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Onorbit IMU Alinement Error Budget

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SHUTTLE PROGRAM

ONORBIT IMU ALINEMENT ERROR BUDGET

By R. W. Corson, McDonnell Douglas Technical Services Co.

JSC Task Monitor: T. J. Blucker, Mathematical Physics Branch

Approved: ______________________
Emil R. Schiesser, Chief
Mathematical Physics Branch

Approved: ______________________
Ronald L. Berry, Chief
Mission Planning and Analysis Division

Mission Planning and Analysis Division

National Aeronautics and Space Administration

Lyndon B. Johnson Space Center

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1.0 SUMMARY

The Star Tracker (ST), Crew Optical Alignment Sight (COAS), and Inertial Measurement Unit (IMU) form a complex navigation system with a multitude of error sources. The purpose of this document is to present a complete list of the system errors and to combine these errors in a rational way to yield an estimate of the IMU alignment accuracy for STS-1. The expected standard deviation in the IMU alignment error for STS-1 type alignments was determined to be 72 arc seconds per axis for star tracker alignments and 188 arc seconds per axis for COAS alignments. These estimates are based on current knowledge of the star tracker, COAS, IMU, and navigation base error specifications, and have been partially verified by preliminary Monte Carlo analysis.

2.0 INTRODUCTION

The purpose of an IMU alignment is to reposition the inertial platform of the IMU to a desired orientation with respect to the Mean of 1950 inertial coordinate system. In order to reposition the platform to a desired orientation, the present orientation must first be determined. This is accomplished by measuring the positions of two stars relative to the present platform orientation. The star measurements are acquired by using either the star tracker (ST) or the Crew Optical Alignment Sight (COAS) instrument and are saved in the computer memory as line of sight (LOS) unit vectors in the IMU platform coordinate system:

$$\vec{S}_m = S_x \vec{i}_p + S_y \vec{j}_p + S_z \vec{k}_p$$
$$\vec{T}_m = T_x \vec{i}_p + T_y \vec{j}_p + T_z \vec{k}_p \qquad (1)$$

The subscript m denotes measured star vectors and p denotes platform coordinates. The measured star LOS unit vectors are used to define the axes of an inertial star coordinate system $\vec{X}_m$, $\vec{Y}_m$, $\vec{Z}_m$ by means of the following equations:

$$\vec{X}_m = \vec{S}_m$$
$$\vec{Y}_m = \vec{S}_m \times \vec{T}_m / |\vec{S}_m \times \vec{T}_m| \qquad (2)$$
$$\vec{Z}_m = \vec{X}_m \times \vec{Y}_m$$

These equations relate the orientation of the measured star coordinate system with respect to the IMU platform system and are used to define the corresponding transformation matrix:

$$\left[T_p^m\right] = \begin{bmatrix} \vec{X}_m \\ \vec{Y}_m \\ \vec{Z}_m \end{bmatrix} \qquad (3)$$

The onboard computer memory also contains a catalogue of the navigation stars expressed in Mean of 1950 coordinates. Using the catalogue unit vectors, $\vec{S}_a$ and $\vec{T}_a$, corresponding to the measured vectors, the actual star coordinate system axes can be formed in a similar manner:

$$\vec{X}_a = \vec{S}_a$$
$$\vec{Y}_a = \vec{S}_a \times \vec{T}_a / |\vec{S}_a \times \vec{T}_a| \qquad (4)$$
$$\vec{Z}_a = \vec{X}_a \times \vec{Y}_a$$

The corresponding actual star coordinate system with respect to the Mean of 1950 coordinate system transformation matrix follows from

$$\left[T^{a}_{M50}\right] = \begin{bmatrix} \vec{X}_a \\ \vec{Y}_a \\ \vec{Z}_a \end{bmatrix} \qquad (5)$$

Using the matrices (3) and (5), the alignment software then computes the Mean of 1950 to measured IMU platform transformation:

$$\left[T^{mp}_{M50}\right] = \left[T^{m}_{p}\right]^{T} \left[T^{a}_{M50}\right] \qquad (6)$$

Having determined the present platform orientation, the software uses matrix (6) in combination with the desired platform transformation matrix $\left[T^{dp}_{M50}\right]$ to calculate a measured to desired platform transformation matrix.

$$\left[T^{dp}_{mp}\right] = \left[T^{dp}_{M50}\right] \left[T^{mp}_{M50}\right]^{T} \qquad (7)$$

Next, the software extracts torquing angles from matrix (7) and applies these torquing angles simultaneously to the three platform axes to reposition it to the desired orientation.

