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Experience from the In-Flight Calibration of the Extreme Ultraviolet Explorer (EUVE) and Upper Atmosphere Research Satellite (UARS) Fixed Head Star Trackers (FHSTs)

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Abstract

Since the original post-launch calibration of the FHSTs on EUVE and UARS, the Flight Dynamics task has continued to analyze the FHST performance. The algorithm used for inflight alignment of spacecraft sensors is described and the equations for the errors in the relative alignment for the simple 2 star tracker case are shown. Simulated data and real data are used to compute the covariance of the relative alignment errors. Several methods for correcting the alignment are compared and results analyzed. The specific problems seen on orbit with UARS and EUVE are then discussed. UARS has experienced anomalous tracker performance on an FHST resulting in continuous variation in apparent tracker alignment. On EUVE, the FHST residuals from the attitude determination algorithm showed a dependence on the direction of roll during survey mode. This dependence is traced back to time tagging errors and the original post launch alignment is found to be in error due to the impact of the time tagging errors on the alignment algorithm. The methods used by the FDF to correct for these problems is described.

I. Introduction

The Flight Dynamics Facility (FDF) has implemented the algorithm described by Shuster, et. al. (Reference 1) in the Multimission Three-Axis Stabilized Spacecraft (MTASS) Flight Dynamics Support System (FDSS). This system has been used to determine alignments among the FHSTs and the Fine Sun Sensors (FSSs) for the EUVE and UARS missions. Although the software is capable of computing alignments for the Earth Sensor Assemblies on UARS, the nature of the Earth Sensors (residuals varying by an order of .1 deg over the period of an orbit) makes the algorithm inappropriate for use for these sensors. The algorithm has performed well for these missions, but is being replaced by a method devised by William Davis of CSC for the next generation of sensors; specifically, Charge Coupled Device (CCD) Star Trackers which provide multiple star observations simultaneously (Reference 2). In the time since UARS was launched (September 12, 1991), the FDF has become experienced in the application of the alignment algorithm and has an increased understanding of some of the implications and pitfalls associated with the algorithm and with alignment calculation in the general sense.

II. Overview of Alignment Algorithm

Once a spacecraft has been launched, only relative sensor alignments can be observed. Any attempt to compute absolute alignments must include a priori information from pre launch data. The algorithm, from a high level point of view, is comprised of the following steps:

(1) Measurements from the sensors are grouped together based on the times the measurements were made. Ideally, simultaneous measurements are desired for this approach. As an attempt to minimize the impacts of propagation errors, only observations relatively close in time are propagated to a common time using the gyro data. The actual criteria for grouping is an user input, usually observations closer in time than 2 seconds are grouped. The maximum propagation errors for FDF processing is less than .1 arcsec based on observed gyro performance.

(2) The derived measurements then used for the alignment process are the differences in the dot products of the reference and the observed vectors. This derived measurement is independent of the attitude.

(3) A maximum likelihood estimate of the alignments is computed which minimized the appropriate weighted sum of the squares of the differences between observed and reference scalar products of the star directions.

III. Mission Descriptions (Sensor Complements)

For both UARS and EUVE, the primary sensor complement consists of 2 FHSTs (arbitrarily designated as FHST 1 and FHST 2), 1 FSS and the gyros (the NASA Standard Inertial Reference Unit, DRIRU-II). Normal onboard and ground processing uses the FHSTs and the gyros for attitude determination. For the current FSS transfer function, a substantial sampling of observations across the FSS field of view (FOV) is required in order to accurately align the FSS. During normal mission operations, this data is not routinely available. However, the alignment of the FHSTs can be determined relative to each other without recourse to FSS data, and this is the normal operational procedure. The problem is now well defined; given a sensor complement of two FHSTs and the gyros, what is the best approach to maintaining the alignment of the FHSTs.

IV. Statistics of 2 FHST Alignment

Reference 1 gives the complete mathematical derivation of the alignment algorithm for multiple sensors. However, the simpler 2 FHST case of concern for the two missions (EUVE and UARS) is worth examining in its own right. Following the derivation of Reference 1, let the unit vector to the observed star in the sensor frame be denoted by $\hat{U}_{i,k}$, where i = 1 or 2 for FHST 1 or FHST 2 and k is a time index. The observed vector is related to the true vector by

$$\hat{U}_{i,k} = \hat{U}_{i,k}^{true} + \Delta\hat{U}_{i,k} \tag{1}$$

with $\Delta\hat{U}_{i,k}$ assumed Gaussian, zero-mean and white with covariance $R_{\hat{U}_{i,k}}$.

