The Results of the In-Flight Attitude Sensor Calibration for the Arthur Holly Compton Gamma Ray Observatory*

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ABSTRACT

The Arthur Holly Compton Gamma Ray Observatory (GRO) was launched by the shuttle Atlantis in April 1991. This paper presents the results of the attitude sensor calibration that was performed during the early mission.

The GSFC Flight Dynamics Facility (FDF) performed an alignment calibration of the two fixed-head star trackers (FHSTs) and two fine Sun sensors (FSSs) on board Compton GRO. The results show a 27-arcsec shift between the boresights of the FHSTs with respect to prelaunch measurements. The alignments of the two FSSs shifted by 0.20 and 0.05 degree. During the same time period, the Compton GRO science teams performed an alignment calibration of the science instruments with respect to the attitude reported by the onboard computer (OBC). In order to preserve these science alignments, FDF adjusted the overall alignments of the FHSTs and FSSs, obtained by the FDF calibration, such that when uplinked to the OBC, the shift in the OBC-determined attitude is minimized.

FDF also calibrated the inertial reference unit (IRU), which consists of three dual-axis gyroscopes. The observed gyro bias matched the bias that was solved for by the OBC. This bias drifted during the first 6 days after release. The results of the FDF calibration of scale factor and alignment shifts showed changes that were of the same order as their uncertainties.

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1. INTRODUCTION AND BACKGROUND

The Arthur Holly Compton Gamma Ray Observatory (GRO) was launched by the shuttle Atlantis in April 1991. This paper presents the results of the attitude sensor calibration that was performed during the early mission by the Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF).

1.1 Summary

Section 1 of this paper provides an introduction and background information, consisting of a summary of the paper and its results, a brief history of the GRO mission, a description of the attitude sensors, and the attitude requirements. Section 2 discusses the purpose of in-flight calibration of the attitude sensors, describing the impact of calibration errors and how such errors are parameterized. Section 3 provides an overview of the methods used for the in-flight calibration of the attitude sensors and briefly summarizes the algorithms and FDF software system. Section 4 provides the results of the calibration. These results include a description of the data, the numerical results, and how the results were used. Section 5 gives a brief discussion of these results.

FDF performed an alignment calibration of the two fixed-head star trackers (FHSTs) and two fine Sun sensors (FSSs) on board Compton GRO. The results show a 27-arcsec shift between the boresights of the FHSTs with respect to prelaunch measurements. The alignments of the two FSSs shifted by 0.20 and 0.05 degree. During the same time period, the Compton GRO science teams performed an alignment calibration of the science instruments with respect to the attitude reported by the onboard computer (OBC). In order to preserve these science alignments, FDF adjusted the overall alignments of the FHSTs and FSSs, obtained by the FDF calibration, such that when uplinked to the OBC, the shift in the OBC-determined attitude is minimized.

FDF also calibrated the inertial reference unit (IRU), which consists of three dual-axis gyroscopes. The observed gyro bias matched the bias that was solved for by the OBC. This bias drifted during the first 6 days after release. The results of the FDF calibration of scale factor and alignment shifts showed changes that were of the same order as their uncertainties.

1.2 Mission and Brief History of Compton GRO

The Compton Gamma Ray Observatory was the second great observatory launched by the National Aeronautics and Space Administration (NASA). Its purpose is to observe astronomical sources in the the gamma ray spectrum. The 18,000-kg spacecraft has four gamma ray instruments, which cover a wide range of capabilities. These capabilities include fields of view (FOV) ranging from all-sky down to 4 degrees, a total energy range of 0.1 to 30,000 MeV, a time resolution of as small as 0.1 ms, and a position resolution of as small as 5 arcmin (1σ).

The shuttle Atlantis was launched from the Kennedy Space Center on April 5, 1991 at 14:22:44 UTC. The observatory was deployed on April 7, 1991. During the deployment, the high-gain antenna became stuck, and the astronauts performed an unscheduled extravehicular activity (EVA) to free it. Compton GRO was released from the shuttle at 22:37 UTC into a near-circular orbit with a semimajor axis of 6833 km and an inclination of 28.48 degrees. Attitude calibration maneuvers were performed from April 9 through April 14, 1991. That was followed by a series of observations designed to calibrate the scientific instruments. Calibrated attitude sensor alignments were uplinked on May 14, 1991. On May 16, the spacecraft maneuvered to its first science target, which initiated the start of normal operations. Normal operations consist of 2-week observation periods, during which Compton GRO is maintained in an inertial attitude.

1.3 Attitude Sensors of Compton GRO

Compton GRO is a multimission modular spacecraft (MMS) with two FHSTs, two FSSs, an IRU, two three-axis magnetometers (TAMs), and coarse Sun sensors (CSSs). Attitude control during normal

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operations is performed with reaction wheels and magnetic torquer bars. This discussion is limited to the in-flight calibration of the FHSTs, FSSs, and IRU. FDF did perform a bias determination for the primary TAM (bias = [0,0,-4] mG). However, based on comparisons of FHST attitude solutions to FSS/TAM attitude solutions, the error in the FSS/TAM solutions meets the requirement of less than 2 degrees (3σ) without the bias solution; thus no changes to the TAM bias were made.

The FHSTs are the NASA standard star tracker built by Ball Aerospace Systems Division (serial numbers 7 and 8). This model uses digital electronics, which replace much of the analog electronics of previous models. These devices are capable of locking onto and tracking the position and magnitude of one star at a time. The valid magnitude range is 2.0 to 5.7. The FOV is an 8-degree square and the digital resolution is 7.78 arcsec per count. The position measurements have a random error of 8 to 24 arcsec (1σ), depending on the magnitude and position in the FOV, and systematic calibration errors of less than 10 arcsec (1σ). For Compton GRO, the FHSTs are mounted with their boresights separated by 90 degrees.