Ideally, the applied torquing angles would reposition the platform to the desired orientation; however, due to system errors the platform will not be perfectly aligned to the desired position. The angular displacement between the desired orientation and the orientation actually attained after repositioning is referred to as the IMU misalignment. The purpose of this document is to establish the expected magnitude of this misalignment.

The development, so far, has uncovered two sources of error in the alignment process: (1) the determination of the torquing matrix and (2) the actual application of the torquing commands in the hardware. It is reasonably assumed that the errors in the torquing process are negligible; therefore, the errors of significance are in the determination of the torquing matrix from the measured star vectors. Combining equations (6) and (7), the torquing matrix can be rewritten as

$$\left[T^{dp}_{mp}\right] = \left[T^{dp}_{M50}\right] \left[T^{a}_{M50}\right]^{T} \left[T^{m}_{p}\right] \qquad (8)$$

The three transformations used to compute the torquing matrix (8) are all candidate error sources. Two of the matrices on the right-hand side can be immediately eliminated. First of all, since there is no uncertainty in the desired platform orientation, $\left[T_{M50}^{dp}\right]$ is taken to be exact. Second, even though there do exist catalogue errors which would corrupt $\left[T_{M50}^{a}\right]$, these errors (a result of stellar motions) are very small and this matrix is taken to be exact. The IMU misalignment, therefore, is totally dependent on the errors in the measured star with respect to the platform transformation, $\left[T_{p}^{m}\right]$. There are many system errors that contribute to the corruption of this matrix. A complete list of these errors is presented and then combined in a rational manner to yield an estimate of the IMU alignment accuracy for STS-1 type alignments.

3.0 DISCUSSION

The IMU alignment error is a direct result of errors in the star with respect to platform coordinate transformation, $\left[T_P^m\right]$. This transformation is corrupted by the instantaneous star measurement errors and also by the IMU platform drift. Furthermore, since the technique used (coordinate system defined by equation (2)) to form this matrix is sensitive to geometry, the star pair separation also affects the alignment error. The random measurment errors, the IMU drift, and the pair separation are all related to the RMS IMU alignment error by the following equation (Reference 1)

$$\omega = \left[\sigma_0^2 \ (1 + 2\csc^2\delta) + \sigma_d^2 \left(t_s^2 + (t_s^2 + t_t^2)\csc^2\delta - 2t_st_t\cot^2\delta\right)\right]^{\frac{1}{2}} \quad (9)$$

σ_0^2 is the variance of the per axis star measurement error,

σ_d^2 the variance of the per axis IMU drift rate,

t_s the age of the most recent star sighting,

t_t the age of the oldest star sighting and,

δ the star pair separation angle.

It is assumed that the measurement errors and the drift rates are isotropic, zero mean, independent random variables in the derivation of this equation. The RMS IMU alignment error indicator (9) is equivalent to an RSS of the mean and standard deviation of the total alignment error. Since STS-1 alignments will ensure that the pair separation is approximately 90 degrees and that both star measurements are not significantly aged, the RMS IMU alignment error simplifies to ($\delta \approx \pi/2$, $t_s \approx 0$, $t_t \approx 0$).*

$$\omega = \sigma_0 \sqrt{3} \quad (10)$$

Determination of an estimate of the one sigma per axis star sighting error, σ_0, is the subject of the following section.

*Since this paper is addressing STS-1 alignments, the error source associated with IMU gyro bias drift is not a factor in estimating the alignment error. In general, though, it is a factor whenever star measurements used for alignments are "old" (see equation (9)).

3.1 STAR SIGHTING ERRORS

Star positions relative to the IMU platform are determined by the sequence of transformations from the celestial sphere to the platform. These transformations are listed in Figures 3.1-1 and 3.1-2 for the star tracker and COAS systems, respectively. Each of these transformations is determined by preflight or onorbit calibration or by hardware sensors in real time. Associated with each transformation measurement is an uncertainty or error which is also listed in Figures 3.1-1 and 3.1-2. These errors are rotational errors and, therefore, are associated with a unique direction. For example, the azimuth resolver error is a rotational error which occurs about the platform azimuth axis. Each error is a vector and, hence, corrupts the star measurement in a particular direction. The projection of these error vectors into sensor coordinates is determined by the relative orientation between the coordinate system associated with the error and the direction of the star. For a given star, platform, and vehicle body geometry, each error corrupts the measured star LOS in a unique direction. Since the total error is a vector sum of the individual error components, it is, therefore, a function of the sequence of transformations from the IMU platform to the celestial sphere. In order to determine a value of the variance in the sighting error, σ_0^2, that is independent of the vehicle and IMU platform attitudes, an assumption is made to expand the population of random variables to include these geometry effects.

