{Temp Change}} = \frac{\text{meru}}{^\circ\text{F}}$				

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PREPARED BY: P. Kerrigan
DATE: 2/2/65

MC25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS

SHEET 13 OF 20

Date ______________
Station ______________

Unit No. ______________
Part No. NA 2021611
NA 2021602
NA 2021500

RUNDOWN TIME (4.2.2.5)

(Wheel on 2 hrs. minimum prior to test)

	Phase A	Phase B
Synch. Voltage	______ volts	______ volts
Current	______ ma	______ ma

Shorted Rundown Time From Ass'y.

SERVO SERIES WHEEL RUNDOWN TIME RECORD

Test	Wheel Hours	Date	Test Status & Stations	Total Rundown Time	24000 to 6000 rpm	SPEC	IS	OOS	INSP
1							1		
							2		
2							1		
							2		
3							1		
							2		
4							1		
							2		
5							1		
							2		
6							1		
							2		
7							1		
							2		
8							1		
							2		

Average Shorted Rundown Time			
RMS Deviation			

Summary Formula

$$\sqrt{\frac{\sum_{n-1}^{n-8} (RDT_N - RDT_{Ave})^2}{8}} = \text{RMS Deviation}$$

Checked By: ______________ Approved By: ______________ Witnessed By: ______________

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MC25-849

25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS
PREALIGNED GYRO

PREPARED BY: P. Kerrigan
DATE: 2/2/65

SHEET 14
OF 20

Date ____________
Station ____________

PREALIGNMENT
(4.2.3.4)

Unit No. ____________
Part No. NA 2021500

A. Thermal Calibration

Thermistor Padding	SPEC	IS	OOS	OPER
Thermistor Resistance @ 135° ± 0.1°F ____ Ω				
Padding Resistor ____________ Ω	[illegible]			
Total Resistance ____________ Ω	[illegible]			

B. Magnetic Suspension Current Phasing

Suspension Capacitors	SPEC	IS	OOS	OPER
Shrouded Gyro SG & TG ________ mfd	[illegible]			
Final Prealignment				
Modules SG & TG ________ mfd	[illegible]			
SG Phase Angle (Suspension) _____ °				
TG Phase Angle (Suspension) _____ °	[illegible]			
SG Suspension Current ________ ma				
TG Suspension Current ________ ma				

RADIAL FREEDOM

SG	E MAX	PHASE	E REST	PHASE	CENTERING VALUE	RATIO	SPEC		IS	OOS	OPER
(X)1-8							Opposite Phase	[illegible]			
(X)4-5											
(Y)2-3							Opposite Phase				
(Y)6-7											
TG											
(X)1-8							Opposite Phase	[illegible]			
(X)4-5											
(Y)2-3							Opposite Phase				
(Y)6-7											

Centering Formula 1. TG1-8 E MAX - TG1-8 E REST = TG1-8 Centering Value
Example: 2. Larger Centering Value ÷ Smaller Centering Value = Ratio

Checked By: ____________ Approved By: ____________ Witnessed By: ____________

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DATE: 2/2/65

25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS
PREALIGNED GYRO

SHEET 15
OF 20

Date____________________ Unit No.____________________

Station____________________ Part No. NA 2021500

PREALIGNMENT
(4.2.3.4)

B. MAGNETIC SUSPENSION CURRENT PHASING (cont'd.)

		Spec.	IS	OOS	OPER
TG	Rest Current (I_R)______ma I_R + 10%___				
	Current after short removed ma				
SG	Rest Current (I_R)______ma I_R + 10%___				
	Current after short removed______ma				

C. BIAS ADJUSTMENT

	Spec.	IS	OOS	OPER
Uncompensated Value (UBD)__________ meru				
Final bias compensation resistor__________ Ω				
Final BD Value __________ meru	<_____meru			

D. IA ALIGNMENT

	Spec.	IS	OOS	OPER
In-Phase component of SG OUTPUT When rotated about SRA ______________ mv				

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PREPARED BY: P. Kerrigan

DATE: 2/2/65

MC 25-849
25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS
PREALIGNED GYRO

SHEET 1
OF 2

Date ____________________

Station ____________________

Unit No. ____________________

Part No. NA 2021500

PREALIGNMENT
(4.2.3.4)

E. GYRO TRANSFER FUNCTION

Transfer Function of Shrouded Gyro ____________ mv/mr

Preamp Feedback Resistor Value ____________ Ω

	Stop Voltages	Values	SPEC	IS	OOS	OPER
CCW Rotation for 2.9089 mr	______ mv	mv mv				
CW Rotation for 2.9089 mr	______ mv	mv mv				
Average →		mv				
$TF = \frac{\text{Average}}{2.9089\ \text{mr}}$		$\frac{\text{mv/sec}}{\text{mr/sec}}$				

Checked by: ____________ Approved by: ____________ Witnessed by: ____________

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MC25-849

25 IRIG APOLLO II

INSPECTION DATA & CALCULATIONS

TORQUE COMMAND RATE

PREPARED BY P. Kerrigan

DATE: 2/2/65

SHEET 17 OF 20

Date ____________

Station ____________

Unit No. ____________

Part No. NA 2021500

IA UP 10^o 3200 pps

TM +	TM -	SPEC
Average	Counts	
Count Spread		Counts Max.
Torque Current		X
SFR Voltage		X
• Selected TG Padding Resistor		X

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MC25-849

25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS
TORQUE COMMAND RATE
SIDE LOADING

PREPARED BY: P. Kerrigan
DATE: 2/2/65

SHEET 18 OF 20

Date ____________

Station ____________

Unit No. ____________

Part No. NA 2021500

	Sum of 1° Counts		Spread 11° to E_{Steady}	Spec.
	TM+	TM-		
E_{Rest}		mv		
2°-11°			TM+	Counts Max.
3°-12°				
4°-13°				
5°-14°				
6°-15°				
7°-16°				
8°-17°				
9°-18°				
10°-19°				
11°-20°				
12°-21°				
13°-22°				
14°-23°			TM-	Counts Max.
15°-24°				
16°-25°				
E_{Steady}	mv			

Checked By: ____________ Approved By: ____________ Witnessed By: ____________

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MC25-849

PREPARED BY: P. Kerrigan

DATE: 2/2/65

25 IRIG APOLLO II
INSPECTION DATA & CALCULATIONS
[illegible] PREALIGNED GYRO [illegible]

SHEET 19
OF 20

Date ________________
Unit No. ________________
Station ________________
Part No. NA 2021500

INSULATION RESISTANCE
(4.2.2.2)

	Terminals	Resistance	SPEC	IS	OOS	OPER
	PIN P - CASE					
	PIN Z - CASE					
	PIN D - CASE					
	PIN R - CASE					
	PIN L - CASE					
	PIN F - CASE					
	PIN W - CASE					
	PIN E1 - CASE					
	PIN P - PIN R					
	PIN Z - PIN W					
	PIN L - PIN F					
	PIN W - PIN E1					

Checked By: __________ Approved By: __________ Witnessed By: __________

PREPARED BY: P. Kerrigan
DATE: 2/2/65

MC25-849
25 IRIG APOLLO II
INSPECTION DATA

Date ____________ Unit No. ____________

FLOAT MILLIWATTMETER TRACE SAMPLE FROM FINAL TEN HOURS OF QUALIFICATION

CALIBRATION
__________ MW/MM

TAPE SPEED
__________ IN /HR

Checked By: __________ Approved By: __________ Witnessed By: __________

APOLLO II IRIG Specification
MC 25-867
Release Date Feb 2, 1965
Release Revision -
Class A Release
TDRR 15909

Pre-Amp Assembly Procedure

Date	Revision Letter	TDRR No.	Pages Revised	Approval MIT	Approval NASA
2/2/65	----	15909	Initial Release	WR.	Hm
4/30/65	A	18828	1 & 2	WR.	WJR
5/18/65	B	19186	1	WR.	WJR

TP# 11938

This MC specification consists of page i
to – and 1 to 3 inclusive.

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASS.

PREPARED BY J. Feldman
DATE 22 January 1965

MC 25-867

SHEET 1
OF 3

Pre-Amp Assembly Procedure

The following assembly procedure should serve as a guide to the assembly of the gyro preamp module (drawing number 2021785). Some changes in the order or method outlined here may be needed to simplify the assembly.

1. Assemble a kit of parts per drawing 2021785.

2. Swage terminals to bottom wiring board, (drawing number 2021782) using steps 1 to 3 page 3.

3. Punch remaining holes in wiring boards 2021781 and 2021782.

4. Set one wiring board (either top or bottom whichever will afford easier assembly) on to a holding fixture (a sheet of styrafoam could also serve as a holding fixture) and insert electrical components into appropriate slots or holes.

5. Place second wiring board in place.

6. Insert spacers (drawing number 2021763) between boards.

7. Perform necessary welding on top surface of board. Do not make connection between R5 and R10.

8. Pick up bottom wafer board from holding fixture and turn over the assembly.

B 9. Perform the necessary welding on the other side of the board. Do not install a ribbon connecting P11, R5, R10 and R9.

B A 10. Perform electrical tests per MC 25-868 to obtain the value of the R2 resistor. Test fixture jumpers will be needed to connect P11 to R5 and R10 to R9 during this test.

B 11. Insert R2 and weld it to the module. Install and weld the ribbon connecting P1 R5, R10 and R9.