The IRU is the DRIRU II manufactured by Teledyne. It consists of three dual-axis gyroscopes, giving a total of six channels of information. The precision output of this device is in the form of pulses that provide increments of rotation. Each gyroscope operates at two rate ranges, the low rate being 0.05 arcsec per pulse and the high rate being 0.8 arcsec per pulse. For Compton GRO, inertial attitudes are maintained in the low-rate range and maneuvers are done in the high-rate range. The angular rate bias is specified to vary by no more than 0.0012 arcsec/sec over 6 hours and 0.0008 arcsec/sec over one year.

The FSS, manufactured by Adcole, has a 64-by-64-degree FOV. It consists of two orthogonal sensor heads, each of which provides the angle between the Sun and a plane defined by a slit and a set of reticules. The digital resolution is about 0.004 degrees per count. The noise of each measurement is specified to be half the digital resolution. The calibrated accuracy is specified to be less than 0.02 degree. The two FSSs on Compton GRO are mounted so that their FOVs overlap by about 2 degrees.

1.4 Attitude Requirements for Compton GRO

The Compton GRO mission requires coarse attitude determination to an uncertainty of 2 degrees (3σ) per axis, using FSS, TAM, and IRU data. Fine attitudes determined using FHST and IRU data are required with an uncertainty of 0.024 degrees (3σ) per axis. After each maneuver, the attitude must be within 0.5 degree of the target attitude so that the OBC can correctly identify stars.

2. PURPOSE OF IN-FLIGHT CALIBRATION

Before launch, the manufacturers of spacecraft and attitude sensors measure the alignments and other calibration quantities. These measurements, made before and after various vibration, thermal, and vacuum tests, show slight shifts in calibration parameters. The shock and vibration of launch and the weightlessness, temperature, and vacuum of the space environment also result in slight shifts in calibration parameters. Such shifts introduce error into the attitude determination process. To reduce this error, the attitude sensor models are constructed to incorporate small changes in calibration parameters; in-flight sensor measurements are then used to solve for small shifts in calibration parameters from the best prelaunch values. This section presents models for small adjustments to calibration and discusses the impact of calibration errors.

2.1 FHST and FSS Alignment Calibration Error

The mission requires alignment calibration of the FHSTs and FSSs. Let M_{AS} be the prelaunch value of the 3-by-3 transformation matrix from the sensor coordinates to the coordinates of the attitude control system (ACS), which coincides with the body coordinates of the spacecraft. Each sensor has its own value for this

matrix, which gives the alignment of the sensor with respect to the ACS. Let $M_{AS'}$ be the postlaunch value of the alignment matrix and let $M_{SS'}$ be the difference between the prelaunch and postlaunch alignment matrices, sometimes called the misalignment matrix, such that

$$M_{AS'} = M_{AS} M_{SS'} \qquad (1)$$

To perform an alignment calibration, an algorithm must determine $M_{SS'}$ for each sensor. For the Compton GRO and many other missions, it is assumed that all the matrices in equation 1 are orthonormal; thus there are only three degrees of freedom to each matrix. Let $M_{SS'}$ be parameterized by the 3-vector $\vec{\theta}$ as follows:

$$M_{SS'} = M_{AS}^T \, \text{Rot}(\vec{\theta}) \, M_{AS} \qquad (2)$$

$\vec{\theta}$ is the Euler rotation vector which is converted to the corresponding rotation matrix with the function $\text{Rot}(\vec{\theta})$,

$$\text{Rot}(\vec{\theta}) = \cos(\theta) \; I \; + \; \frac{1 - \cos(\theta)}{\theta^2} \, \vec{\theta} \, \vec{\theta}^T \; - \; \frac{\sin(\theta)}{\theta} \begin{bmatrix} 0 & -\theta_3 & \theta_2 \\ \theta_3 & 0 & -\theta_1 \\ -\theta_2 & \theta_1 & 0 \end{bmatrix} \qquad (3)$$

where $\theta = |\vec{\theta}|$ and I is the 3-by-3 identity matrix. The postlaunch alignment becomes

$$M_{AS'} = \text{Rot}(\vec{\theta}) \, M_{AS} \qquad (4)$$

The algorithm discussed in Section 3 solves for a value of $\vec{\theta}$ for each of the two FHSTs and each of the two FSSs on board Compton GRO. Unfortunately, not all 12 components of these four vectors are independently observable. An overall rotation of all the attitude sensors with respect to the scientific instruments or the body coordinate system is not observable by any calibration process that is limited to using attitude sensor data: thus only 9 of the 12 degrees of freedom in these alignments are observable. The criteria for the selection of the unobservable degrees of freedom are discussed in Section 3.

FHST and FSS alignment errors have two main effects on the attitude of the spacecraft. First, an overall alignment error introduces a systematic error in the pointing of the scientific instruments. This overall error is related to the three unobservable degrees of freedom already mentioned. Second, the relative alignment errors between these sensors results in higher measurement residuals and inconsistencies between attitude solutions obtained with one FHST and both FHSTs.

2.2 IRU Calibration Errors

The OBC and FDF ground software use the following model of the digital IRU output to obtain the measured angular velocity of the spacecraft, $\vec{\omega}$,

$$\vec{\omega} = G \begin{bmatrix} k_x & \Delta N_x \\ k_y & \Delta N_y \\ k_z & \Delta N_z \end{bmatrix} \frac{1}{\Delta t} - \vec{b} \qquad (5)$$