Assumption 1

All possible sets of azimuth, pitch, and roll gimbal angles (inner roll gimbal angle constrained to zero) are considered. Consequently, the magnitudes of the resolver sinusoidal biases are random, and the directions of the resolver sinusoidal bias, resolver biases, and gimbal nonorthogonalities are also random.

Furthermore, calibration uncertainties make it necessary to form several additional assumptions.

Assumption 2

All possible LRU configurations are considered. Consequently, the magnitudes of the resolver biases and gimbal nonorthogonalities are random and the star tracker biases are random.

Assumption 3

All possible vehicles and missions are considered. Consequently, the navigation base errors are random and the IMU, star tracker, and COAS LRU installation errors are random.

Tables 3.1-1 and 3.1-2 present the modified (or normalized) error covariance matrices (lower off-diagonal elements are the correlation coefficients) for each of the error components in the Star Tracker and COAS systems, respectively, in units of arc sec^2. The individual covariance matrices are derived from the star tracker, COAS, IMU, and navigation base accuracy specifications given in Appendix A. The individual error components are all assumed to be zero-mean, independent random variables;

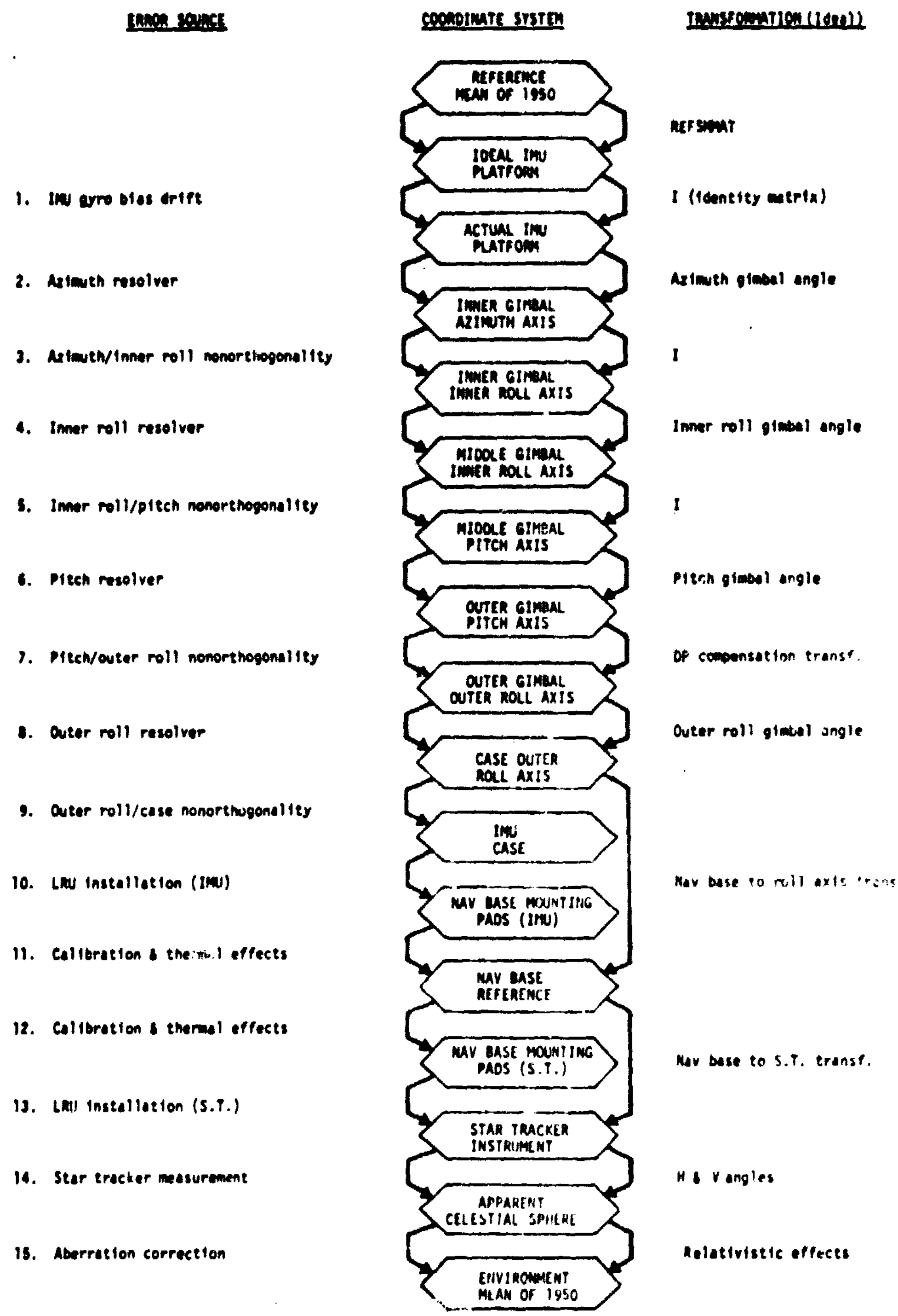

Figure 3.1-1 COORDINATE SYSTEMS, ERROR SOURCES, & TRANSFORMATIONS FOR THE STAR TRACKER, IMU AND NAV BASE SYSTEM

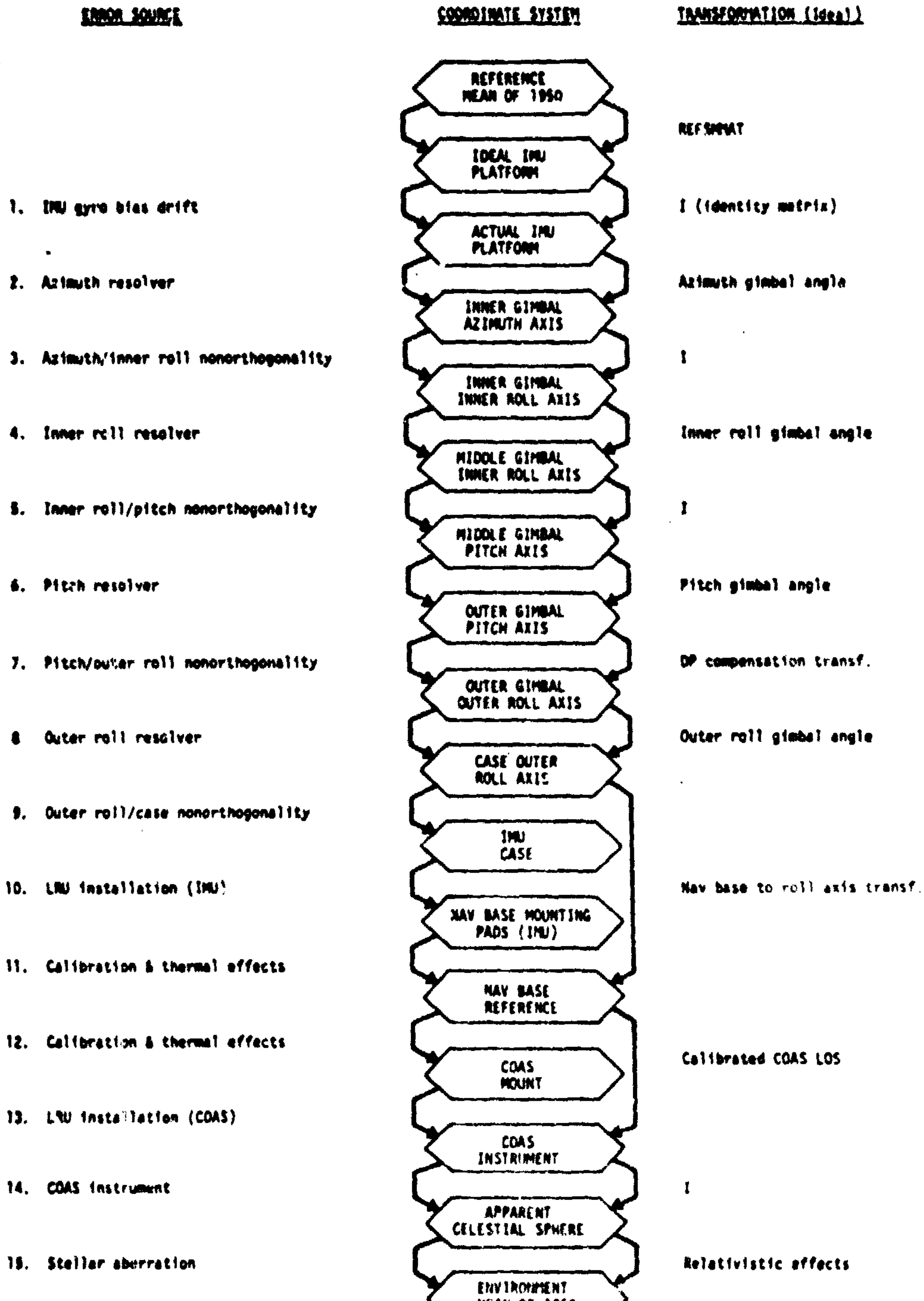

Figure 3.1-2 COORDINATE SYSTEMS, ERROR SOURCES, & TRANSFORMATIONS FOR THE COAS, IMU AND NAV BASE SYSTEM