The measurements from the two FHSTs are assumed to be statistically independent. Let $\hat{W}_{i,k}$ denote the measured direction in the spacecraft body frame. Then the alignment matrix for FHST i, S_i, is the orthogonal matrix defined by

$$\hat{W}_{i,k} = S_i\hat{U}_{i,k} \tag{2}$$

and, therefore,

$$\hat{W}_{i,k} = S_i(\hat{U}_{i,k}^{true} + \Delta\hat{U}_{i,k}) \equiv \hat{W}_{i,k}^{true} + \Delta\hat{W}_{i,k} \tag{3}$$

At this point define the misalignment matrix by $S_i = M_i S_i^0$ with S_i^0 the a priori alignment matrix. To first order in the misalignment vectors Θ_i,

$$M_i = I + \begin{bmatrix} 0 & \theta_3 & -\theta_2 \\ -\theta_3 & 0 & \theta_1 \\ \theta_2 & -\theta_1 & 0 \end{bmatrix} \equiv I + [[\Theta_i]] \tag{4}$$

with I the identity matrix. As in Reference 1, do not confuse the subscripts on θ denoting components of the vector Θ_i with the subscripts on Θ_i which label the FHSTs. Define the "uncalibrated" body-referenced observation vector as

$$\hat{W}_{i,k}^0 \equiv S_i^0\hat{U}_{i,k} \tag{5}$$

and write

$$\hat{W}_{i,k}^0 = M_i^T\hat{W}_{i,k} \approx (I - [[\Theta]])\hat{W}_{i,k}^{true} + \Delta\hat{W}_{i,k}^0 \tag{6}$$

with M_i^T denoting the transpose of M_i. To achieve attitude independence, we now consider the dot products of the observation vectors for the two FHSTs and ...te that (neglecting the random errors in the reference vectors) the dot products of the true observation vectors can be replaced by the dot products of the reference vectors to write the equation from Reference 1,

$$\hat{W}^0_{1,k} \bullet \hat{W}^0_{2,k} \cong \hat{V}_{1,k} \bullet \hat{V}_{2,k} + (\hat{W}^0_{1,k} \times \hat{W}^0_{2,k}) \bullet (\Theta_1 - \Theta_2) + \hat{W}^{true}_{1,k} \bullet \Delta\hat{W}^0_{2,k} + \hat{W}^{true}_{2,k} \bullet \Delta\hat{W}^0_{1,k} \quad (7)$$

Define the measurement

$$z_k = \hat{W}^0_{1,k} \bullet \hat{W}^0_{2,k} - \hat{V}_{1,k} \bullet \hat{V}_{2,k} = (\hat{W}^0_{1,k} \times \hat{W}^0_{2,k}) \bullet (\Theta_1 - \Theta_2) + \Delta z_k \equiv H_k(\Theta_1 - \Theta_2) + \Delta z_k \quad (8)$$

with

$$\Delta z_k \cong \hat{W}^{true}_{1,k} \bullet \Delta\hat{W}^0_{2,k} + \hat{W}^{true}_{2,k} \bullet \Delta\hat{W}^0_{1,k} \quad (8a)$$

and

$$H_k = (\hat{W}^0_{1,k} \times \hat{W}^0_{2,k})^T \, . \quad (8b)$$

Replace $\hat{W}^{true}_{i,k}$ by $\hat{W}^0_{i,k}$ (to lowest order in the covariance) so that the statistics of Δz_k are given by

$$E\langle \Delta z_k \rangle = 0$$
$$E\langle \Delta z_k^2 \rangle = P_{z_k} = (\hat{W}^0_{1,k})^T R_{\hat{W}^0_{2,k}} \hat{W}^0_{1,k} + (\hat{W}^0_{2,k})^T R_{\hat{W}^0_{1,k}} \hat{W}^0_{2,k} \quad (9)$$

With our assumptions, the $\Delta\hat{W}^0_{i,k}$ will be Gaussian, zero-mean and white. Further assume the errors to be uniformly distributed so that (for unit measurement vectors) the covariance of the measurement vector errors in the body frame can be written in the form:

$$R^0_{W_{i,k}} = \sigma_i^2 (I - \hat{W}^0_{i,k} \hat{W}^{0\,T}_{i,k}) \quad (10)$$

for σ denoting the standard deviation of the measurement error. The application of maximum likelihood estimation techniques to compute $\Psi = (\Theta_1 - \Theta_2)$ leads to the negative-log-likelihood function

$$J_\Psi(\Psi) = \frac{1}{2} \sum_k \left[(z_k - H_k \Psi)^T P^{-1}_{z_k} (z_k - H_k \Psi) \right] + \log(\det P_{z_k}) + \log(2\pi) \quad (11)$$