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where G is a 3-by-3 matrix that transforms the IRU outputs to the ACS, $\vec{b}$ is a bias vector, k_i is the scale factor for the ith IRU axis, and ΔN_i is the change in the accumulated angle counts during the time interval Δt. By allowing the G-matrix to be nonorthogonal, the nonorthogonality of the IRU measurement axes can be taken into account. The adjustable parameters of this model are G, the ks, and $\vec{b}$. Small variations of these parameters are applied to obtain an improved rate, $\vec{\omega}'$,

$$\vec{\omega}' = (I + \delta A) \ G \begin{bmatrix} (1 + S_x) \ k_x \ \Delta N_x \\ (1 + S_y) \ k_y \ \Delta N_y \\ (1 + S_z) \ k_z \ \Delta N_z \end{bmatrix} \frac{1}{\Delta t} - (\vec{b} + \delta\vec{b}) \tag{6}$$

where δA is a 3-by-3 matrix of small adjustments to the prelaunch value of alignment, S_i is a small adjustment to the scale factor of the ith axis, and δb is an adjustment to the prelaunch value of the bias. Since δA contains independent adjustments to three axes, this matrix has six degrees of freedom. However, by allowing all nine components to vary, the scale factor adjustments can also be incorporated. Let δM be the 3-by-3 matrix that includes both alignment and scale factor adjustments as follows:

$$\vec{\omega}' = (I + \delta M) \ G \begin{bmatrix} k_x \ \Delta N_x \\ k_y \ \Delta N_y \\ k_z \ \Delta N_z \end{bmatrix} \frac{1}{\Delta t} - (\vec{b} + \delta\vec{b}) \tag{7}$$

If $\vec{\omega}'$ is the true angular rate vector and the bias is assumed small, then the rate error is given to first order in the calibration error by

$$\delta\vec{\omega} = \vec{\omega}' - \vec{\omega} \approx \delta M \ G \ \vec{\omega}' - \delta\vec{b} \tag{8}$$

For an inertially pointing attitude, $\vec{\omega}'$ is very small, so the errors in the IRU alignment and scale factors do not contribute any first-order errors to the attitude solution. The IRU bias error does contribute significantly to the rate error at all times, which is why it is continuously solved for by the OBC. During a maneuver, IRU alignment and scale factor errors can accumulate to produce a noticeable effect on the attitude. This is especially true for Compton GRO, because the OBC uses only IRU data during maneuvers to compute the attitude. Section 3 discusses the algorithm that uses maneuver data to solve for adjustments to the IRU calibration parameters.

2.3 Calibration Parameters Uplinked

FDF has the capability to provide calibrated parameters for the attitude sensors in the form of uplink tables to the OBC. The information in these tables includes postlaunch alignments $M_{AS'}$ for each of the two FHSTs and each of the two FSSs and a postlaunch IRU alignment matrix $G' = [I + \delta M] G$. The OBC uses a Kalman filter to continuously solve for the spacecraft attitude and the IRU bias; thus ground-determined biases need not be uplinked. However, the ground-determined bias is compared with the OBC-determined bias.

3. METHOD OF IN-FLIGHT CALIBRATION

This section describes two algorithms used for the in-flight calibration of the Compton GRO attitude sensors. The alignments of the FHSTs and FSSs were determined by FDF with an algorithm derived by Shuster

(1982). FDF solved for the IRU alignments, scale factors, and biases with an algorithm originated by Davenport (Keat 1977). This section also presents an overview of the FDF attitude ground support system (AGSS) for attitude calibration of Compton GRO.

3.1 Calibration of FHST and FSS Alignments

Malcolm Shuster has derived two algorithms for determining the in-flight alignments of attitude sensors such as FHSTs and FSSs (Shuster 1982 and 1990, Bierman 1988). Both algorithms work by comparing the dot products of unit vectors in spacecraft coordinates from different sensors measured at the same time with the dot products of the corresponding unit vectors in inertial coordinates. The vectors in inertial coordinates come from a star catalog or Sun ephemeris. Errors in the alignments used to compute the measured spacecraft coordinate vectors produce differences in these dot products. The algorithms parameterize the alignment adjustment to each sensor with the Euler rotation vector $\vec{\theta}$ defined in Section 2.

These vectors are varied in a batch least-squares process to minimize the differences between dot products. These algorithms have the advantage of not requiring IRU propagation or attitudes except to identify stars. An overall rotation applied to all the sensors does not affect the relative measurements or the dot products. The Shuster algorithms resolve these three unobservable degrees of freedom by incorporating the prelaunch alignments into the least-squares sum. In effect, the three unobservable degrees of freedom retain their prelaunch value. The two algorithms differ in the way they weight the data in the least-squares sum. The older algorithm (Shuster 1982) does not optimally weight the data: this weighting ignores correlations between dot products which share a measurement vector. However, it is not necessary for a least-squares algorithm to be optimally weighted to give good results. Given sufficient data, the solved-for alignments of the older algorithm are still valid. However, the older algorithm assumes that the weighting is optimal in the derivation of the covariance of the solution. Thus, the solution is correct, but the covariance of the solution is not correct. Shuster remedied this problem in a newer version of the alignment algorithm (Bierman 1988 and Shuster 1990) in which correlations between dot products at the same time are optimally weighted. However, the newer algorithm still ignores correlations between dot products at different times; the capability to optionally weight such correlations would be very difficult to implement. The FDF Compton GRO attitude ground support system uses the older algorithm, because the newer algorithm was not available soon enough.

During the early mission of Compton GRO, the scientific instruments were calibrated before the attitude sensor calibrations were uplinked. The science calibrations included an alignment adjustment with respect to the attitude provided by the OBC. FDF personnel noticed that the alignments provided by the Shuster algorithm would shift the attitude computed by the OBC and thus degrade the alignment calibration of the scientific instruments. To prevent this, FDF personnel adjusted the overall alignment of the FHSTs and FSSs with a single rotation, which minimized the shift to the OBC-determined attitude. The algorithm for doing this adjustment is presented in the appendix. The adjusted alignments are indicated with double-prime subscripts, $M_{AS''}$ and $M_{SS''}$.