	Navigation Base Coordinates (SEC^2)			Star Tracker Coordinates (SEC^2)		
AZIMUTH RESOLVER	443.80	.00	.00			
	.00	443.80	.00			
	.00	.00	443.80			
AZIMUTH TO INNER ROLL	.00	.00	.00			
	.00	.00	.00			
	.00	.00	.00			
INNER ROLL RESOLVER	443.80	.00	.00			
	.00	443.80	.00			
	.00	.00	443.80			
INNER ROLL TO PITCH	.00	.00	.00			
	.00	.00	.00			
	.00	.00	.00			
PITCH RESOLVER	.00	.00	.00			
	.00	665.71	.00			
	.00	.00	665.71			
PITCH TO OUTER ROLL	.00	.00	.00			
	.00	450.00	.00			
	.00	.00	450.00			
OUTER ROLL RESOLVER	1331.41	.00	.00			
	.00	.00	.00			
	.00	.00	.00			
OUTER ROLL TO IMU CASE	.00	.00	.00			
	.00	400.00	.00			
	.00	.00	400.00			
LRU INSTALLATION (IMU)	400.00	.00	.00			
	.00	400.00	.00			
	.00	.00	400.00			
IMU PADS TO NAV BASE REFERENCE	118.39	.00	.00			
	.00	118.39	.00			
	.00	.00	25.00			
NAV BASE REFERENCE TO ST PADS	118.39	.00	.00			
	.00	118.39	.00			
	.00	.00	25.00			
LRU INSTALLATION (ST)				400.00	.00	.00
				.00	400.00	.00
				.00	.00	400.00
STAR TRACKER MEASUREMENT				1805.36	.00	.00
				.00	1805.36	.00
				.00	.00	.00
STELLAR ABERRATION				.00	.00	.00
				.00	.00	.00
				.00	.00	.00
-Z STAR TRACKER TOTAL				5245.23	.11	-6.41
				+.00	5061.10	-.36
				-.00	-.00	3253.58
-Y STAR TRACKER TOTAL				5067.27	.44	33.24
				+.00	5058.75	-.08
				+.01	-.00	3433.89

*the diagonal elements are variances, the upper off-diagonal elements are covariances, and the lower off-diagonal elements are correlation coefficients. Matrix elements denoted as +.00 or -.00 are not equal to zero but are less than .005.