12. Assemble module terminals per drawing 2021761 and assemble to the housing per drawing 2021779.

Rev A 4/30/65

13. Place the welded subassembly into the housing (2021779).

14. Weld the leads (item 2 of drawing 2021761) to the module.

15. Apply a mold release material per SCD1006843 to the module terminals (item 2 of drawing 2021782).

16. Screw the mold cover (MIT drawing number 124891) to the mounting holes in the module.

17. Assemble the mold cover flush with the preamp case. The terminals will be projecting through the holes in the cover.

18. Attach a pouring spout to the potting fixture, using GE RTV 11 with quick curing catalyst to fasten. At same time seal around base of case and mold cover.

19. Place the potting fixture, dumper and stycast 1090 (per SCD1010305) with catalyst 11 (per SCD1010306) in an oven at 150°F for 30 minutes.

20. Pour the potting material into the dumper* and place the dumper into the bell jar with the module under the spout.

21. Evacuate the bell jar per ND1002036.

22. Slowly release the resin until the mold is filled and the spout level remains constant.

23. Remove the module from the bell jar and place it in the oven and cure per ND1002036.

24. Separate the spout from the potting fixture.

25. Gently tap the fixture from the module.

26. Clean the excess potting material from the module and terminals.

27. The spout flashing should be made at least flush with the module.

A 28. Perform final electrical inspection per MC 25-868.

* If no dumper is available it would be necessary to expose to air while hand pouring.

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CAMBRIDGE, MASS

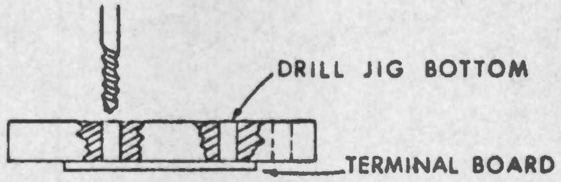
PREPARED BY J. Feldman
DATE 22 January 1965

MC 25-867

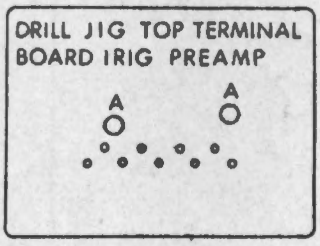
SHEET 3
OF 3

SWAGING TERMINALS TO TERMINAL BOARD

STEP 1

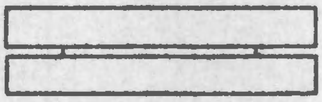


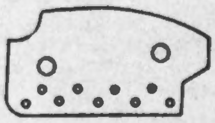
Using double sticky tape, line up terminal board with profile (or with holes up to light and looking through holes) on lower drill jig, turn jig over and drill terminal board through pilot holes "A". 3/32 (.0937) drill.



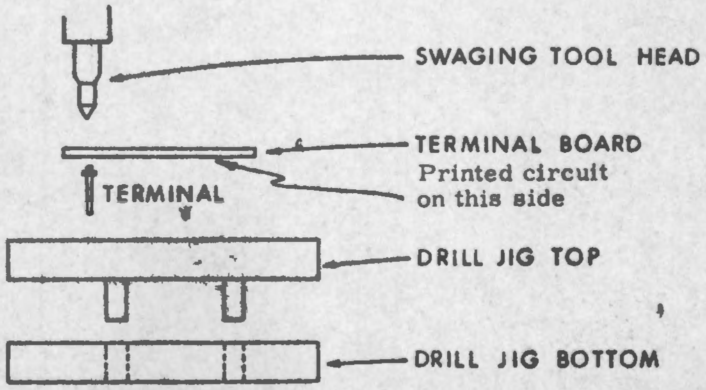
STEP 2

Sandwich terminal board between the top and bottom jig plates. Drill the nine (9) terminal holes. #58 (.042) drill.





STEP 3



Place terminals in holes as shown then place board (printed side down) such that all terminals are engaged in their respective holes. Swage.

APOLLO II IRIG Specification
MC 25-868
Release Date Mar. 8, 1965
Release Revision --
Class A **Release**
TDRR 17180

IRIG Preamplifier Specifications and Test Procedure

Date	Revision Letter	TDRR No.	Pages Revised	Approval	
				MIT	NASA
3/8/65	---	17180	Initial Release		
5/11/65	A	19836	1, 2, 3	WR	
5/25/66	B	29311	1	WK	A. C. METZGER

TP# 11938

This MC specification consists of page i
[illegible] ___ and 1 to 3 inclusive.

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE MASS

MC 25-868

PREPARED BY Manuel Kramer

IRIG PREAMPLIFIER SPECIFICATIONS
AND TEST PROCEDURES

SHEET 1
OF 3

DATE 5 March 1965

1. ELECTRICAL SPECIFICATION

1.1 PRIMARY. The assembly shall perform as specified in this section (1.1) within the limits of the following constraints:

a.	Supply Voltage:	25 to 30 vdc
b.	Assembly Temperature:	60°F to 140°F
c.	Load Resistance:	10 K

d. Signal ground connected to 0 vdc
e. Preamp Case connected to 0 vdc

1.1.1 Voltage Gain Range. With a 3200 cps sine wave input of 10 mv. rms, the voltage gain shall be adjustable from 88 to 165. This adjustment shall be made by selecting the appropriate value of R12 which will be connected to P10 and P11 during IRIG calibration.

1.1.2 Voltage Gain Stability. After the voltage gain has been adjusted as described in 1.1.1 it shall not vary more than 4 percent for the constraint variations within the limits specified in 1.1.

1.1.3 Phase Shift. With a 3200 cps sine wave input of 10 mv. rms, the phase shift of the output with respect to the input shall be 180° ± 10° for all voltage gains within the range specified in 1.1.1.

1.1.4 Dynamic Range. For all voltage gains within the range specified in 1.1.1, the voltage gain for an output of 10 V rms shall be within 5% of the voltage gain determined by the conditions of 1.1.1.

1.1.5 Harmonic Distortion. The harmonic distortion of the output voltage shall be less than 1 percent under the conditions specified in 1.1.1 and less than 5 percent under the conditions specified in 1.1.4.

1.1.6 Zero Signal Noise. With the input terminals shorted to 0 vdc the output voltage shall be less than 20 mv. rms.

1.1.7 Demodulator Load Correction Resistance, R11. The resistance measured between pin 5 and pin 1 shall be 10K ± 5% ohms.

1.1.8 Resolver Power Factor Correction Capacitance, C3. The capacitance measured between pin 9 and pin 1 shall be 0.01 ± 10% μ f.

1.2 DESIGN MARGIN. Compliance of this assembly with design margin specifications is required prior to acceptance only. The assembly shall perform as specified in this section (1.2) within the limits of the following constraints:

a.	Supply Voltage:	27.5 vdc
b.	Assembly Temperature:	80°F

Rev. A 5/11/65

c. R12: 150K ohms
d. Load Resistance: 10 K ohms
e. Signal ground connected to 0 vdc

1. 2. 1 Loop Gain. With a 3200 cps sine wave input and the output voltage fixed at 1. 0 V rms, the loop gain shall be 20 ± 1 db.

1. 2. 2 Phase Margin. The phase margin shall be greater than 45° under the following conditions:

a. Loop gain shall be as specified in 1. 2. 1.

b. The input voltage shall be maintained at a level equal to that which is required to produce a voltage at the output terminals of 1. 0 V rms at 3200 cps.

1. 2. 3 Gain Margin. The gain margin shall be greater than 6 db under the following conditions:

a. Loop gain shall be as specified in 1. 2. 1.

b. The input voltage shall be maintained at a level equal to that which is required to produce a voltage at the output terminals of 1. 0 V rms at 3200 cps.

2. ELECTRICAL TEST AND NOMINAL SELECTION PROCEDURES

2. 1 PRIMARY. The tests in this section (2. 1) shall be performed within the limits of the following constraints:

a. Supply Voltage: 25 ± 0. 3 vdc and 30 ± 0. 3 vdc
b. Assembly Temperature: 80° ± 10°F
c. Load Resistor: 10 K ohms ± 5%
d. Signal ground connected to 0 vdc

2. 1. 1 Voltage Gain Range. With a 3200 ± 32 cps sine wave of 10 ± 0. 1 mv. rms connected to the input terminals, measure the voltage gain with

a. R12 equal to 150 K ohms ± 2%
b. R12 equal to 17 K ohms ± 2%

2. 1. 2 Voltage Gain Stability. Using data acquired in 2. 1. 1 calculate voltage gain stability for:

a. R12 equal to 150 K ohms ± 2%
b. R12 equal to 17 K ohms ± 2%

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2.1.3 Phase Shift. Apply a 3200 ± 32 cps sine wave of 10 ± 0.1 mv. rms to the input terminals. Measure the phase shift of the output with respect to the input:

a. With R12 equal to 150 K ohms ± 2%
b. With R12 equal to 17 K ohms ± 2%

2.1.4 Dynamic Range. Apply a 3200 ± 32 cps sine wave to the input terminals. Adjust its amplitude to produce 10 ± 0.1V rms at the output terminals:

a. With R12 equal to 150 K ± 2%
b. With R12 equal to 17 K ± 2%

2.1.5 Harmonic Distortion. Measure the harmonic distortion of the output voltage for the conditions of 2.1.1 and 2.1.4.

2.1.6 Zero Signal Noise. Short the input terminals to 0 vdc and measure the output voltage.

2.1.7 Demodulator Load Correction Resistance, R11. Measure the resistance between pin 5 and pin 1.

2.1.8 Resolver Power Factor Correction Capacitance, C3. Measure the capacitance between pin 9 and pin 1.

2.2 DESIGN MARGIN. The tests and nominal selection procedures in this section (2.2) shall be performed within the limits of the following constraints:

a. Supply Voltage: 27.5 ± 0.3 vdc
b. Assembly Temperature: 80° ± 10°F
c. Load Resistance: 10 K ohms ± 5%
d. Signal ground connected to 0 vdc

Rev. A 5/11/65

2.2.1 Loop Gain. Adjust the loop gain to 20 ± 1 db by selecting the appropriate value of R2 under the following conditions:

a. Input Voltage Frequency: 3200 ± 32 cps
b. Voltage at the output terminals maintained at 1.0 ± 0.05 V rms.