3.2 Calibration of the IRU

The IRU of Compton GRO was calibrated in flight by FDF with a batch least-squares algorithm of P. Davenport (Keat 1977). This algorithm uses data from maneuvers. The attitude difference is computed from inertial attitude solutions with FHST and IRU data before and after the maneuver. The attitude difference is also computed by integrating the IRU data over the time interval of the maneuver. The difference between these two attitude differences is directly related to errors in the IRU calibration parameters. Each such maneuver interval can provide 3 of the 12 degrees of freedom of the calibration. Thus, a minimum of four independent maneuver intervals is required for a full calibration. Typically, three of the intervals are chosen to be maneuvers around each of the spacecraft axes. The fourth interval must not duplicate any of the first three intervals: it could be a time span spent at an inertial attitude or a maneuver that is in the opposite direction

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from one of the first three maneuvers. The algorithm assumes the difference between the attitude solutions at each end of the interval to be independent of IRU calibration errors. The IRU alignment and scale factor errors do not contribute significantly to an inertial attitude solution. However, care must be taken to minimize the impact of bias errors on the inertial attitude solution by solving for the attitude at the center of a batch of uniformly distributed data. The same algorithm can also be used to do a partial IRU calibration. A single interval at an inertial attitude is sufficient to solve for the IRU bias.

3.3 FDF Attitude Ground Support System

Figure 1 shows a simplified diagram of the FDF attitude ground support system for calibration. The telemetry processor (TP) reads the raw telemetry data from the flight dynamics data link (FDDL) and unpacks and converts the data to engineering units. The data adjuster (DA) applies the calibration parameters to the engineering data from TP and generates vectors in the spacecraft coordinate system. The DA obtains the calibration parameters from files that initially contain the prelaunch parameters. The fine attitude determination system (FADS) obtains measured FHST and FSS vectors from DA, identifies stars, and solves for the attitude. The FHST/FSS calibration system (FFCAL) obtains star and Sun vectors from DA and identified star information from FADS. It then uses the old Shuster alignment algorithm to solve for improved FHST and FSS alignment matrices. These matrices are adjusted to minimize the shift of the OBC-determined attitude and then written to the calibration file accessed by DA. The IRU calibration system (IRUCAL) obtains fine attitude solutions from FADS and IRU rate vectors from DA. IRUCAL then uses the Davenport algorithm to solve for the IRU calibration parameters and writes the results to a file accessed by DA.
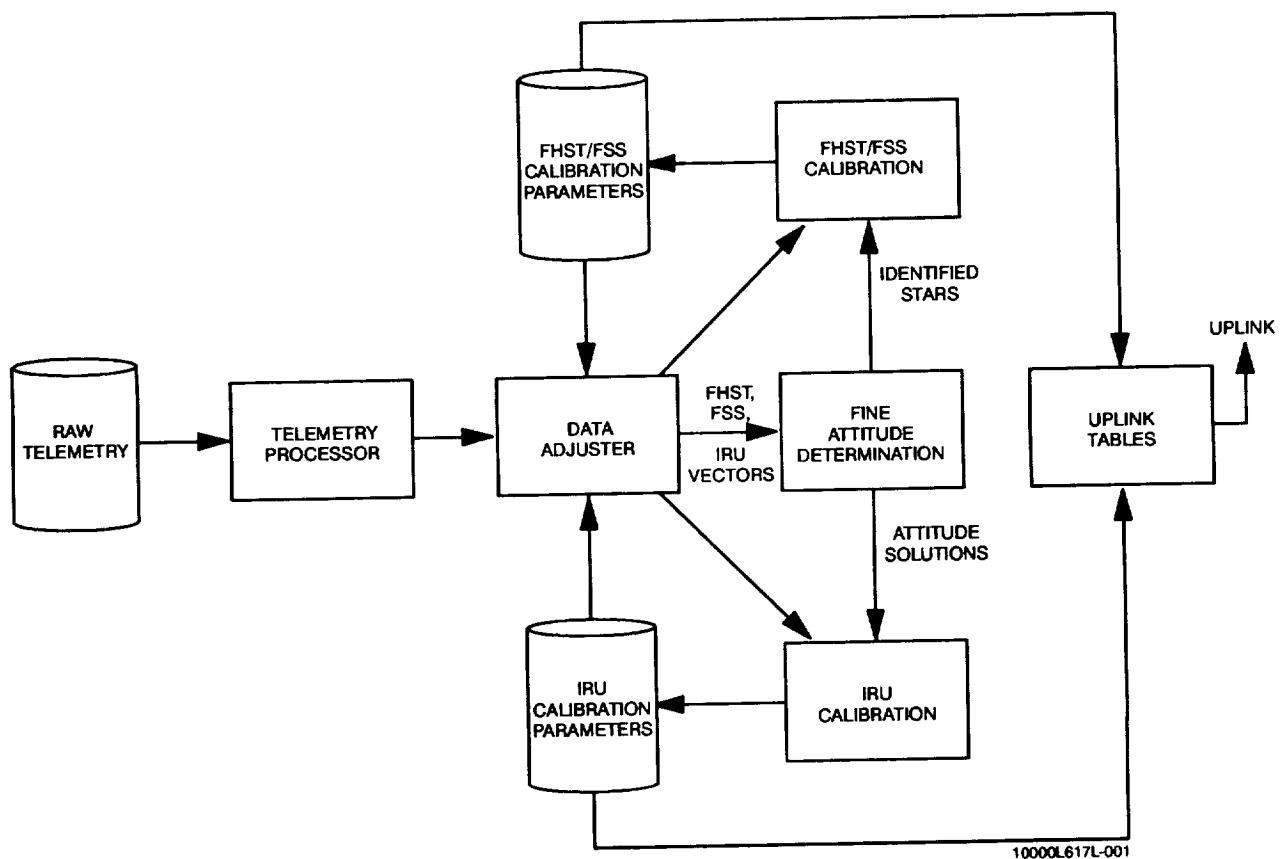