Minimizing $J_\Psi(\Psi)$ over Ψ gives

$$P^{-1}_{\Psi\Psi} \Psi^* = \sum_k H_k^T P^{-1}_{z_k} z_k \quad (12)$$

and

$$P^{-1}_{\Psi\Psi} = \sum_k H_k^T P^{-1}_{z_k} H_k \quad (13)$$

Results from this last equation for the covariance of the relative alignment computation will be shown and discussed in later sections. Note that the variable Ψ is the difference in the misalignment vectors Θ_i showing explicitly that only the relative alignment of FHST 1 to FHST 2 can be computed based on in-flight data.

To determine the actual alignments for the individual sensors requires that a priori information on the alignments be provided.

The algorithm as implemented in the FDF takes the a priori misalignment matrices M_i and the covariance associated with them as input.

V. Covariance of Relative Alignment for EUVE for Simulated Data

An idealized case was simulated, using the EUVE spacecraft star tracker configuration, in which the observation vectors are evenly distributed over the FOVs of each tracker. The relative positions of the UARS star trackers are nearly identical, so that the results can be applied to either spacecraft. The computed covariance of the relative alignment error (in the EUVE body frame) is

$$P_{\Psi\Psi} = \begin{bmatrix} 62.058103 & 0.012787 & 0.008896 \\ 0.012787 & 100.752449 & -35.601872 \\ 0.008896 & -35.601872 & 12.780823 \end{bmatrix} \quad (14)$$

where, for convenience, the covariance matrix is given in the units of arcsec (squared). The importance, or lack thereof, of the scaling of the covariance matrices will be discussed later. The covariance matrix in this form does not tell us much, so consider the eigenvectors and eigenvalues. The eigenvalues, λ_i , arranged as a vector and ordered from smallest to largest, are listed below:

$$\vec{\lambda} = \begin{pmatrix} .178 \\ 62.058 \\ 113.355 \end{pmatrix} arc\sec^2 \quad (15)$$

Instead of listing the eigenvectors, denote the three (unitized) eigenvectors as $\vec{\varepsilon}_i$, corresponding to the λ_i. Then $\vec{\varepsilon}_1$ turns out to be along the cross product of the boresight of FHST 1 with the boresight of FHST2. $\vec{\varepsilon}_3$ is along the average of the two bore sights, and the second eigenvector is given by $\vec{\varepsilon}_3 \times \vec{\varepsilon}_1$. The covariance matrix can be written as

$$\begin{aligned} P_{\Psi\Psi} &= \lambda_1\varepsilon_1\varepsilon_1{}^T + \lambda_2\varepsilon_2\varepsilon_2{}^T + \lambda_3\varepsilon_3\varepsilon_3{}^T \\ &= \lambda_1\varepsilon_1\varepsilon_1{}^T + \tfrac{1}{2}(\sqrt{\lambda_2}\varepsilon_2 + \sqrt{\lambda_3}\varepsilon_3)(\sqrt{\lambda_2}\varepsilon_2 + \sqrt{\lambda_3}\varepsilon_3)^T + \tfrac{1}{2}(\sqrt{\lambda_2}\varepsilon_2 - \sqrt{\lambda_3}\varepsilon_3)(\sqrt{\lambda_2}\varepsilon_2 - \sqrt{\lambda_3}\varepsilon_3)^T \end{aligned} \quad (16)$$