2.2.2 Phase Margin. Measure the phase margin under the following conditions:

a. Loop gain shall be as specified in 1.2.1.

b. The applied voltage shall be maintained at a level equal to that which is required to produce a voltage at the output terminals of 1.0 ± 0.05 V rms at 3200 ± 32 cps.

2.2.3 Gain Margin. Measure the gain margin under the following conditions:

a. Loop gain shall be as specified in 1.2.1.

b. The applied voltage shall be maintained at a level equal to that which is required to produce a voltage at the output terminals of 1.0 ± 0.05 V rms at 3200 ± 32 cps.

History of Key Technologies

The History of Apollo Onboard Guidance, Navigation, and Control

David G. Hoag
The Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts

Introduction

WHEN Apollo astronauts finally walked on the moon, thousands of engineers, scientists, managers, and technicians of many varied disciplines and specialties shared in the glorious accomplishment of an extraordinary national goal. This is the story of an essential part of that endeavor—that of the development and execution of the guidance, navigation, and control systems which, onboard Apollo along with the astronauts, made essential measurements of the spacecraft motions and directed necessary maneuvers for the mission.

The Beginnings

The forerunner of the Apollo guidance, navigation, and control system is found in an unmanned spacecraft and mission study started in 1957 by the Instrumentation Laboratory at MIT under a contract with the Air Force Ballistic Missile Division. The small Instrumentation Laboratory team for this study, led by Milton Trageser and supported by AVCO Corporation, the MIT Lincoln Laboratory, and Thiokol Chemical Corporation, designed a small autonomous spacecraft weighing 150 kg which would take a close-up high-resolution photo of Mars. This Mars probe had several novel features, later incorporated in the Apollo system, including a space sextant to make periodic navigation angle measurements between pairs of celestial objects: the sun, the near planets, and selected stars. The guidance technique utilized original formulations designed by Dr. J. Halcombe Laning and Dr. Richard Battin to operate a small rocket at the appropriate times to put the spacecraft on a corrected trajectory which would utilize the Martian gravity during the close passage such as to send the spacecraft with its Mars picture on a return path back to Earth for physical recovery. Spacecraft attitude control would be accomplished by torquing small momentum wheels using the solar pressure force on adjustable sun vanes to drive the average speed of these wheels toward zero. Overall autonomous operation was managed onboard by a small general purpose digital computer configured by its designer, Dr. Ramon Alonso, for very-low-power drain except at the occasional times needing fast computation speed. A special feature of this computer was the prewired, read-only memory called a core rope, a configuration of particularly high storage density required only one magnetic core per word of memory.

A four-volume report of this work[1] was published in July 1959, and presented to the Air Force sponsors. However, the Air Force was then disengaging from civilian space development, so endeavors were undertaken to interest NASA. Dr. H. Guyford Stever, then a professor at MIT, arranged a presentation for Dr. Hugh Dryden, NASA Deputy Administrator, which took place on September 15, 1959.[*] On November 10, 1959, NASA sent a letter of intent to contract the Instrumentation Laboratory for a $50,000 study to start immediately. The stated purpose was that this study would contribute to the efforts of NASA's Jet Propulsion Laboratory in conducting unmanned space missions to Mars, Venus, and the Earth's moon scheduled in Vega and Centaur missions in the next few years. A relationship between MIT and JPL did not evolve. JPL's approach to these deep space missions appeared to be primarily ground base control with their large antenna tracking and telemetry systems, considerably different from the onboard self-sufficiency method which the MIT group advocated and could best support.

The Instrumentation Laboratory report on the NASA study appeared in four volumes[2] in April 1960. It described the design of a 35-kg pod comprising a self-contained guidance, navigation, and control system intended for mounting on Centaur vehicles to support a variety of space missions. A space sextant, similar to but improved over the Mars probe

David G. Hoag was graduated in 1946 from the Massachusetts Institute of Technology with an SB degree in electrical communications and received in 1950 an SM degree in instrumentation from the MIT Department of Aeronautics. His early career at the MIT Instrumentation Laboratory involved engineering on Navy fire control systems for guns and missiles. From 1958-1961 he was Technical Director of the Instrumentation Laboratory's development of the guidance system for the Navy's Polaris submarine launched ballistic missile. From 1962 to 1973, he was first Technical Director, and later, Program Manager of MIT's development and operational support of the guidance, navigation, and control systems for the Apollo Command Module and lunar landing spacecrafts. He became Head of the Advanced Systems Department in 1973 when the Instrumentation Laboratory became independent of MIT as The Charles Stark Draper Laboratory, Inc. In that role he now leads activities in precision pointing and tracking for directed energy weapons and space based surveillance systems. He is a corresponding member of the International Academy of Astronautics and serves on the advisory board of its journal, Acta Astronautica. He is a member and Past President of the Institute of Navigation. He was elected Fellow of AIAA in 1974 and is a past Chairman of the New England Section, AIAA. In 1979 he was elected to the National Academy of Engineering. He has received several awards for his work on Apollo including the NASA Public Service Award, the Thurlow Award of the ION, and (with Richard H. Battin) the Louis W. Hill Award of AIAA.

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[*] Dryden himself did not hear their talks. The MIT Laboratory team was upstaged by the presence of Premier Kruschev that day visiting in Washington.

EDITORS'S NOTE: This manuscript was invited as a History of Key Technologies paper as part of AIAA's 50th Anniversary celebration. It is not meant to be a comprehensive study of the field. It represents solely the author's own recollection of events at the time and is based upon his own study, would make autonomous navigation measurements. Two single-axis gyroscopes and an accelerometer were included in the design for angle and velocity change measurement. A wide-ranging examination of deep space trajectory studies reported by Laning and Battin showed needed injection velocities, transfer times, and target planet approach paths. A variable time-of-arrival guidance scheme was formulated by Battin to minimize the usage of maneuver fuel. He also worked out strategies for optimum navigation measurement schedules with the sextant. Other features showed the development of ideas started in the Mars probe. Particularly, the configuration of the digital computer was refined by Alonso and Laning.

Early Apollo[3]

The frustration of the MIT Instrumentation Laboratory team to find a place in the unmanned deep space missions continued through the summer of 1960. In November, Dr. C.S. Draper, Director of the Instrumentation Laboratory, had conversations about this and about possible participation in manned space missions with Dr. Harry J. Goett, Director of NASA's Goddard Laboratories and Chairman of the NASA Research Steering Committee on Manned Space Flight.

The manned lunar mission had been under NASA consideration for some time and was being examined by Goett's committee. The Space Task Group at Langley Field formed in October 1958 was working on Project Mercury but was by this time considerably involved in the proposed moon mission. The name Apollo was announced in July 1960, and in August, NASA stated its intent to fund six-month feasibility study contracts which were awarded later in the year to General Dynamics/Convair, General Electric Company, and the Martin Company.

After the Draper and Goett conversation, a meeting at Goddard was held on November 22, 1960 to discuss a six-month $100,000 contract with the Instrumentation Laboratory for an Apollo study and preliminary design. The details were proposed by Trageser of MIT and Robert G. Chilton, of the Space Task Group at Langley. A technical proposal was submitted on December 22, and the contract started in February.

Trageser and Chilton developed the basic configuration of the proposed trial design which prevailed throughout the program. They determined that the system should consist of a general purpose digital computer, a space sextant, an inertial guidance unit (gyro stable platform with accelerometers), a control and display console for the astronauts, and supporting electronics. The in-flight autonomy of the earlier Air Force and NASA studies seemed appropriate to the manned mission, particularly since some urged that the mission should not be vulnerable to interference from hostile countries. It was judged important to utilize the man in carrying out his complex mission rather than merely to bring him along for the ride. In addition, a certain value of self-contained capability was envisioned for future deep space programs for other reasons: First, the transmission and feedback times are too long for fast reaction remote control due to the finite electromagnetic signal propagation velocity. Second, it was envisioned that the United States would eventually have many missions underway at the same time, and it was important to avoid expanding the need for more large, expensive ground stations.

The initial Apollo contract at the Instrumentation Laboratory studied certain navigation measurements easily made by a human, such as the timing of star occultations by the moon and Earth during the circumlunar voyage. Of significant importance, however, Battin devised a generalized recursive navigation formulation† for small flight computer use to incorporate each navigation measurement of any type as it was made, such as the star occultation or a sextant measurement, so as to update and improve in an optimum least-squares sense the estimate of spacecraft position and velocity. Several navigation measurement schemes were proposed as experiments in hopes that they could be studied and verified by the astronauts soon to fly in Mercury.

Organization of the various NASA centers in Apollo was underway in November 1960 in Apollo Technical Liaison Groups coordinated by Charles J. Donlan of the NASA Space Task Group. The Guidance and Control Technical Liaison Group first met in January 1961 under Richard Carley of the Space Task Group. The contract then being negotiated with the MIT Instrumentation Laboratory in the guidance and control area was acknowledged as being essential to augment the Convair, General Electric, and Martin feasibility studies. At the second meeting in April 1961 this group started the preparation of the guidance, navigation, and control specifications for the Apollo spacecraft.