Figure 1. FDF Calibration System for Compton GRO

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4. RESULTS OF CALIBRATION

4.1 Results of FHST/FSS Alignment Calibration

The data used for the FHST/FSS alignment calibration were obtained from observations at six different inertial attitudes (Davis 1991a). These observations include the Sun at four different positions in the FOV of FSS1 and three different positions in the FOV of FSS2. The FFCAL results were then adjusted to be consistent with the science instrument calibration that occurred at the same time. Misalignments of 0.20 degree and 0.05 degree were observed for FSSs 1 and 2, respectively. The significant part of the FHST calibration consisted of a 27-arcsec misalignment between the FHST boresights. These results were validated by comparing the residuals of the fine attitude solutions computed from the calibrated alignments with the residuals computed from the prelaunch alignments. The residuals from the calibrated alignments were significantly smaller than those from the prelaunch alignments. Figure 2 shows an example of the effect of the calibrated alignments on the residuals. The calibrated alignments were then uplinked to the spacecraft.
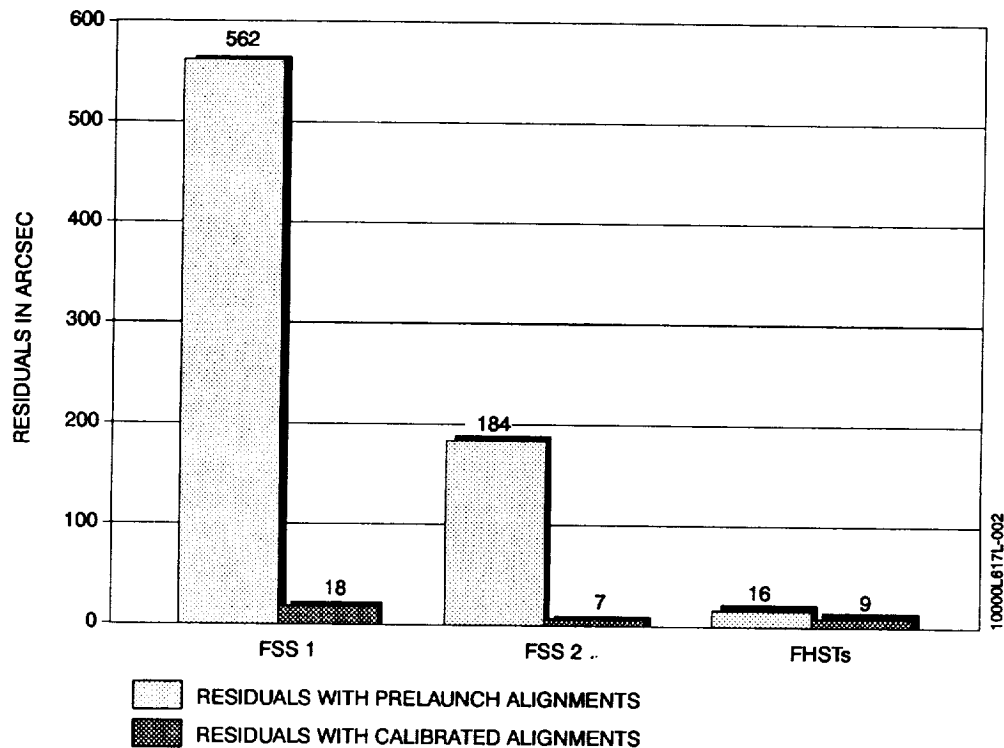

RESIDUALS WITH PRELAUNCH ALIGNMENTS
RESIDUALS WITH CALIBRATED ALIGNMENTS

Figure 2.   Fine Attitude Measurement Residuals with Pre-launch and Calibrated Alignments

Table 1 gives the prelaunch alignment matrices, M_{AS}, obtained from the final OBC database before launch. Table 2 gives the misalignment matrices, $M_{SS''}$, obtained by adjusting the FFCAL results to preserve the average attitude solution with two trackers. Table 3 gives the calibrated and adjusted alignments, consisting of the product of the prelaunch alignment matrices with the misalignment matrices. These matrices were uplinked to the OBC on May 14, 1991. The rotation vectors that rotate the prelaunch alignments to the adjusted calibrated alignment matrices are:

ROTATION VECTORS IN ACS COORDINATES				
	FHST1 (ARCSEC)	FHST2 (ARCSEC)	FSS1 (ARCSEC)	FSS2 (ARCSEC)
X−axis	41.7	56.4	236	−153
Y−axis	−41.7	56.3	−407	2
Z−axis	−13.8	13.7	−562	110
Magnitude	60.5	80.3	733	189

The angle between the FHST boresights of the calibrated alignments is 27.5 arcsec smaller than the angle between the prelaunch boresights.

4.2 Results of IRU Bias Calculation

The FDF operations team used IRUCAL to compute the in-flight IRU biases as a function of time over a 6-month period from April 9 to October 27, 1991 (Kulp 1991). Biases were determined for the three channels of the primary configuration and the three channels of the backup configuration, both in the low-rate IRU mode. For each bias solution, 90 minutes of data were processed. The attitude solutions were computed near each end of a 90-minute data span, and each solution was centered in a 10-minute batch of uniformly distributed FHST data. Figures 3 and 4 show the IRUCAL-determined bias vectors as a function of time for the primary and backup channels. Figure 3 also shows the bias solutions of the OBC. Note that the IRUCAL and OBC bias solutions follow one another and that both show some drift in the x- and z-axes of the primary channels early in the mission.