Table 3.1-1 Normalized* Error Covariance Matrix for each Component of the Star Tracker Error

	Navigation Base Coordinates (SEC^2)			Vehicle Body Coordinates (SEC^2)		
AZIMUTH RESOLVER	531.84	.00	.00			
	.00	531.84	.00			
	.00	.00	531.84			
AZIMUTH TO INNER ROLL	.00	.00	.00			
	.00	.00	.00			
	.00	.00	.00			
INNER ROLL RESOLVER	531.84	.00	.00			
	.00	531.84	.00			
	.00	.00	531.84			
INNER ROLL TO PITCH	.00	.00	.00			
	.00	.00	.00			
	.00	.00	.00			
PITCH RESOLVER	.00	.00	.00			
	.00	797.77	.00			
	.00	.00	797.77			
PITCH TO OUTER ROLL	.00	.00	.00			
	.00	450.00	.00			
	.00	.00	450.00			
OUTER ROLL RESOLVER	1595.53	.00	.00			
	.00	.00	.00			
	.00	.00	.00			
OUTER ROLL TO IMU CASE	.00	.00	.00			
	.00	400.00	.00			
	.00	.00	400.00			
LRU INSTALLATION (IMU)	400.00	.00	.00			
	.00	400.00	.00			
	.00	.00	400.00			
IMU PADS TO NAV BASE REFERENCE	118.39	.00	.00			
	.00	118.39	.00			
	.00	.00	25.00			
NAV BASE TO COAS MOUNT	20125.42	.00	.00			
	.00	20177.66	.00			
	.00	.00	20084.27			
LRU INSTALLATION (COAS)				400.00	.00	.00
				.00	400.00	.00
				.00	.00	400.00
COAS MEASUREMENT				11278.44	.00	.00
				.00	11278.44	.00
				.00	.00	11278.44
STELLAR ABERRATION				161.29	.00	.00
				.00	161.29	.00
				.00	.00	161.29
COAS TOTAL				35139.96	.00	14.88
				.00	35247.23	.00
				+.00	.00	35063.23

*the diagonal elements are variances, the upper off-diagonal elements are covariances, and the lower off-diagonal elements are correlation coefficients. Matrix elements denoted as +.00 or -.00 are not equal to zero but are less than .005.