The following month, on May 25, 1961, President Kennedy in a special message to the Congress urged the nation to "commit itself to achieving the goal, before this decade is out, of landing a man on the moon...."

With the impetus of the presidential challenge, the efforts at the Instrumentation Laboratory changed character. The role the Laboratory would play depended not only on its earlier space studies but also on the fact that another team was in place at the Laboratory, which had just accomplished a similar task to develop the Navy's Polaris missile guidance system on an extremely tight schedule. Ralph Ragan, who led that effort, immediately joined with Trageser, to work with Chilton in defining an Apollo guidance, navigation, and control system to support a flight test as early as 1963. By July 1961 a task statement had been written and on August 10, by letter, NASA contracted the Laboratory for the first year's development of the Apollo guidance and navigation system. This was the first major Apollo contract awarded by NASA. The early start was justified by the central role this function would necessarily have. Key personnel from the Laboratory's Polaris Team joined Trageser, who was named by Dr. Draper as Director of Project Apollo. Ragan became Operations Director, and David Hoag, having been Technical Director of Polaris, became Technical Director of Apollo.

That same August, James Webb, NASA Administrator, invited Dr. Draper and members of the Instrumentation Laboratory Apollo Team to Washington for discussions. The meeting took place on the 31st at NASA Headquarters and continued at Webb's home for dinner that evening. In acknowledging the difficulty of guiding the lunar mission, two things concerned Webb. First, he wanted to know when the guidance system could be ready. Draper provided the accurate forecast: "You'll have it when you need it." Second, he wanted assurances that the equipment would really work. In reply, Draper volunteered to make the first flight and run the system himself. Hardly anyone doubted his sincerity and in letters to NASA officials he repeatedly reminded them of his long experience of over 30 years in instrumentation design, as a pilot, and as a flight engineer. It was Draper's contention that although he himself was both a pilot and an engineer, it would be easier to train an engineer to be a pilot than to train a pilot in the necessary engineering.

The early conceptual work on the guidance and navigation proceeded rapidly. Trageser, Chilton, and Battin had worked out the overall configuration which was to hold to the end. The many maneuvers both in orientation and in translation would require a full three-axis inertial measurement unit with gyros and accelerometers. An optical system would be needed to align the inertial system periodically to the stars. The optical system would also be used to make necessary navigation measurements in a sextant configuration by observing from the spacecraft the direction of the Earth and moon against the background stars. A general purpose digital

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†This and other related space navigation and guidance formulation techniques are described by Battin in Ref. 4. The implementation technology used in Apollo was derived from a legacy described by Draper in Ref. 5.

computer would be required to process all the data, and an arrangement of display and controls for the astronaut to operate the system would be needed. Considerable extension of navigation and guidance theory, trajectory analysis, phenomenological and human limitations to visual sightings of celestial objects, electronic packaging options, materials characteristics, reliability and quality assurance procedures, and management methods all were identified for early study.

It was recognized from the start that the Instrumentation Laboratory would utilize industrial support contractors to augment its engineering team and to produce the designs coming from the engineers. This followed the successful pattern utilized in the development of the Polaris missile guidance system.

Meanwhile, NASA started the procurement process for the spacecraft principal contractor. The request for proposal was issued on July 28, 1961. North American Aviation was selected on November 29 for the Apollo Command Module, Service Module, and boost vehicle adapter. Their contract excluded the guidance and navigation, which was to be government furnished by the industrial support contractors of the Instrumentation Laboratory.

In early 1962, briefings to industry were made for the industrial support to the Instrumentation Laboratory for the guidance and navigation systems. Twenty-one bidders responded and three awards were made on May 8. The A.C. Spark Plug Division, of General Motors, was given responsibility for the production of the inertial system, ground support equipment, and systems integration, assembly, and test. Kollsman Instrument Corporation was the industrial support for the optical subsystems, and Raytheon Company for the computer. Earlier, the A.C. Spark Plug Division had been selected for the gyro production and Sperry for the accelerometer production, both to produce the MIT designs for these inertial system components.

During this early 1962 period, the mission and its hardware were being further defined by NASA, North American Aviation, and the Instrumentation Laboratory. The Space Task Group had evolved into the Manned Spacecraft Center the previous October, and the selection of the Houston, Texas, site for the new center had been made. The Apollo Spacecraft Program Office was formed and managed by Charles Frick and Robert Piland. But a controversy was underway which had strong implications on the whole design process.

A mission plan favored by many included two or more Saturn booster launches from Earth, with an orbital rendezvous to assemble a large spacecraft in Earth orbit for the lunar trip. This spacecraft would then be injected towards the moon and would in its entirety land the three astronauts in the Command Module on the lunar surface using the propulsion of a large lunar landing stage. The guidance and navigation of this maneuver being studied at MIT utilized a large periscope-range-finder so that an astronaut could view the lunar surface during maneuvers as he landed in the awkward position 25 m up on top of the stacked spacecraft. The lunar landing stage would be abandoned on the moon and the Command Module would be lifted on the ascent and return by the Service Module propulsion.

The alternate mission configuration, called Lunar Orbit Rendezvous, had been discussed for some time, particularly by John Houbolt and his colleagues at Langley.[6] In this case, a single Saturn launch would inject a smaller spacecraft assembly towards the moon which included a relatively small Lunar Module for the actual landing, along with the Command and Service Modules, which would remain in lunar orbit. The return, of course, required a rendezvous in lunar orbit which was considered by the critics of this scheme as particularly difficult and dangerous.

Finally in June 1962, the decision was made by NASA in favor of the Lunar Orbit Rendezvous Mission with its real advantages in weight and cost. The procurement process for the Lunar Module was initiated in July and on November 7, Grumman Aircraft Engineering Corporation was chosen to design and build the vehicle.

With this, the Instrumentation Laboratory and the industrial support contractor tasks were expanded to include the guidance and navigation for the Lunar Module. Two additional guidance and navigation sensors would be required, however, and these were assigned to Grumman. They were the landing radar to measure the altitude and velocity of the Lunar Module with respect to the lunar surface, and the rendezvous radar to track a transponder on the Command and Service Modules and provide relative direction and range. Specifications for these radars were written by the Instrumentation Laboratory since the signals were to be used by the guidance and navigation computer in the Lunar Module.

It had been determined somewhat earlier that the first flight test, being scheduled for Earth orbit exercises starting in the fall of 1963, and soon to be rescheduled to 1965, were too soon to be conducted with a full guidance and navigation system design capable of a lunar landing mission. For this reason, a Block I design was identified for the guidance and navigation equipment to support the first Earth orbital flights. A Block II design was to follow for the later lunar flights. With the engineering help of the industrial support contractors, the Instrumentation Laboratory started release of production drawings for manufacture in July 1962, using a formal design review, release, and revision procedure which was followed throughout the program. (The last design release drawing, numbered 38,868 was made in 1975, and defined the erasable memory load for the guidance and navigation computer in the last Command Module used to rendezvous with the Soviet Cosmonauts in the Apollo-Soyuz mission.)

System Design and Development

Although initial design pushed the then current state-of-the-art, the early decisions on configuration and the technology used were essentially frozen except to fix problems. Many engineering improvements were proposed on an otherwise working design. Design and configuration controls necessarily rejected most of these changes so that a stable set of hardware and software elements could be well checked out, delivered on schedule, and safely support the mission. Thus by the time of the lunar flights, the system was not (and of course could not be) demonstrating the latest technology available in the guidance and control art.

The remaining part of this narrative is partitioned into sections covering the inertial sensing, optical sensing, computer, displays and controls, other hardware, software, and flight experience. More technical details than are given here can be found in Refs. 7-10.

Inertial Sensing System

The inertial measurement unit borrowed its technology heavily from the Polaris missile guidance experience at the Laboratory. John Miller assembled a Laboratory team and was supported by Hugh Brady and others from A.C. Spark Plug in the inertial system design. The mechanical design was undertaken by John Nugent, who had done that work for Polaris. In order to simplify the mechanism considerably and to achieve more accuracy in the alignment to the stars, the inertial measurement unit was provided with only three degrees of freedom in its gimbals, although four gimbals would have imposed no limitations on spacecraft attitude. With the natural choices for aligning the system for flight, only some unusual orientations of the spacecraft would put the gimbals into lock where the alignment would be lost. The resulting constraint in the design irritated the astronauts, although, in retrospect, they had no particular trouble with the attitude limitations during missions.

It was the alignment to the stars of the inertial measurement unit which made this design significantly different from that of the Polaris system which was erected with gravity and gyrocompass action.

The Apollo computer compared precision angle readouts of the inertial gimbal angles with the precision celestial sighting angles of the optics and provided alignment corrections to the gyros. The design of the inertial and optical angle interfaces to the computer was undertaken by Jerold Gilmore. The subsystem, called the coupling data unit, included analog and digital converters in an elaborate arrangement of system operational modes among the inertial, optical, and computer hardware.

As the inertial system design developed, it came under attack as not having sufficient inherent or proven reliability to support Apollo in spite of considerable attention to this important issue. If a single gyro wheel stopped running or if a single gyro developed excessive drift instability, the mission could fail and the astronauts would be endangered. Many design, test, and operational techniques evolved to achieve the final reliability record: over 2500 h of in-flight operations of the inertial measurement unit supporting all Apollo missions (over 7500 gyro unit flight hours in addition to ground test time) without any failures.