4.3 Results of IRU Alignment/Scale Factor Calibration

The Compton GRO calibration team used IRU data and fine attitude solutions with the IRUCAL utility to solve for IRU alignment, scale factor, and bias during the early mission (Davis 1991b). Maneuvers were done with all channels in the high-rate mode. The calibration team used data from four calibration maneuvers on April 9 through April 13, 1991. The full IRU calibration was done with data intervals from the following maneuvers:

MANEUVER AXIS AND ANGLE (DEGREES)	SENSORS FOR INITIAL ATTITUDE	SENSORS FOR FINAL ATTITUDE	INTERVAL DURATION (MINUTES)
X 60	FHST1 FHST2	FSS2 FHST2	19
Z −28	FHST1 FHST2	FHST1 FHST2	15
Y 31	FSS1 FHST2	FHST1 FHST2	15
Y −60	FSS1 FHST2	FHST1 FHST2	20

Table 1. Prelaunch FHST and FSS Alignments for Compton GRO; M_{AS}

ROTATION MATRIX FROM PRELAUNCH FHST1 FRAME TO ACS FRAME

$$\begin{bmatrix} -0.707293868 & 0.000641730 & -0.706919372 \\ -0.706919611 & -0.000965840 & 0.707293212 \\ -0.000228880 & 0.999999344 & 0.001136780 \end{bmatrix}$$

ROTATION MATRIX FROM PRELAUNCH FHST2 FRAME TO ACS FRAME

$$\begin{bmatrix} -0.706911922 & -0.000668710 & -0.707301319 \\ 0.707300782 & 0.000884930 & -0.706912220 \\ 0.001098630 & -0.999999404 & -0.000152590 \end{bmatrix}$$

ROTATION MATRIX FROM PRELAUNCH FSS1 FRAME TO ACS FRAME

$$\begin{bmatrix} 0.003753100 & -0.865531862 & 0.500839829 \\ 0.999986291 & 0.001422380 & -0.005035412 \\ 0.003645920 & 0.500851870 & 0.865525305 \end{bmatrix}$$

ROTATION MATRIX FROM PRELAUNCH FSS2 FRAME TO ACS FRAME

$$\begin{bmatrix} 0.000871080 & 0.034161031 & 0.999415934 \\ 0.999991417 & -0.004071418 & -0.000732420 \\ 0.004044019 & 0.999408066 & -0.034164291 \end{bmatrix}$$

Table 2. Postcalibration and Adjustment Alignment Change Matrices; $M_{SS''}$

ROTATION MATRIX FROM ADJUSTED FHST1 FRAME TO PRELAUNCH FHST1 FRAME

$$\begin{bmatrix} 0.99999991 & -0.00028956 & 0.00006638 \\ 0.00028955 & 0.99999990 & 0.00000000 \\ -0.00006631 & 0.00000001 & 0.99999988 \end{bmatrix}$$

ROTATION MATRIX FROM ADJUSTED FHST2 FRAME TO PRELAUNCH FHST2 FRAME

$$\begin{bmatrix} 0.99999989 & -0.00039545 & 0.00006634 \\ 0.00039545 & 0.99999987 & 0.00000000 \\ -0.00006634 & 0.00000003 & 0.99999996 \end{bmatrix}$$

ROTATION MATRIX FROM ADJUSTED FSS1 FRAME TO PRELAUNCH FSS1 FRAME

$$\begin{bmatrix} 0.99999373 & -0.00220720 & 0.00272080 \\ 0.00220561 & 0.99999742 & 0.00058720 \\ -0.00272209 & -0.00058124 & 0.99999596 \end{bmatrix}$$

ROTATION MATRIX FROM ADJUSTED FSS2 FRAME TO PRELAUNCH FSS2 FRAME

$$\begin{bmatrix} 0.99999959 & 0.00051921 & 0.00053489 \\ -0.00051950 & 0.99999973 & 0.00053081 \\ -0.00053462 & -0.00053110 & 0.99999961 \end{bmatrix}$$

Table 3. Postcalibration and Adjustment Alignment Matrices; $M_{AS''}$

ROTATION MATRIX FROM CALIBRATED & ADJUSTED FHST1 FRAME TO ACS FRAME

$$\begin{bmatrix} -0.70724671 & 0.00084653 & -0.70696623 \\ -0.70696675 & -0.00076114 & 0.70724624 \\ 0.00006060 & 0.99999928 & 0.00113677 \end{bmatrix}$$

ROTATION MATRIX FROM CALIBRATED & ADJUSTED FHST2 FRAME TO ACS FRAME

$$\begin{bmatrix} -0.70686513 & -0.00038918 & -0.70734814 \\ 0.70734791 & 0.00060520 & -0.70686522 \\ 0.00070319 & -0.99999967 & -0.00015251 \end{bmatrix}$$

ROTATION MATRIX FROM CALIBRATED & ADJUSTED FSS1 FRAME TO ACS FRAME

$$\begin{bmatrix} 0.00048072 & -0.86582899 & 0.50033978 \\ 0.99999690 & -0.00078186 & -0.00231379 \\ 0.00239455 & 0.50033946 & 0.86582589 \end{bmatrix}$$