The computed eigenvalues λ_2 and λ_3 can be seen to be related by

$$\sqrt{\frac{\lambda_2}{\lambda_3}} = \tan(\alpha / 2) \quad (17)$$

for α denoting the angle between the FHST bore sights (72.996 deg for EUVE). With this result, it can be seen that

$$P_{\Psi\Psi} = \lambda_1 \varepsilon_1 \varepsilon_1^T + \frac{1}{2}(\lambda_2 + \lambda_3)\left\{\hat{B}_1 \hat{B}_1^T + \hat{B}_2 \hat{B}_2^T\right\} \quad (18)$$

for $\hat{B}_i$ the unit vector along the boresight of FHST i. This is an important result: for the case of ideally distributed observations (evenly over the FOVs of both trackers), the error in the computed relative alignment angle has a large component along each FHST boresight and a much smaller component in the direction of the cross product of the bore sights. Dividing the uncertainty equally between the two trackers, the relative alignment uncertainty (1-sigma) for FHST i is given by $\sqrt{\frac{\lambda_1}{2}}$ about the cross product of the bore sights and by

$$\sqrt{\frac{1}{2}(\lambda_2 + \lambda_3)} \quad (19)$$

about the boresight $\hat{B}_i$. The reference frame defined by the eigenaxes for the simulated ideal case, will be denoted as the "average boresight frame."

VI. Results: Covariances of Relative Alignment for UARS and EUVE

Since launch, FHST 1 for UARS has exhibited anomalous behavior. The scale factor relating the FHST output to a measurement position has been decreasing monotonically with respect to time and the alignment has undergone an apparent rotation about the nominal boresight of the tracker. This anomaly has been reported on several missions previously (References 2 and 3), and is not the intended subject of this paper. The scale factor is adjusted routinely so that the net FHST measurement noise is equivalent to that of the unaffected FHSTs.

For UARS, the FDF attitude operations task routinely computes the relative alignment of the star trackers in order to monitor the behavior of the anomalous tracker. Since these alignments are not intended for uplink to the UARS spacecraft, only 2 hours of data are used. Assuming the 1-sigma FHST error for UARS to be 12 arcsec (based on typical residuals seen in the attitude determination process), this leads to fairly large variations in the covariances. The estimate of the error based on equation

(19) in the determination of the FHST rotation about its boresight is typically of the order of 50 arcsec based on 2 hours of data.

Data was collected from a recent (January 19 through 21, 1995) set of slews for EUVE, resulting in a total of 2779 observation pairs. The eigenvalues ε_i of the alignment covariance matrix were calculated using equations 8b, 10 and 13, and assuming FHST noise of 23.5 arcsec based on results from routine attitude determination. The angle from ε_1 to the cross product of the EUVE bore sights was 0.36 deg while $\vec{\varepsilon}_3$ was at an angle of 0.23 degrees from the average of the bore sights. The eigenvalues of the covariance matrix (using the 23.5-arcsec FHST error number) were as follows:

$$\vec{\lambda} = \begin{pmatrix} 0.4 \\ 263. \\ 423. \end{pmatrix} \text{arcsec}^2$$

giving an estimate of 19 arcsec as the 1-sigma error in the determination of the FHST rotation about its boresight. The near alignment of the eigenaxes with the average boresight frame indicates that the FHST field of views were covered uniformly enough to approach the idealized case simulated in Section IV.

VI. Discussion of Covariance Results

As shown, inflight data can only determine the relative alignment between the two trackers. This leaves 3 degrees of freedom in the determination of the two alignment matrices for the two trackers. A common approach, one used on EUVE, is to arbitrarily choose one sensor (FHST 2 for EUVE) as the reference and apply the results from the inflight data to adjusting the alignment of the other sensor only. This approach is reasonable for the first post launch alignment using inflight data. However, if this approach is followed for following alignments, the inaccuracy in the alignment of the reference sensor about its boresight (on the order of an arc minute for UARS and EUVE based on recent alignment data) will result in a large shift of the non-reference sensor. Experience has shown that an one arc minute rotation of FHST 2 about its boresight will result in about a 1 arcsec change in the computed attitude. Holding FHST 2 fixed and forcing FHST 1 to adjust for the same apparent rotation will result in about a 20 to 30 arcsec change in the attitude. The exact attitude changes seen will depend on the location of the observed stars in the FHST FOVs

Any method for choosing the 3 extra degrees of freedom can be used initially; but, once this choice has been made, it is clear that care must be taken for later alignment updates. The inflight alignment process can determine the separation angles between sensors with good accuracy (down to the 1 arcsec level given sufficient data) but the determination of the sensor orientation about its boresight should be considered a much "noisier" value. As shown by the simulation for the ideal data case, the relative alignment error can be considered to be concentrated about the sensor bore sights. The usual desire when updating sensor alignments inflight is to reduce the impact of the new alignments on the attitude determination process. For UARS and EUVE, the science instruments' pointing is known relative to the spacecraft attitude, and a significant disturbance in the spacecraft attitude would require a realigning of the science instrument. For UARS, the original post launch alignment was computed after the science instruments had already been aligned to the onboard computer's determined attitude. This is not a wise procedure, but the FDF responded by forcing the computed FHST alignments to leave the average boresight frame invariant. This constraint minimized the attitude disturbance resultant from the alignment process.