Optical System

Philip Bowditch, Alex Koso, and others at MIT, along with Thornton Stearns and others from Kollsman, undertook the design of the optical system. The team examined a number of configurations before a satisfactory sextant design was achieved. This instrument was configured with one of its lines-of-sight fixed along the axis of penetration of the spacecraft hull. This line was associated with the Earth or moon side of the navigation angle. The other line-of-sight associated with the reference star was split from the first and tipped away by an articulating mirror in such a fashion that the navigation angle could be measured in any plane. The angle of tilt of the mirror, in conventional sextant fashion, was the desired measurement and was encoded for use by the computer navigation and alignment algorithms. The astronauts' task was to orient the spacecraft so that the Earth or moon was satisfactorily in the field of view, and then adjust the mirror and the measurement plane to get the star image superimposed in his view on the selected Earth or moon feature. In order to acheive the necessary 10-arc-s accuracy of this measurement the instrument was provided with a 28-power eyepiece. However the field of view was thereby so severely limited that a second independent, articulating instrument at unity power and wide field called the scanning telescope was provided to serve as a finder for the sextant and to which the sextant articulating line-of-sight could be slaved.

Much attention went into the design of this wide field scanning telescope so that the astronaut would have a good chance of recognizing constellations and identifying stars. The enormous problem of scattered light in the instrument washing out the visibility of dimmer stars was never completely solved. A really satisfactory engineering compromise among such things as the degree of articulation, the field of view, light traps, and sun shields was not found. Only with the optics objectives in the shade and without the sun illuminated Earth, moon, or other spacecraft in the field of view could a good view of the stars be obtained. This problem lessened in importance as actual mission techniques developed. An early concept required that the inertial system be turned off most of the mission time in order to conserve spacecraft power. It was to be turned on, aligned, and used only during the guidance and control of rocket maneuvers. For a number of reasons the operations policy changed so as to leave the inertial system active throughout the mission. The procedure then became one in which periodically, perhaps twice a day, the inertial measurement unit drift in orientation was corrected to the stars using the sextant whose small field of view prevented problems from scattered sunlight. To do this, the computer would use the inertial measurement unit gimbal angles to point the sextant star line approximately to the selected star. The gyro drift was small enough so that the star would always appear brightly in the sextant field of view. The astronaut would then center the image, thereby giving the necessary data to the computer to realign the inertial unit. In this way accurate inertial alignment was maintained throughout the mission. Similarly, the computer could orient the spacecraft and point the optics towards any targets suitably specified by the astronaut.

The scanning telescope, in spite of the scattered light problem with stellar targets, provided an excellent tracking instrument for navigation sightings to the Earth or moon while in low orbit around these bodies. For this required function, line-of-sight rates were too fast to use the sextant. (Indeed, the precision of that instrument was not needed.) The navigation angle was measured by the computer between the prealigned inertial measurement unit and the line-of-sight to the surface target being tracked by the astronaut with the scanning telescope.

The orientation relationships between the inertial unit and the optical lines-of-sight demanded strict attention to the stability of alignment between these instruments. Bowditch designed a lightweight but stiff and stable structure called a navigation base as a common mounting support for both instruments. It was secured to the spacecraft with kinematic mounts so as to isolate it from spacecraft strains which could otherwise induce unwanted twisting. A complicating factor was that the optics penetrated the spacecraft pressure hull, the objectives being in the hard space vacuum, while the eyepieces were in the ⅓-atm cabin pressure. The total force of this pressure was about 3500 N and careful consideration of the location of the force center with respect to the mounts was required. Relative motion was accommodated by a double-walled metal bellows which at the same time provided the seal of cabin pressure.

Associated with the optics design was the question of the suitability of the Earth and moon as navigation targets. Considerable theoretical and experimental work was undertaken early by Dr. Max Peterson, William Toth, and Dr. Frederic Martin. The moon, without an atmosphere, had crisp visual features and horizon when illuminated by the sun. The Earth, on the other hand, might have most, if not all, of its suitable landmarks obscured by clouds at the critical time. In addition, the sunlit Earth horizon, owing to intense scattered sunlight in the atmosphere, is invisible from space and no distinct visual locator can be identified. Photometric equipment to measure the systematic change in brightness with altitude above the true limb in the blue part of the spectrum was designed into the sextant along with an automatic star tracker to solve this problem. Later, for reasons of cost and complexity, these were removed. The visual sightings of the Earth horizon were re-examined for navigation use. A simulator with photometric fidelity of the situation was devised. It appeared that the human was capable of choosing some locator in the fuzzy horizon which he could duplicate with considerable accuracy. Before each mission the navigator astronaut would come to the Instrumentation Laboratory to train on this simulator. With practice he could duplicate his sighting point within a few kilometers over the desired range of distances to the Earth. (Later, early in his actual mission, he made several sightings to calibrate his horizon locator in the real situation.)

Digital Computer

The computer design was undertaken by Eldon Hall, who has designed the Polaris missile computer. Laboratory members assisting him included Dr. Ramon Alonso, Dr. Albert Hopkins, and Hugh Blair-Smith. In addition, they were supported by Jack Poundstone and other engineers from Raytheon, who had worked with Hall earlier on the Polaris missile computer.

A compelling necessity was to design a reliable computer with sufficient capacity and speed, yet with a very limited size, weight, and power drain.

The machine configuration chosen wawa 16-bit, parallel, general purpose, real-time digital control computer. Initially configured with magnetic core-transistor logic, the change was soon made to an integrated circuit logic using technology just then in the early stages of being developed by the semiconductor industry. The deliberate choice was made to use only one type of integrated circuit logic, a three-input NOR gate. Although wider variety could have substantially reduced the number of devices per computer, the dedication in manufacture and quality control to the single-circuit type gave important gains in reliability.

The fixed memory was the high-density read-only core rope developed in connection with the Mars probe. This meant that the contents of this indestructable memory had to be determined early in order to allow time for manufacture. Rather than a disadvantage, risky last minute changes of the program just before flight were physically prevented. A rope memory program was necessarily well tested before it flew on an Apollo mission.

A coincident-current magnetic erasable memory provided for temporary storage. The size was kept to a minimum both in the number of words and in the 16 bits per word, for low-power consumption. The initial decision in the Block I design was 1024 words of erasable, but this was doubled for Block II based upon the experience in programming the earlier machine. Without changing the computer volume, the fixed memory likewise grew from an initial 12,288 words to 24,576 words in Block I to 36,864 in Block II. To the programmers, even these large numbers were to seem inadequate as the functions to be performed in the computer on the lunar missions expanded substantially over original forecasts.

Both memories, operating on a 12-μs cycle time, were configured to look identical to the program. A very limited basic instruction repertoire was expandable by powerful interpretive routines written by Charles Muntz which saved program word use at the cost of speed. Over 200 input and output circuits for numerous interfaces with other hardware were provided to perform the real-time control function. Certain discreet input and timing signals could be arranged to interrupt the program underway so that urgent tasks could be serviced in real time without the need of continuously scanning inputs.

Displays and Controls[11]

A most important input/output function was provided by a display and keyboard and associated software control ingeniously designed by Alan Green. The keyboard allowed the input of the 10 digits and seven other coded functions on separate keys. The display included three 5-digit numbers plus sign to indicate numerical data, and three 2-digit numbers to identify the function being performed by numeric codes for "verbs," "nouns," and "program." The verb-noun format permitted a sort of language of action and object such as "display-gimbal angles" or "load-star number." The program number identified the major background computation underway in the machine.

With this display and keyboard the astronaut had enormous flexibility and power in communicating with and directing the computer's operation. Many hours of study and training time on real equipment were required by the astronauts. An early reticence by crew members was in time replaced by enthusiasm and confidence in their ability to use the computer to manage many aspects of their mission. Dr. Draper's early statement about training engineers vs training pilots might have been true, but the astronauts with their pilot (and engineering) background developed a competence in the guidance and navigation of Apollo which could not have been surpassed.

The computer display and keyboard permitted the crew to operate most guidance, navigation, and control functions. In addition the left-hand translation command controller and the right-hand rotational command controller were used appropriately for these maneuvers when commanded manually for computer action. Those operations associated with the use of the optics in manually tracking Earth, moon, and stellar targets and in making the navigation angle measurements were accomplished with appropriate controllers near the eyepieces.

Other Hardware Design

Many of the hardware design decisions were easily made in tradeoff among members of the design team. The experience of the industrial support contractors and their concern for manufacturing producibility strongly influenced these decisions. Accommodations had to be made to recognize test, checkout, and mission operations of the astronauts and the Ground Mission Control. The largest problem, however, was reaching agreement on those design features which were affected by and influenced the hardware design of the spacecrafts. This was embodied in the negotiations of the so-called interface control documents which were to be agreed upon and signed off. Then each party could proceed with the confidence that he was protected against changes on the other side of the interface from affecting his design.

Numerous "coordination meetings" were held starting in 1962 between the Instrumentation Laboratory and North American with NASA participation in order to negotiate these decisions affecting both parties in the design of the Command and Service Modules. In early 1963, coordination meetings with Grumman concerning the interacting decisions on the Lunar Module started.

One complicating factor, which in the end returned enormous savings, was the self-imposed groundrule of the designers that as much as possible identical guidance[‡] hardware elements would be used in both the Command and Lunar Modules. The difficulty with this was that a successful agreement with North American for the Command Module interface could be upset by a second negotiation with Grumman for the same piece of guidance hardware in the Lunar Module. The effort paid off in manufacture, test, and astronaut training. The expensive guidance items, the inertial measurement unit, and the computer, as they came off the production line, could then go to either spacecraft. Most of the small hardware components of the guidance were similarly interchangeable when the same function was accomplished in each spacecraft. The guidance turned out to be the only significant hardware that had this interchangeability. Most other spacecraft elements of the Command and Service Modules were not usable on the Lunar Module and vice versa.