ROTATION MATRIX FROM CALIBRATED & ADJUSTED FSS2 FRAME TO ACS FRAME

$$\begin{bmatrix} 0.00031903 & 0.03363069 & 0.99943420 \\ 0.99999357 & -0.00355182 & -0.00019969 \\ 0.00354310 & 0.99942801 & -0.03363162 \end{bmatrix}$$
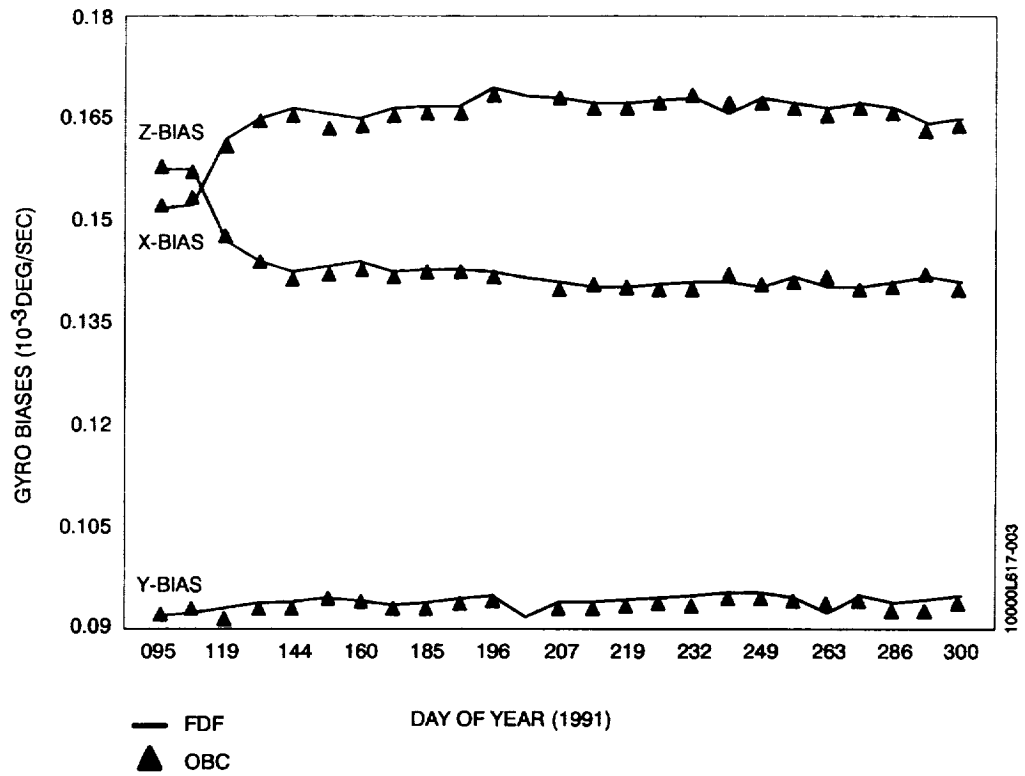
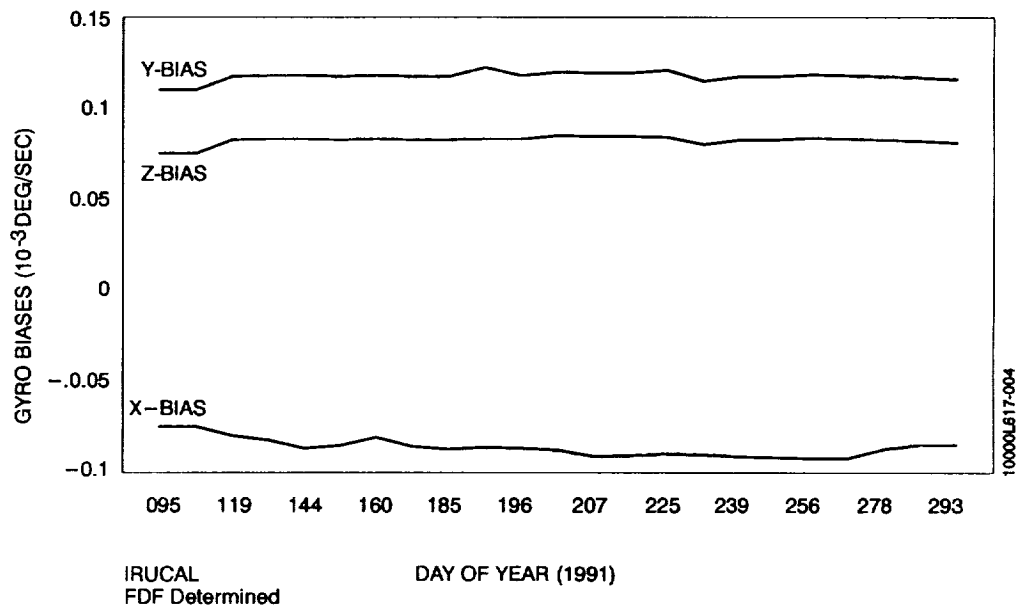**Figure 3.   GRO OBC and Ground Gyro Biases Primary Configuration**

Figure 4.   GRO Gyro Biases Backup Configuration

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Even though two of the maneuvers are around the y-axis, they contribute different information about the calibration parameters because they are in different directions.

The solved-for corrections to the primary configuration scale factor/alignment calibration and its uncertainty are:

<div align="center">

Solved-for δM-Matrix   Uncertainty

</div>

$$\delta M = \begin{bmatrix} 0.000167 & 0.000374 & 0.000167 \\ -0.000511 & -0.000265 & -0.000048 \\ -0.000547 & 0.000365 & 0.000037 \end{bmatrix} \pm \begin{bmatrix} 0.000507 & 0.000229 & 0.000610 \\ 0.000524 & 0.000223 & 0.000602 \\ 0.000527 & 0.000229 & 0.000608 \end{bmatrix}$$

The observed corrections are of the same order as the estimated uncertainties. To improve these results, it would be necessary to process larger amounts of data or process different data with lower errors. A major source of error in processing the above data for IRU calibration comes from the FSS. The lack of coverage by both FHSTs forced the use of FSS data for three of the eight attitude solutions. The FSS has an inherent error (not removed by alignment calibration) of about 0.022 degrees (0.00038 radians). The IRU calibration uncertainties could be reduced by using only FHST data to compute the epoch attitudes: such data may be available in more recent maneuvers. On the other hand, the observed uncertainties in the calibration and the observed error after maneuvers are easily within the requirements of a successful mission; these results were thus not uplinked to the OBC. The OBC and the ground software are still using the prelaunch measurements of the scale factor and alignment. That alignment/scale factor matrix is

$$\begin{bmatrix} 1.00000 & 0.00108 & 0.00079 \\ -0.00100 & 1.00000 & -0.00156 \\ -0.00056 & 0.00128 & 1.00000 \end{bmatrix}$$

The solved-for high-rate gyro biases are

primary configuration		
channel X2	bx = 1.66E-4 deg/sec	+/- 0.10E-4 deg/sec
channel Y1	by = 0.99E-4 deg/sec	+/- 0.09E-4 deg/sec
channel Z1	bz = 1.41E-4 deg/sec	+/- 0.10E-4 deg/sec
backup configuration		
channel X1	bx = -0.84E-4 deg/sec	+/- 0.10E-4 deg/sec
channel Y2	by = 1.22E-4 deg/sec	+/- 0.09E-4 deg/sec
channel Z2	bz = 0.81E-4 deg/sec	+/- 0.10E-4 deg/sec

These solutions reflect the gyro bias during maneuvers when the IRU is in the high-rate mode. The high-rate bias agrees with that obtained from low-rate data to within the estimated uncertainty.