When the next inflight alignment update is made, a suggestion based on operational experience and the results in Section V is to give relative weights to the existing alignments for each sensor i as described below.

As stated previously, the covariance of the current (prior to the alignment process) is input to the algorithm. These covariances are input in the body frame of the spacecraft. This allows the unobservable degrees of freedom to be determined based on the a priori information. The suggested way to prescribe these covariances is as follows. Weigh the variance of the error about the cross product of the two FHSTs by a product of $\frac{\lambda_1}{\lambda_2+\lambda_3}$ relative to that about the boresight $\hat{B}_i$. For the EUVE and UARS missions, which share similar sensor geometries, the idealized values can be used, giving a relative weighing factor of 0.00086. The covariance of the previous alignment for FHST i, P_i, is then given by

$$P_i = c\left[\frac{\lambda_1}{2}\left\{\left(\hat{B}_1\times\hat{B}_2\right)\left(\hat{B}_1\times\hat{B}_2\right)^T\right\}+\frac{1}{2}(\lambda_2+\lambda_3)\hat{B}_i\hat{B}_i^T\right]$$

where the c term is provided to scale the covariance in order to reduce the effect of the previously computed alignment on the current processing. In operations, the usual approach is to allow the alignment to be determined mainly by the data input to the algorithm. The previous alignment is based on old data and the uncertainty is not well known (FHSTs alignment might not be updated in the onboard processing for months at a time) or the task is interested in trending the alignment results based solely on the current data. This will result in computed alignments which adjust the separation angle between the two trackers equally relative to the spacecraft body frame, and which allow each sensor to adjust its rotation about its boresight freely (for Scale terms large with respect to the assumed FHST noise). The impact on attitude determination due to this approach will be small unless the computed alignments result in large boresight rotations.

On UARS, the FHST 1 anomaly has resulted in a rotation of 1050 arcsecs since launch (as of November 1994). In this example, the impact on the ground attitude determination is still fairly small - a typical case shows a 7 arcsec change in the attitude determined based on the corrected alignment. The corrected alignment results in a large reduction in the FHST residuals (by a factor of approximately 5). Since UARS is constantly rotating at a 1 revolution per orbit rate (RPO), the boresight rotation effects tend to cancel due to averaging over the FOV.

An inertially fixed spacecraft would suffer a range of attitude errors resulting from a FHST misaligned about its boresight depending on the location of the observed stars in the tracker FOV. If the tracked star is exactly along the FHST boresight, the error in the observation would be zero, but this error would increase with the radial distance from the boresight to the edge of the FOV. The actual attitude disturbance seen would depend on the relative placement of the FHSTs, but would be limited in the worst case to be no greater than the error due to the boresight rotation in an observation at the farthest allowable point from the center of the FOV. The UARS and EUVE missions limit the observations used in the attitude determination process (onboard) to be within 4 degrees of the FHST boresight. The 1050 arcsec rotation of UARS results in a 73 arcsec error in the observation vector at 4 degrees from the boresight.

VI. EUVE FHST Data Timing Problems

For the EUVE mission, the FDF routinely performs attitude determination and updates various data bases so that the long term performance of the sensors can be monitored. For FHST trending, EUVE is put into the Survey mode, where the spacecraft rotates at 3 revolutions per orbit (3-RPO or approximately .19

deg/sec) about the x-axis (denoted as the roll axis) in the body frame. This allows multiple stars to sweep through the FHST FOVs and so is valuable for attaining information on the FHST performance. The rotation in the Survey mode can be either positive or negative about the x-axis, and it was noted that the averaged FHST residuals in the z-axis in the body frame showed a dependence on the roll direction. The y-axis is nearly parallel to the average boresight direction and the y-residuals show little impact due to the rotation about the x-axis. Figure 1, which displays the average of the FHST 1 residuals for EUVE for days when EUVE was in Survey mode (Flight day is the number of days since launch), clearly shows this dependence.