The first important interface to be negotiated was the location of the guidance equipment in the spacecraft. North American and the Instrumentation Laboratory first examined wall space to the left of the left-hand couch where the astronaut could use the eyepieces to make sightings. The final location was on the lower wall at the foot of the center couch. This required that the astronaut using the equipment would have to leave the couch and stand in the lower equipment bay. For those stressful times when the crew were constrained to their couches, all the guidance equipment except the optics could be operated through the computer from the main panel within reach using a main panel computer display and keyboard. A particular worry about the lower wall location for the guidance and navigation was that the optics there penetrated the hull on the hot side of the Command Module during return through the atmosphere. Initially a door covering these optics with a heat shield was provided for

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[‡] From this point on, "guidance" will mean guidance, navigation, and control.

protection but was later removed from the design when analysis showed the hardware could tolerate the stress with suitable additional design changes.

Once the guidance equipment was located in the spacecraft, James Nevins, Nugent, and Bowditch immediately started in overall configuration design and mockup so that quite early the astronaut operations with the equipment could be tested and revised as needed.

Because of the operational complexity of the mission, the first mockup included a film projector to display procedures, maps, and charts to the astronaut. However, as the design of the whole operation progressed and the logic of the crew operation with the computer evolved, the film viewer was removed from the design. Hand-held notebooks such as used in Mercury and Gemini would suffice.

The exercise of the mockup with a pressurized space suit emphasized a problem. With his helmet on, the astronaut could not get his eye close enough to the eyepieces to perform his sighting tasks. The solution was to design special eyepieces, necessarily bulky but with sufficient eye relief, which could be attached in place of the regular eyepieces when sightings in the helmet were required. The storage of these large units was found conveniently in the space recently vacated by the film viewer.

The design verification of the guidance hardware was initiated by Ain Laats in his systems test laboratory using specialized test equipment to examine the first production units of the assembled system. Of particular concern were the interactions among the inertial and optical sensors, the computer, the computer software, and astronaut functions when working all together. One of the earliest computer programs called SUNRISE was coded for this function. Special computer control program routines, hardware test code, and prelaunch systems functions were developed in this activity by Thomas Lawton, Ain Laats, Robert Crisp, and others.

The early apprehension concerning equipment reliability produced requirements for in-flight fault diagnosis and repair. The Block I design carried spare plug-in modules which could be used to replace failed modules. However, an event in the last Mercury spacecraft flight in May 1963 changed this in-flight repair policy. On the 19th orbit the Mercury automatic control system failed so that astronaut Gordon Cooper had to fly the last three orbits of the mission manually. The fault was due to corrosion of electrical connections from the high humidity and contamination accompanying the human in his cabin. From then on Apollo hardware designs in the cabin were required to be sealed from moisture. This effectively eliminated plug-in modules since in-flight usable connectors could not be satisfactorily sealed without unacceptable weight penalties. However, even for fixed modules, the sealing led to weight increases because the packages had to withstand the large cabin pressure changes without buckling.

Without the in-flight repair, the concern for reliability remained so that the initial Block II design concept provided for two identical computers in the Command Module operating in parallel for redundancy. This seemed to be excessively conservative to Cline Frasier, of the Guidance and Control Division in Houston, and he directed the return to the single computer concept. The wisdom of his decision was borne out in that no in-flight computer hardware failures occurred. The combined failure rate, both preflight and on missions, was a small fraction of that of any other computer designed then or since for aerospace application. Such near perfect reliability was achieved at considerable effort, attention to design, a deliberate constraint to a minimum number of different parts, a detailed engineering qualification of design and components, and 100% stress testing of the parts to be used in manufacture.

The concern for safety identified backup hardware. In the Command Module, North American provided a simple, independent panel instrument with a single accelerometer which was called an Entry Monitor. Although never needed for backup use, it was useful to the astronauts as an independent means to watch the velocity change of maneuvers being made by the primary system. Similarly in the Lunar Module, Grumman provided through TRW and Hamilton Standard an independent abort guidance system for a safety backup and also used as an independent monitor of the primary Lunar Module system.

As the program entered 1964, it appeared that necessary interface decisions between the guidance hardware and the spacecrafts were lagging. To meet this problem Dr. Robert C Duncan, the Chief of the Guidance and Control Division at Houston, instituted and chaired a series of Guidance Implementation Meetings. The first meeting which involved North American in the design decisions concerning the Command Module guidance system took place in June Subsequent meetings were held approximately biweekly unti February 1965. A second set of meetings with Grumman or the Lunar Module guidance and navigation occurred at the same pace between September 1964 and April 1966. These meetings followed a tight agenda of technical issues to be resolved and involved presentations by the spacecraft designer, the Instrumentation Laboratory, and occasionally other involved parties. Following this, Duncan either made a decision which was then incorporated in the appropriate Interface Control Document, or he requested further study and scheduled new presentations at a future meeting.

A very significant decision took place early in this period concerning the implementation of the spacecraft attitude control autopilots. Prior to this time, this function was to be performed by analog hardware under design responsibility of the spacecraft manufacturers. These analog autopilots, which flew the Block I spacecrafts, were satisfactory, but lacked flexibility and required extensive specialized hardware.

It was Duncan who directed in June 1964 that the autopilo functions would be done digitally utilizing the hardware of the guidance system. To accommodate these new tasks, the speed of the computer was doubled and a much larger instruction repertoire was provided. Input and output interfaces were expanded in order to send appropriate signals to the individual attitude jets, to the main engine gimbals, and to the thrust level servos, and to receive the appropriate feedback signals from some of these elements. The memory capacity had been increased earlier for the lunar mission and was considered adequate for the autopilots.

Duncan's decision came with considerable controversy. The antagonists had shown that even expanded, the computer memory was insufficient and the computer was too slow to perform the necessary wide bandwidth control. They were right if one used the digital computer to perform digitally the same functions handled by the earlier analog circuits. The advocates argued that the proposed implementation would capitalize upon the flexibility, and nonlinear complex computations, natural to a digital computer. It was the right decision. By skillful design only 10% of the computer memory was devoted to the autopilots and only 30% of computer computation time was needed during times of high autopilot activity. A significant amount of complex hardware was eliminated, and moreover, the flexibility of the digita computer delivered better control performance and considerable improvements in efficiency in conserving the spacecraft fuel. The digital autopilot designs were the products of Dr. William Widnall, Gilbert Stubbs, and George Cherry at the Instrumentation Laboratory and Dr. Kenneth Cox at the Manned Spacecraft Center.

With the satisfactory conclusion of the hardware Implementation Meetings, the designers were able to complete their tasks with reasonable assurance that the requirements would not change. This turned out to be true for the most part. The significant event affecting this was the January 1967 fire on the launch pad and the tragic loss of three astronauts

More stringent specifications of fire resistance in the cabin's pure oxygen atmosphere turned out to be reasonably straightforward to meet for the guidance equipment.

Except for this, the hardware design remained relatively stable after 1965. The year 1965, however, was the peak year of hardware activity in which almost 600 man years of effort on guidance hardware was expended at MIT out of an MIT total for the hardware part of the program of approximately 2000 man years. Hardware problems did arise after 1965, but it usually turned out that the expense in dollars and time in solving them by redesign could be avoided by putting the burden of adapting to the problem on the computer program software. This was also true of hardware problems in other parts of the spacecraft.

Software Design

Adapting to hardware problems was only one of the many things which made generating the computer program software difficult. The primary complication was that the details of the mission continually changed and indeed were difficult to get defined in the first place. Then too, so many different programs were needed—different programs for the Block I and II computers, different programs for the unmanned and manned flights, different programs for the Earth orbital and lunar missions, and different programs for the Command Module and Lunar Module computers.

The effort needed for the software design turned out to be grossly underestimated. Until the first lunar landing in 1969, approximately 1400 man years of effort at MIT were applied to the task. The peak activity occurred one year earlier in 1968 with a man year total of 350.

Parts of the computer programming were accomplished early and were essentially independent of mission objectives. These included the basic code for the computer executive system, sequence control, timing and interrupt structure, unchanged since originally designed by Dr. Laning, and the management of the interfaces with the computer display and keyboard unit, telemetry, etc. Also completed relatively early were the complex but not time-critical data processing routines of navigation, guidance targeting, trajectory extrapolation, and lunar ephemeris calculations. Much of the analytical and algorithmic foundation for these came from Battin's earlier work for the unmanned space mission studies. For Apollo, Dr. Battin, Dr. James Miller, Norman Sears, and other analysts made significant improvements in the efficiency and performance of these routines, many of which were of fundamental significance.

The digital autopilots, guidance steering, and other mission specific functions operating during the more stressful parts of the flights required considerable coordination with external agencies—the spacecraft designers, the Manned Spacecraft Center, and the astronauts. Several formal data exchange procedures were attempted, but the most effective in many cases were the direct personal contacts the individual analysts and programmers established with others who they learned had the accurate information.

The computer program requirements were recorded for each mission by the Instrumentation Laboratory in a multivolume document called the "Guidance System Operating Plan" developed initially by John Dahlen and James Nevins. However, the often tardy publication of these plans made them more of a report of what was in the code rather than a specification of what should be coded. The individual programmers also generally drew their detailed flowcharts after the code was written. Standard format flowcharts were then prepared by a large special documentation team and were used primarily for mission planning and real-time support.