There was no observable change in scale factor and alignment to within the estimated uncertainty of the solution. The solved-for gyro bias is consistent with results obtained from data at inertial attitudes.

5. CONCLUSIONS AND RECOMMENDATIONS

The in-flight attitude sensor calibration provides results that meet the requirements of the mission. The time history of the IRU bias is especially relevant to this and other missions with the same type of sensor. It would be useful to repeat the FHST/FSS alignment calibration to observe any time dependence on these parameters. It would also be worthwhile to redo the IRU alignment calibration with only FHST/IRU data for the attitude solutions to obtain a result with lower uncertainty.

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APPENDIX — ADJUSTMENT ALIGNMENT SOLUTIONS TO PRESERVE OBC ATTITUDE

This appendix describes the method used to adjust the alignment results from the Shuster algorithm so that the OBC computes the same average attitude with the adjusted alignments as with the prelaunch alignments. This adjustment is done to preserve the alignment calibration of the scientific instruments, which is done with respect to the OBC-determined attitude using the prelaunch FHST alignments. Let the following matrices represent alignments that transform from the sensor to the ACS coordinates for the prelaunch alignments, solved-for alignments, and adjusted solved-for alignments.

	prelaunch	solution	adjusted solution
FHST1 TO ACS	M_{AT1}	$M_{AT1'}$	$M_{AT1''}$
FHST2 TO ACS	M_{AT2}	$M_{AT2'}$	$M_{AT2''}$
FSS1 TO ACS	M_{AF1}	$M_{AF1'}$	$M_{AF1''}$
FSS2 TO ACS	M_{AF2}	$M_{AF2'}$	$M_{AF2''}$

where the subscripts A, T1, T2, F1, and F2 mean the ACS, FHST1, FHST2, FSS1, and FSS2 coordinate frames, respectively. The unprimed, single-primed, and double-primed subscripts stand for prelaunch, solved-for, and adjusted solved-for alignments, respectively. The columns of each of these matrices provide the x-, y-, and z-axes of each sensor in the ACS coordinate system. Let $\hat{X}_A^{T1}$, $\hat{Y}_A^{T1}$, and $\hat{Z}_A^{T1}$ be the axes of the FHST1 prelaunch alignment. Then

$$M_{AT1} = \left[\begin{array}{ccc} \hat{X}_A^{T1} & \hat{Y}_A^{T1} & \hat{Z}_A^{T1} \end{array} \right]$$

A similar relationship applies to the other sensor coordinate frames. The sensor boresight is defined by its z-axis.

To preserve, on the average, the attitude computed by the OBC with the two FHSTs, consider the following intermediate coordinate frame (subscript N) obtained from the boresights of the two trackers, $\hat{Z}_A^{T1}$, and $\hat{Z}_A^{T2}$,

$$M_{AN} = \left[-\frac{\hat{Z}_A^{T1} + \hat{Z}_A^{T2}}{\left| \hat{Z}_A^{T1} + \hat{Z}_A^{T2} \right|} \quad \frac{\left(\hat{Z}_A^{T1} + \hat{Z}_A^{T2}\right) \times \left(\hat{Z}_A^{T1} \times \hat{Z}_A^{T2}\right)}{\left| \left(\hat{Z}_A^{T1} + \hat{Z}_A^{T2}\right) \times \left(\hat{Z}_A^{T1} \times \hat{Z}_A^{T2}\right) \right|} \quad \frac{\hat{Z}_A^{T1} \times \hat{Z}_A^{T2}}{\left| \hat{Z}_A^{T1} \times \hat{Z}_A^{T2} \right|} \right]$$

The z-axis of this coordinate frame is along the direction formed by the cross-product of the boresights of the prelaunch alignments. The x-axis is opposite the direction formed by the sum of the boresights. The x- and z-axes are perpendicular. The y-axis completes the orthonormal frame. This intermediate coordinate frame is defined to be close to the ACS coordinate frame, although that definition is not necessary for the adjustment method. The prelaunch alignments can then be expressed as follows:

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$$M_{AT1} = M_{AN} \, M_{NT1} \qquad M_{AT2} = M_{AN} \, M_{NT2}$$

Together, the two matrices M_{NT1} and M_{NT2} contain only three degrees of freedom, the angle between the boresights and a rotation angle of each tracker around its boresight. It is claimed here without proof that all pairs of tracker alignment matrices, related by a small rotation, with the same intermediate frame will produce, on the average, the same attitude solution.

The matrix $M_{AN'}$, computed from the FHST boresights of the Shuster algorithm, is in general different from the matrix M_{AN}, computed from the prelaunch matrices. Adjust the solved-for alignments as follows:

$$M_{AT1''} = M_{AN} \, M_{N'A} \, M_{AT1'}$$

$$M_{AT2''} = M_{AN} \, M_{N'A} \, M_{AT2'}$$

$$M_{AF1''} = M_{AN} \, M_{N'A} \, M_{AF1'}$$

$$M_{AF2''} = M_{AN} \, M_{N'A} \, M_{AF2'}$$

where $M_{N'A} = M_{AN'}{}^{T}$. The intermediate coordinate frame $M_{AN''}$, computed from the FHST boresights of the adjusted solved-for alignments, equals M_{AN}. Thus, attitude solutions computed with the adjusted solved-for alignments will, on the average, be the same as attitudes computed with the prelaunch alignments.