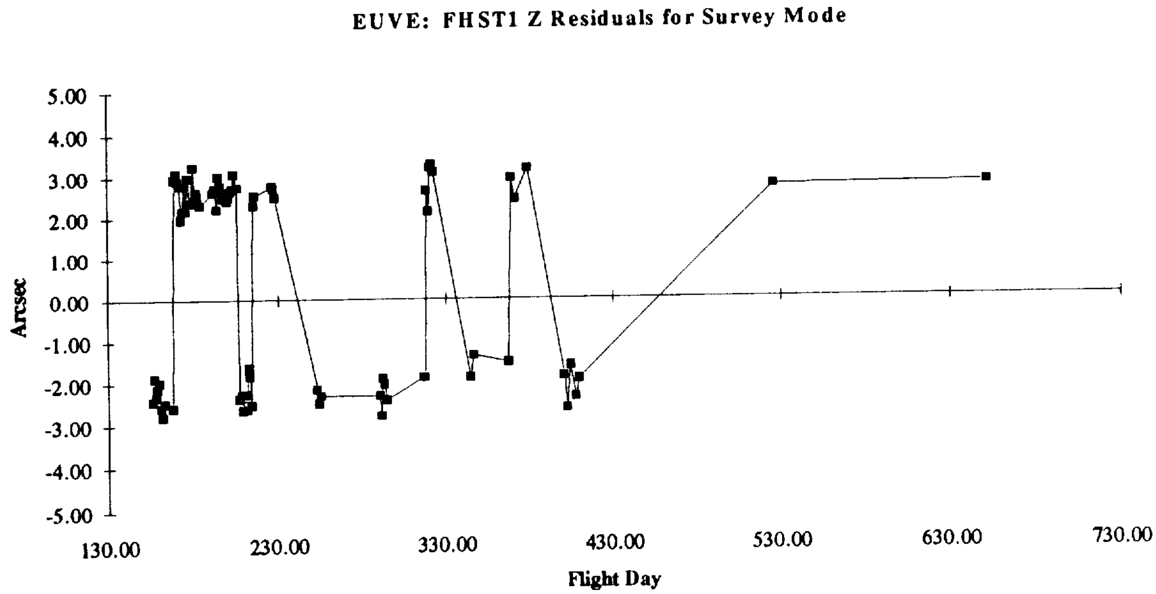

Figure 1

The negative average residuals occurred on days where the rotation rate was positive about the x-axis, while the positive residuals coincided with negative roll rates. For comparison, the plot for the x-axis residual (which are unaffected by rotations about the x-axis) shows no such behavior (Figure 2).

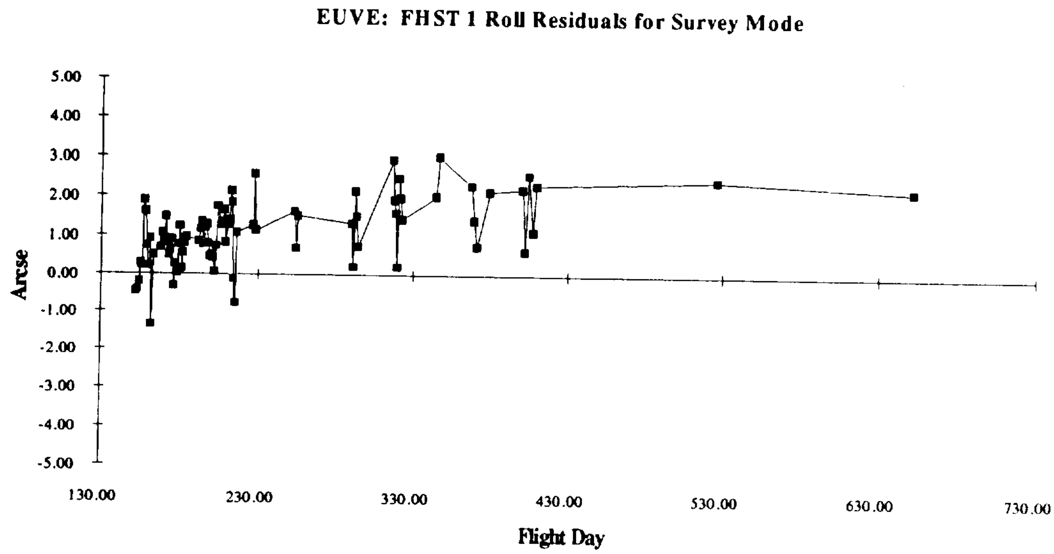

Figure 2

Although the magnitudes of the FHST residuals were still acceptable, it is clear that there is a systematic error in the FHST observations. FHST alignments were computed using positive roll data and compared to alignments which used just negative roll data. The alignments based on negative roll data only, when expressed in the spacecraft body frame, showed a relative alignment change of 79 arcsecs about the x-axis.