The very early programs for the first few unmanned Earth orbital test flights were each assembled by a small dedicated group led by a chief engineer-programmer. For the first Command Module flight, Alex Kosmala spent many weeks of long hours leading the design and coding of program CORONA. Similarly, Daniel Lickly's great personal effort produced the program SOLARIUM. Each of these was an amazing tour de force which was impractical for the more complex manned missions. The computer program for each of these later missions was the assigned responsibility of a senior engineer who assumed a more technical management role. The task first was to partition the job suitably for the analysts, specification writers, programmers, test engineers, and documentation specialists. The leader established schedules and progress milestones, reassigned resources to solve inevitable problems, and generally was responsible for the quality of the program. Names notable here are Dr. James Miller for the first Lunar Module program SUNBURST, Dr. Frederick Martin for the Command Module program COLOSSUS, and George Cherry for the Lunar Module program LUMINARY. These last two were the programs used for the lunar landing missions. Martin and Cherry also did a substantial part of the design of the powered flight guidance steering functions for these programs. Alan Klumpp made major contributions to the landing program in the Lunar Module. Daniel Lickly established the atmospheric entry design for the Command Module.

Much of the detailed code of these programs was written by a team of specialists led by Margaret Hamilton. The task assignments to these individuals included, in addition to writing the code, the testing to certify that the program element met requirements. Overall testing of the assembled collection of program elements necessarily required concentrated use of the considerable human and machine resources at the Instrumentation Laboratory. The programs had to be as near error-free as possible and all anomalies had to be understood and recorded for possible affect on the mission. Actually, no program errors were ever uncovered during the missions, but every program flew with some known and documented problems.

The highest level of testing was performed with a high-fidelity digital simulation of the computer, spacecraft hardware, and mission environment. The creation, development, and maintenance of this simulator by Dr. Miller, Keith Glick, Lance Drane, and others included many diagnostic features essential to its effective use. Testing of the programs with the real hardware was done by Ain Laats in his systems test lab. Wide bandwidth aspects of the program were evaluated in a digital/analog hybrid simulator assembled by Phillip Felleman and Thomas Fitzgibbon. This hybrid simulator was also arranged to operate with the displays and controls of a pair of cockpit simulators to exercise crew functions in operating the Command Module and Lunar Module. These cockpit simulators were the responsibility of James Nevins assisted by Richard Metzinger, Ivan Johnson, and others. The ill-fated crew who died in the fire used this Command Module simulator in Cambridge for their training of what would have been the first manned Apollo flight. The use of the Cambridge facility was necessary because neither of the mission simulators at Houston or Cape Kennedy was ready.

Another simulator using real guidance system hardware and a surplus radar mount to simulate spacecraft motion was assembled around this time by Nevins and Albert Woodin. This was mounted on a roof at MIT using real stars and moon, weather permitting. Astronauts and managers who might have been at first skeptical of the system were soon enthusiastic in their ability to align the inertial system to the stars and navigate the Cambridge rooftop.

The content of the flight computer software very clearly determined specific capabilities and procedures in conducting the Apollo mission. As stated earlier, the original philosophy underlying the guidance design was onboard self-sufficiency of the astronauts in managing their mission. Early software was written with this crew-directed autonomy in mind, although it was based only intuitively on exactly how the crew would perform their tasks. The issue became clearer as the astronauts participated in the hardware and software design decisions and particularly on mockup and simulator evaluations and the experience being gained in Gemini flights. Initially the flight crew changed the software specifications so that they would participate step by step in the computer decisions during the mission phases. This necessarily made a heavy workload for the astronaut at the computer display and controls. As they gained more familiarity with the system and more confidence in it, the philosophy was modified to allow the computer to flow through the normal mission logic without the necessity for authorizing keystrokes from the operator. However, the astronauts could watch, interrupt, and modify the functional flow if they so chose.

Another decision from the crew resulted in configuring details of the trajectories to be flown so that they could better monitor their progress and, if a failure occurred, they would be in a simpler situation from which to take over with backup hardware and procedures. For example, the Lunar Module guidance was easily capable of injecting the vehicle on the ascent from the moon's surface onto a trajectory which would go directly to a rendezvous with the Command Module. However, the actual procedure used involved a number of more simple maneuvers called the concentric flight plan which has been used in Gemini rendezvous exercises.

Gemini was flown for the last time in late 1966, and the attention of the astronauts and the ground controllers was put fully onto Apollo. By this time, however, the computer programs were already straining the memory capacity. The Flight Operations Directorate at Houston had taken over the management of the MIT software contract in March 1966 under Howard W. Tindall. One of Tindall's first actions was to hold a computer memory storage meeting with all involved parties to decide what computer capabilities should be in the limited program space. This occurred on Friday the 13th of May and was thereby nicknamed "black Friday" by those whose favorite program elements were eliminated. Two more black Friday meetings were required and several "tiger teams" were assigned to keep the computer program within its bounds. An outcome was that some programs were eliminated that had provided the complete onboard self-sufficiency. The ground tracking facility and the Mission Control at Houston would be able to perform these functions and would, furthermore, relieve the astronauts of some of their work burden. Enough was left in the onboard computer programs, however, for the crew to rescue themselves and return to Earth in case communications were lost.

The management of the software effort, assigned at the time to Edward Copps, necessarily became far more structured. Tindall, supported by others from the Manned Spacecraft Center, held monthly Software Development Plan Meetings in Cambridge to watch progress and the allocation of resources to software tasks. After the programs were essentially complete but still subject to revisions, these meetings changed character to that of a Software Control Board held oftentimes in Houston. Even after the code in the fixed memory for a given spacecraft was released for manufacture, desired program changes were identified. The logical similarity of fixed and erasable memory and the flexibility of executive and software designs did allow the prelaunch or in-flight loading of special programs into the erasable memory. This was done only under strict authorization of Tindall's Software Control Board. Many of these so-called erasable programs were used in flight to handle miscellaneous problems.

During the latter part of this period, Tindall also conducted in Houston what were called Data Priority Meetings. These were held to establish the specific trajectory characteristics, operating timelines, and the interacting ground control and astronaut procedures under all normal and unusual conditions. The guidance hardware and particularly the computer programs in the memory influenced strongly the specific paths possible in conducting the mission. Accordingly the task was put to Malcolm Johnston, at MIT, to search out the needed detailed design data available from the engineers in Cambridge for the Data Priority activity in Houston. It was the product of these meetings that finally tied together all mission operations with the guidance, navigation, and control.

Crew training in these operations on the mission simulators required the detailed guidance system instructions provided tirelessly by Russell Larson working with the astronauts at Houston and Cape Kennedy.

Flight Experience

The flight experience of the Apollo guidance system shows a remarkable consistency with expectation punctuated with outright surprises.

The understanding of these surprises and the recommending of appropriate courses of action fell in large part on the Instrumentation Laboratory teams providing guidance system mission support in place at Houston, Cape Kennedy, and Cambridge. During the quiet times of the flights, only perhaps four lab engineers would be on duty, but the number rose at times to several dozen performing special analyses, lab tests, and simulation during more active phases. Leaders of this activity were Philip Felleman, Russell Larson, and Stephen Copps.

The first mission carrying the guidance system was Apollo 3, which flew in August 1966. It was an unmanned, high-energy, suborbital trajectory with four separate guidance controlled burns of the Service Module propulsion rocket. These were arranged such that the Command Module would enter the atmosphere with about 20% more specific energy than that in normal returns from the lunar missions. This was planned in order to stress test the re-entry heat shield. The landing east of Wake Island about 350 km short of the intended target was due to an unanticipated error in the aerodynamic model of the Command Module. The actual lift available was less than design intent so that even though the guidance commanded full upwards lift, the vehicle dropped into the ocean early. The guidance indicated splash point was within 18 km of the Navy's reported retrieval point—this after an hour and a half of uncorrected all inertial navigation through high-acceleration maneuvers.

Apollo 4, November 1967, also unmanned, was guided into a high apogee trajectory after two Earth orbits and was to be given an extra rocket burn on the way down to simulate the lunar return velocity. However, in this automatic maneuver, a ground controller in Australia, confused by a delay in telemetry, sent an engine turn-on signal from the ground just after it had already been initiated automatically by the guidance system. This action transferred rocket cutoff responsibility away from the onboard system. The ground controller sent the cutoff signal 13.5 s later than required for the planned entry test conditions. It was, therefore, a severe entry test for both the heat shield and the guidance system. The latter controlled the entry into a range stretching skip out of the atmosphere and a re-entry back into it with a splash into the ocean 3.5 km different from the point intended as indicated by extrapolated ground tracking data.

Apollo 5, in Earth orbit in January of 1968, was the only unmanned test with the Lunar Module. The mission went as planned until the time of the first guidance controlled Lunar Module rocket burn. The system initiated ignition as planned and using the approved model for thrust buildup looked for the acceleration to rise as expected. A change in the rocket pressurization, not recognized by the software, delayed the thrust buildup longer than acceptable by a safety criterion built into the computer program. The system, as designed, then immediately signalled shutoff. As a result, since the problem was not immediately understood, the remaining rocket burns were controlled by a simple backup system. All primary mission objectives were met.

Apollo 6, in April 1968, had a mission similar to Apollo 4, but unfortunately the Saturn booster third stage could not be restarted for the lunar trajectory injection simulation burn. Consequently, the spacecraft Service Module was used for this under guidance system control. Since the resulting burn was necessarily very long as targeted, not enough fuel was left for the maneuver needed to drive the spacecraft back into the atmosphere at lunar return velocity. With lower velocity the vehicle did not have enough specific energy to reach the planned target, and it fell short by almost 100 km, with the guidance indicating a splash within 4 km of that later reported by the recovery force.