Table 3.1-2 Normalized* Error Covariance Matrix for each Component of the COAS Error therefore, the variance of the total error will be the sum of the variances of the individual components. The majority of the error statistics are expressed in navigation base coordinates; however, the measurement error properties are desired in the sensor coordinate system for IMU alignment accuracy estimation. The error covariance matrices expressed in the navigation base coordinates, therefore, are first rotated into the sensor coordinate systems, and then added to the sensor error covariance matrices to yield a total error covariance matrix in each of the three sensor coordinate systems (-ZST, -YST, and COAS). Rotational errors about the sensor boresight axes will have negligible effects on the star measurements because the optical sensors are narrow field of view instruments. From the three axis covariance matrices, then, the two-axis measurement plane error covariance matrices (normalized) are extracted for the star tracker

$$COV_{-ZST} = \begin{bmatrix} \sigma_h^2 & \sigma_{hv} \\ \rho_{hv} & \sigma_v^2 \end{bmatrix} = \begin{bmatrix} 5245.23 & 0.11 \\ +0.00 & 5061.10 \end{bmatrix}$$

$$COV_{-YST} = \begin{bmatrix} \sigma_h^2 & \sigma_{hv} \\ \rho_{hv} & \sigma_v^2 \end{bmatrix} = \begin{bmatrix} 5067.27 & 0.44 \\ +0.00 & 5058.75 \end{bmatrix} \qquad (11)$$

and for the COAS

$$COV_{-Z\ COAS} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \rho_{xy} & \sigma_y^2 \end{bmatrix} = \begin{bmatrix} 35139.96 & 0.00 \\ 0.00 & 35247.23 \end{bmatrix}$$

$$COV_{+X\ COAS} = \begin{bmatrix} \sigma_y^2 & \sigma_{yz} \\ \rho_{yz} & \sigma_z^2 \end{bmatrix} = \begin{bmatrix} 35247.23 & 0.00 \\ 0.00 & 35063.23 \end{bmatrix} \qquad (12)$$

Note that rotation of the navigation base errors into the sensor coordinate systems introduces cross correlation terms. The correlation coefficients, however, are very small (<.005) and the errors about the coordinate axes can be assumed to be independent. The derivation of the alignment error equation (9) assumed that the star measurement errors are isotropic in the sensor measurement plane. The insignificant differences in the diagonal elements and the negligible magnitudes of the off-diagonal elements in each of the sensor error covariance matrices are commensurate with this assumption. Note, also, that for a given sensor type, the error properties can be assumed to be independent of the sensor LRU and angular position. The single-axis measurement error variance for each sensor type, therefore, is approximated by simply averaging the four variance samples of each axis of each sensor in matrices (11) and (12)*. This averaging process result in the following values for the one sigma per axis star sighting error for the star tracker and COAS sensors:

$$(\sigma_0)_{ST} = 72 \text{ arc seconds}$$
$$(\sigma_0)_{COAS} = 188 \text{ arc seconds} \quad (13)$$

3.2 IMU ALIGNMENT ERROR

The total RMS IMU alignment error (1σ) based upon the estimated system measurement errors (13) is approximately 124 arc seconds for a star tracker alignment and 325 arc seconds for COAS alignments. As stated previously, the RMS alignment error indicator, ω, is equivalent to an RSS of the mean and standard deviation of the total alignment error. Furthermore, the 1 sigma per axis alignment errors, σ_x, σ_y, σ_z (star coordinates) are related to the total RMS error by

$$\omega^2 = \sigma_x^2 + \sigma_y^2 + \sigma_z^2 \quad (14)$$

If the per axis components are assumed to be equal

$$\sigma_x = \sigma_y = \sigma_z = \omega_0 \quad (15)$$

an approximate value can be obtained for these components by combining equations (10), (14) and (15) leading to

$$\omega_0 = \frac{\omega}{\sqrt{3}} = \sigma_0 \quad (16)$$

Preliminary Monte Carlo analysis has verified that this is a reasonable assumption. The actual single axis alignment error properties will be slightly different; and these differences are a function of the directions of the axis.

The expected standard deviation in the IMU alignment error for STS-1, therefore, is 72 arc seconds per axis for star tracker alignments and 188 arc seconds per axis for COAS alignments.

* This is equivalent to the introduction of two additional random variables: (1) the identity of the sensor LRU type and (2) the orientation of the sensor measurement plane with respect to the star coordinate system.

4.0 CONCLUSIONS

The one sigma per axis IMU alignment error values presented herein are based on current knowledge of the star tracker, COAS, IMU and navigation base errors and are the best estimates of the alignment system performance to date. Furthermore, preliminary Monte Carlo analysis of IMU alignment accuracy has verified both the value of σ_0 for star tracker measurements and equation (9) for several cases. Results of the preliminary analysis and additional simulation studies will be documented in the near future.