The dependence of FHST performance on roll direction implies a potential timing problem in the data. Residuals from some sample attitude determination processes (using a 2 hour time span) were collected and used to create a histogram to display the number of residuals with a given error (using a bucket size of approximately .5 arcsec). For the z-axis residuals, the errors are displayed as a time (in seconds) which would give the computed error based on the 3-RPO rotation rate. The reason for this will be discussed later. Figure 3 shows the histogram for the z-residuals for FHST 1 while Figure 4 contains the same plot for FHST 2. Data from a 2 hour time span on June 11, 1992 was used for these plots.

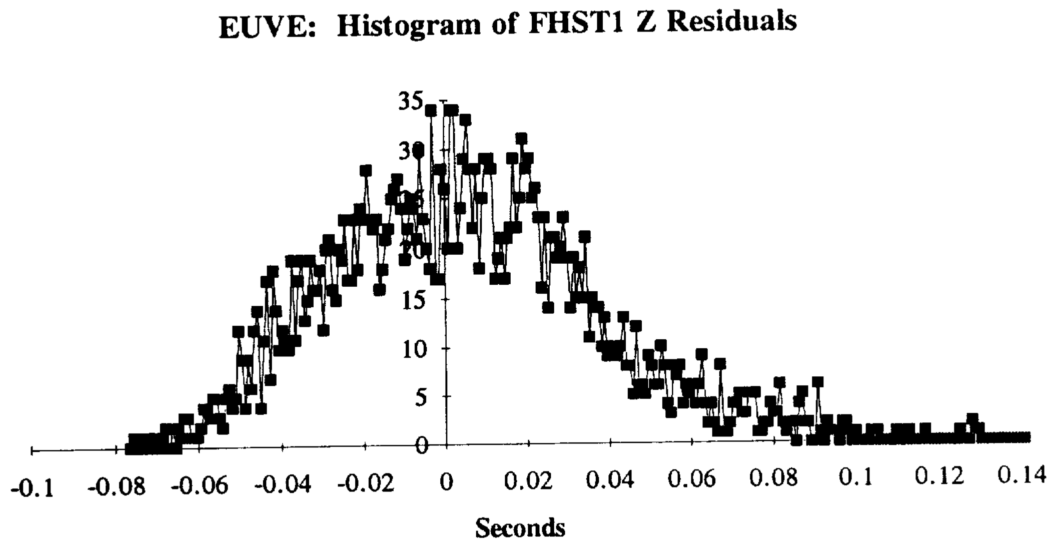

Figure 3

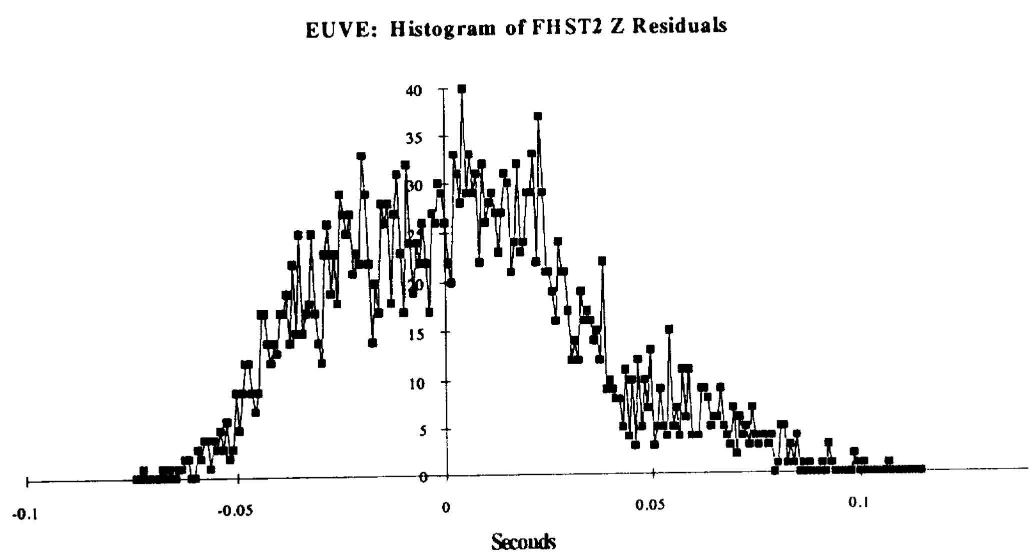

Figure 4

As before, the x-axis histogram of residuals for one of the FHSTs, FHST 1, is shown in Figure 5 for comparison. In this figure the residuals are in arcsecs.