The first manned flight, Apollo 7, October 1968, exercised a rendezvous with the spent third stage of the Saturn booster from about 100 miles separation. The sextant was used by astronaut Don Eisele to give direction information to the computer referenced to the stellar aligned inertial system. No ranging data were obtained as the equipment was not yet available. Nevertheless, the computer converged upon a good rendezvous solution. Three times during the flight untested procedures used by the crew caused the computer to "restart" successfully. Restart was a software feature provided in all programs to protect against data loss and provide instant recovery from logically improper activity. Many times in later flights, restart accommodated safely to computer logic and operational problems.

Apollo 8, with the first men to orbit the moon, December 1968, was a wonderful success of man and machine. All of the guidance features in the Command Module were exercised with few problems. In the very first application of onboard autonomous navigation in space, astronaut James Lovell made over 200 sextant sightings on the way out to the moon. His computer solution of the nearest approach to the backside of the moon agreed within 2.5 km of that later reconstructed from ground tracking data. The critical return-to-Earth maneuver, Christmas morning, was so accurate that only a single 1.5-m/s midcourse maneuver was required 5 h later. Lovell's trans-Earth navigation with the sextant indicated approach to the center of the entry corridor within 30% of the normal tolerance. By this he showed that he could have returned safely without the help of the ground control. At one point early in the return, Lovell, thinking he was telling the computer that he was using star number 01, actually punched in the command for the computer to go to the Earth prelaunch program 01. This caused all sorts of mischief including the loss of the inertial system alignment. He had no problem getting all this quickly and properly rearranged.

Apollo 9, which flew a very complex mission in March 1969, exercised almost all functions of the Lunar Module guidance in Earth orbit including the rendezvous with the Command Module. The only in-flight guidance hardware failure in the program occurred early in this mission. A tiny pin became dislodged from the scanning telescope angle counter display, rendering the counter useless. The counter, however, was only a backup to the normal readout of the computer display, so fortunately the problem had no impact on the mission. At one point, astronaut David Scott loaded the celestial coordinates of Jupiter into the computer and asked it to point the optics at the planet. He was rewarded with a fine display of Jupiter and her moons in the 28-power instrument. Later, he loaded the computer with the orbital parameters of the Lunar Module which had by then been abandoned and sent away into a high orbit. There it was in the eyepiece 5000 km away.

Apollo 10, in May 1969, was a complete lunar mission, except the actual touchdown on the moon was bypassed as planned. All guidance functions were uneventful except that a new technique and program were developed during the flight to put the vehicle into a stable rotation of 3 revolutions per hour during the long coast to the moon. This spin had been used earlier in Apollo 8 to keep the thermal loads on the skin from the sun equalized, but on that mission occasional firings of the attitude jets were commanded by the control system to hold the spin as required. Besides wasting fuel, the noise of these firings disturbed the crew's sleep. During Apollo 10, Joseph Turnbull, in Cambridge, exercised various methods on a simulator for initiating the spin so that the residual fluid motions in all the fuel tanks would not later on destabilize the spacecraft motions. His procedures were radioed to the crew via Mission Control in Houston; on the second try it worked, and stability was achieved without further thruster activity.

Finally on July 20 and 21, 1969, Apollo astronauts first walked the "magnificent desolation" of the moon's surface. The actual landing was particularly exciting, however, due to alarms in the computer during the descent. These alarms were caused by an erroneous mode switch position resulting in maximum pulse rate signals being sent to the computer from the rendezvous radar, which was, of course, not needed during the landing. The computer, already operating near capacity, was overloaded by these extraneous inputs causing it to restart and display the alarms. The ground controllers and Neil Armstrong were on top of the problem. They knew well that the computer, in restarting, would keep the essential programs running for the landing. However, Armstrong's attention was diverted during the time he should have been using the window display which would indicate to him what the lunar surface was like at the point where the guidance system was bringing him. When he finally looked, it was a young ray crater strewn with large rocks. It was too late to retarget the computer for the more efficient trajectory change to a more suitable point. Instead, he selected a semiautomatic altitude hold mode and maneuvered across the crater to a landing at "Tranquility Base."

Apollo 12, in November 1969, was hit by two lightning strikes early in the boost to Earth orbit. The large current pulses, passing through the innards of the Command Module because of the electrical insulating properties of the external heat shield, caused power transients which forced the computer to restart both times. Although the computer did not lose any memory, the interface circuits to the inertial system were temporarily affected and spacecraft commander Charles Conrad reported a tumbling inertial platform. Fortunately, the Saturn booster guidance system, further distant from the current pulse, was not disturbed and completed its normal function. The crew was able to realign the inertial system to the stars while in Earth orbit, and continue the mission. They landed on the moon on the edge of the small crater in which had sat the unmanned Surveyor spacecraft since its arrival 2½ years earlier.

The emergency and rescue of the Apollo 13 crew in April 1970, after the explosion and loss of oxygen and power in the Service Module, urgently depended upon a quick maneuver to get back on the Earth's return trajectory using the only propulsion available, that of the Lunar Module. The Lunar Module autopilot was not designed to push the heavy Command and Service Modules through the limber docking joint as a normal control mode. However, for just a contingency such as this, the necessary software had been developed and was included in the computer program; but it was very little tested. The critical maneuver was accomplished with stable control. Without Service Module power and in order to conserve the limited life Command Module batteries for the entry, the guidance system there was shut down completely. After three days of cold, rough treatment for the precision instruments, would the inertial system get reheated without harm, get started and realigned, and retain its original calibration for guiding entry? The entry proceeded normally and splash in the ocean was indicated within 1 km of the target.

The February 1971 mission of Apollo 14 was normal for the guidance system until about 3½ h before the scheduled powered descent onto the moon. At that time the Lunar Module computer started receiving intermittent faulty signals from the main panel abort button, which, if they occurred during the descent to the moon, would irrevocably start the abort sequence sending the vehicle back into orbit. As in every mission, the Instrumentation Laboratory§ support engineers in Houston, Cape Kennedy, and Cambridge were monitoring progress and immediately started working on a way of preventing the mission from being terminated needlessly. Among the various ideas proposed, one suggested by a young engineer, Donald Eyles, was selected and after hurriedly being tested on the simulators in Cambridge was sent over the circuits to the Mission Control Center in Houston for their evaluation. This procedure, which was sent up to the crew as soon as they came around from the back of the moon, involved four sets of computer input keystrokes to be made onboard at appropriate times in the descent. The first of these would fool the necessary part of the computer logic into thinking that it was already in an abort mode while the landing programs, nevertheless, would continue to bring the vehicle down to the lunar surface. The astronauts had only 10 min after receiving this computer reprogramming procedure before they had to start their descent. They accepted it; and the landing went flawlessly, exactly to the planned spot on the moon.

There were three more lunar landing missions, three Earth orbital visits to the Skylab, and the rendezvous with the Soviet cosmonauts in Soyuz. Although the Apollo guidance, navigation, and control system continued to get involved in the unexpected, any further account would be anticlimactic to the dramatic saving of the Apollo 14 and its objective—the landing of men on the moon.

Acknowledgments

This account is written from the point of view of one who experienced these hectic but exciting years. The intent is to underline significant events and everchanging design emphasis and to support this with limited anecdotal items and reminiscences. An enormous amount of material has been left out for practical reasons, and many worthy names regretfully remained unmentioned. Technical details have been deliberately played down; they can be found in the references. One overall message is simple: In an incredible and audacious task, the landing of men on the moon, the guidance systems for the spacecrafts were created out of the prolific imagination and hard work of many people.

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§Actually, a year earlier, the Instrumentation Laboratory had been renamed The Charles Stark Draper Laboratory in honor of its founder.

the years and currently includes space policy, and the legal and economic issues associated with increased utilization of space.

This Fall, all the members of the Tufts Chapter attended the November Section meeting at Automatix and enjoyed the discussion of robotic and artificial vision systems. Every Spring, the New England Section holds a monthly meeting at the Tufts Faculty Club which is always well attended. We hope to see everyone at Tufts on February 28 for the next Section meeting. More information on the activities of the Chapter can be obtained from the President, Nakul Talcherkar at 623-7736 or faculty advisor, Robert Greif at 381-3239.

---Robert Greif

Company Profile: Intermetrics Inc., Cambridge, Mass.

Intermetrics Inc. is an internationally recognized, high technology company successfully engaged in a broad spectrum of contract and product activities for government and commercial customers. In addition to being the world's largest independent builder of language compiler systems, Intermetrics is involved in the development of real-time applications software in the aerospace field and the manufacture of customized, turnkey systems for factory productivity monitoring and petrochemical flow control.

Founded in 1969 by five senior staff members from the Apollo project at the M.I.T. Instrumentation Laboratory, now C. S. Draper Lab., the company now has about 600 employees of which over 300 are located at its Cambridge, Massachusetts headquarters.

In the aerospace area, Intermetrics provides customized applications software and systems engineering services for the design, testing, implementation and operation of advanced avionics systems, including in-flight computer systems, computerized simulations, and laboratory testing environments. Intermetrics custom-built software programs monitor and initiate various in-flight or in-use procedures for aircraft, space vehicles and ships. Intermetrics is currently involved in various stages of several major programs, including the Space Shuttle, the Global Positioning Satellite Navigation System (GPS or Navstar), the Navy F-14 aircraft, the Air Force B-1 aircraft, the Grumman X-29 Forward Swept Wing Aircraft, the Navy's Command Flight Display project and the Boeing 757/767 commercial airplane.

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