5.0 REFERENCES

1. Corson, R. W., "Orbit IMU Alignment", JSC IN No. 78-FM-34, June 1978.

2. Onboard Navigation Systems Characteristics", Mission Planning and Analysis Division, JSC IN No. 79-FM-5, March 1979.

3. Holloway, T. W., "Onorbit Flight Techniques Meeting No. 27 Minutes", NASA Memorandum No. CA5-78-48, 31 August 1978.

APPENDIX

STAR TRACKER, COAS, IMU, AND NAVIGATION BASE ACCURACY SPECIFICATIONS

The following is a summary of all the measurement and calibration errors associated with the IMU alignment system. All error values are one sigma and are given in units of arc seconds. They are obtained from the current star tracker, COAS, IMU and navigation base accuracy specifications (References 2 and 3). These one sigma values are then used to form the covariance matrices presented in Tables 3.1-1 and 3.1-2. For each type of IMU error, suitable assumptions are made as to how the particular IMU error is distributed in the navigation base coordinate system.

A.1 IMU RESOLVER ERRORS

The various elements making up the total per axis resolver error are presented in Table A.1-1. An RSS process is performed on these elements to obtain the final one sigma resolver error.

TABLE A.1-1 RESOLVER READ-OUT ERRORS

Error Source	Instantaneous (COAS)	Averaged * (ST)
Bias	30	30
RMS sinusoidal bias (1st harmonic)	$7.6/\sqrt{2}$	$7.6/\sqrt{2}$
RMS sinusoidal bias (8th harmonic)	$19.0/\sqrt{2}$	$19.0/\sqrt{2}$
RMS sinusoidal bias (9th harmonic)	$4.2/\sqrt{2}$	$4.2/\sqrt{2}$
RMS sinusoidal bias (16th harmonic)	$20.0/\sqrt{2}$	$20.0/\sqrt{2}$
Noise	12	$12/\sqrt{21}$
Quantization	$20/\sqrt{3}$	$(20/\sqrt{3})/\sqrt{21}$
RSS Total	39.9	36.5

* Noise and quantization are random errors and are reduced by the ST software 21 sample averaging algorithm.

The assumptions which permit the transforming of the one sigma resolver errors into the navigation base coordination system and the resultant covariance matrices are now presented

1. Azimuth and Inner Roll Resolver Errors are assumed to be random uniformly distributed in the three space of the navigation base coordinate system, therefore

$$COV_{ST} = \begin{bmatrix} 443.80 & 0.00 & 0.00 \\ 0.00 & 443.80 & 0.00 \\ 0.00 & 0.00 & 443.80 \end{bmatrix}, \sigma = 36.5/\sqrt{3}$$

$$COV_{COAS} = \begin{bmatrix} 531.84 & 0.00 & 0.00 \\ 0.00 & 531.84 & 0.00 \\ 0.00 & 0.00 & 531.84 \end{bmatrix}, \sigma = 39.9/\sqrt{3}$$

2. The Pitch Resolver Error is assumed to be random uniformly distributed in the Y, Z- plane of the navigation base coordinate system, therefore

$$COV_{ST} = \begin{bmatrix} 0.00 & 0.00 & 0.00 \\ 0.00 & 665.71 & 0.00 \\ 0.00 & 0.00 & 665.71 \end{bmatrix}, \sigma = 36.5/\sqrt{2}$$

$$COV_{COAS} = \begin{bmatrix} 0.00 & 0.00 & 0.00 \\ 0.00 & 797.77 & 0.00 \\ 0.00 & 0.00 & 797.77 \end{bmatrix}, \sigma = 39.9/\sqrt{2}$$

3. The direction of the Outer Roll Resolver Error is parallel to the navigation base X-axis, therefore

$$COV_{ST} = \begin{bmatrix} 1331.41 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \end{bmatrix}, \sigma = 36.5$$

$$COV_{COAS} = \begin{bmatrix} 1595.53 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \end{bmatrix}, \sigma = 39.9$$

A.2 GIMBAL NONORTHOGONALITIES

The assumptions which permit the transforming of the one sigma gimbal nonorthogonality errors into the navigation base coordinate system and the resultant covariance matrices are now presented.