EUVE: Histogram of FHST 1 X Residuals

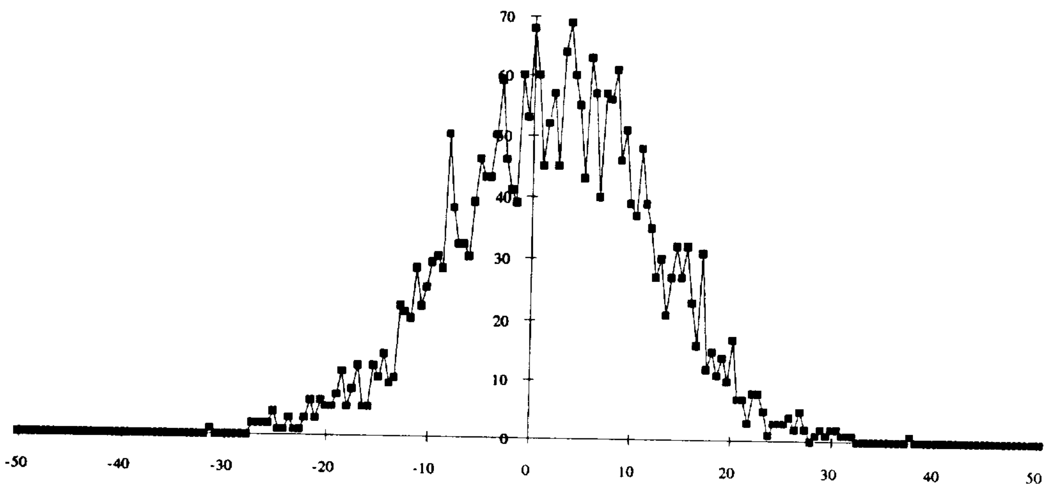

Figure 5

Note that the x-axis histogram in Figure 5 is symmetrical about zero while the z-axis residual histograms are not. The z-axis residuals can be affected by time tagging errors while the x-axis residuals are invariant. What can be seen is that the z-axis residuals extend out twice as far in the positive direction. The sample cycle of the FHST should now be described.

When a star is being tracked by the FHST, vertical and horizontal measurements (in the FHST frame) are alternated every 0.05 seconds. A complete star observation is made every 0.1 seconds. On the ground, we apply time offsets to apply a time tag which, it was hoped, would be within -0.05 to +0.05 of the actual measurement time. The results shown in Figures 3 and 4 can be explained if the vertical observation is occasionally an additional 0.05 seconds old, as the vertical FHST observation translates roughly into the Z-axis of the spacecraft body. These larger residuals occur with no discernible pattern in the observations.

VI. EUVE FHST Data Timing Problem: Discussion and Correction

The data used to align the FHSTs for EUVE post launch consisted entirely of positive roll data only. For calibration of star trackers, it is desirable to operate the spacecraft in a maneuvering mode so that many different stars will pass through all areas of the FOVs. Unfortunately, it can be seen that this makes the observations sensitive to time tagging problems. Based on the EUVE experience, calibration slews should include rotations in both the positive and negative directions about the slew axes. This will allow the ground processing to check for consistency in the solutions and therefore to observe any time tagging errors. This was not done for the initial EUVE post launch alignments, which leaves the problem of making the correction.

Various approaches to calculating the correct alignment have been implemented. First is to take alignment solutions based on negative roll data and average the relative alignment correction with solutions based solely on positive roll data. Second is to perform new maneuvers that have equal time spans with positive and negative rolling. Third, the large residual observations which appear to contain the additional 0.5 second delay can be edited from the alignment process. Unfortunately, the third approach proved unfruitful. Although the dependence of the alignment results on the roll direction could be reduced, the nature of the time tag error is that observations within the .1 error span can still be in error although the observation residuals do not appear as outliers. The second approach is feasible if the number of observations during the positive roll time period is exactly equal to the number of observations during the negative roll time period. This is an unwieldy constraint, leaving the first option as the one actually taken for the operational solution to the problem. The net correction of 40 arcsec in the alignment was made following the guidelines suggested in this paper, so that the maximum attitude disturbance is less than 3 arcsec for EUVE in inertial mode.

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