1. Azmith to Inner Roll and Inner Roll to Pitch gimbal nonorthogonalities are assumed to be perfectly compensated, therefore

$$COV = \begin{bmatrix} 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \end{bmatrix}$$

2. The Pitcn to Outer Roll Gimbal Nonorthogonality is assumed to be random uniformly distributed in the navigation base Y, Z-plane, therefore

$$COV = \begin{bmatrix} 0.00 & 0.00 & 0.00 \\ 0.00 & 450.00 & 0.00 \\ 0.00 & 0.00 & 450.00 \end{bmatrix}, \quad \sigma = 30/\sqrt{2}$$

3. The Outer Roll to Case Nonorthogonality is constrained to the navigation base Y, Z-plane, therefore

$$COV = \begin{bmatrix} 0.00 & 0.00 & 0.00 \\ 0.00 & 400.00 & 0.00 \\ 0.00 & 0.00 & 400.00 \end{bmatrix}, \quad \sigma = 20$$

A.3 IMU INSTALLATION ERROR

The IMU case to mounting pads error is assumed to be 20 arc seconds for each navigation base axis, therefore

$$COV = \begin{bmatrix} 400.00 & 0.00 & 0.00 \\ 0.00 & 400.00 & 0.00 \\ 0.00 & 0.00 & 400.00 \end{bmatrix}, \quad \sigma = 20$$

A.4 NAVIGATION BASE ERRORS

The elements which make up the navigation base error are presented in Table A.4-1. An RSS process is performed on these elements to obtain the one sigma per axis nav base errors.

TABLE A.4-1

Error Source	Navigation Base Axis		
	X	Y	Z
Thermal navigation base bending	$(41/3)/\sqrt{2}$	$(41/3)/\sqrt{2}$	0
Mounting pads to navigation base calibration error	5	5	5
RSS Total	10.9	10.9	5

1. IMU Pads to Navigation Base Error

$$COV = \begin{bmatrix} 118.39 & 0.00 & 0.00 \\ 0.00 & 118.39 & 0.00 \\ 0.00 & 0.00 & 25.00 \end{bmatrix}$$

2. Navigation Base to ST Pads

$$COV = \begin{bmatrix} 118.39 & 0.00 & 0.00 \\ 0.00 & 118.39 & 0.00 \\ 0.00 & 0.00 & 25.00 \end{bmatrix}$$

3. Navigation Base to COAS Mount

This transformation is calibrated preflight and onorbit. IMU alignments will nominally be done using an onorbit calibrated COAS. The onorbit calibration is performed by using a star tracker aligned IMU to determine the relative orientation between the COAS instrument and the navigation base. The COAS calibration, therefore, is corrupted by the star tracker alignment error. Actually, all the errors in the measured transformations between the COAS and the navigation base (Figure 3.1-2) contribute to the calibration error. These include COAS to M50, M50 to IMU platform (star tracker alignment error) and IMU platform to Nav Base. Summation of these error covariance components yields the total calibration error covariance matrix.

$$COV = \begin{bmatrix} 20125.42 & 0.00 & 0.00 \\ 0.00 & 20177.66 & 0.00 \\ 0.00 & 0.00 & 20084.27 \end{bmatrix}$$

A.5 OPTICAL SENSOR LRU INSTALLATION ERROR

$$COV = \begin{bmatrix} 400.00 & 0.00 & 0.00 \\ 0.00 & 400.00 & 0.00 \\ 0.00 & 0.00 & 400.00 \end{bmatrix}$$

A.6 OPTICAL SENSOR ERRORS

1. Star Tracker Measurement Error (h = horizontal, v = vertical, B = boresite)

TABLE A.6-1

Error Source	Star Tracker Axis		
	h	v	B
Bias	$60/\sqrt{2}$	$60/\sqrt{2}$	0
Average random*	$(15/\sqrt{2})/\sqrt{21}$	$(15/\sqrt{2})/\sqrt{21}$	0
RSS total	42.5	42.5	0

* Random errors are reduced by the star tracker software 21 sample averaging algorithm.

2. COAS Instrument Errors

TABLE A.6-2

Error Source	Vehicle Body Axis		
	X	Y	Z
Cabin pressure variation	50	50	50
Temperature variation	4	4	4
Glass bending	0	0	0
Vehicle dynamics	75	75	75
Crew vision	21	21	21
COAS instrument (parallax)	52	52	52
RSS Total	106.2	106.2	106.2

A.7 STELLAR ABERRATION

1. The stellar aberration error is assumed to be perfectly compensated by the star tracker software, therefore.

$$COV_{ST} = \begin{bmatrix} 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 \end{bmatrix}$$

2. The COAS software does not correct for aberration; therefore, aberration is an additional source of error and is approximated by.

$$COV_{COAS} = \begin{bmatrix} 161.29 & 0.00 & 0.00 \\ 0.00 & 161.29 & 0.00 \\ 0.00 & 0.00 & 161.29 \end{bmatrix}$$

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