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# Operational Support for Upper Atmosphere Research Satellite (UARS) Attitude Sensors\*

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## Abstract

The Upper Atmosphere Research Satellite (UARS) has several sensors that can provide observations for attitude determination: star trackers, Sun sensors (gimbaled as well as fixed), magnetometers, Earth sensors, and gyroscopes. The accuracy of these observations is important for mission success. Analysts on the Flight Dynamics Facility (FDF) UARS Attitude task monitor these data to evaluate the performance of the sensors, taking corrective action when appropriate. Monitoring activities range from examining the data during real-time passes to constructing long-term trend plots. Increasing residuals (differences) between the observed and expected quantities is a prime indicator of sensor problems. Residual increases may be due to alignment shifts and/or degradation in sensor output. Residuals from star tracker data revealed an anomalous behavior that contributes to attitude errors. Compensating for this behavior has significantly reduced the attitude errors. This paper discusses the methods used by the FDF UARS attitude task for maintenance of the attitude sensors, including short- and long-term monitoring, trend analysis, and calibration methods, and presents the results obtained through corrective action.

## Introduction

**UARS Mission Description.** UARS carries 10 science instruments that perform its mission objectives: to study (1) energy input and loss in the upper atmosphere, (2) the global photochemistry and dynamics of the upper atmosphere, (3) the relationships among these processes as well as the coupling between the upper and lower atmosphere (Reference 1). To achieve its mission goals, UARS is flying at approximately 585 kilometers (km) altitude in a nearly circular orbit, which has a 57-degree (deg) inclination and an Earth-oriented attitude. The UARS attitude is expressed as a 3-1-2 (yaw-roll-pitch; Z-X-Y) Euler rotation, with reference to the Orbital Coordinate System (OCS). The OCS is defined as having the yaw axis parallel to the negative of the Earth-to-spacecraft vector and the pitch axis pointing parallel to the negative of the orbit normal vector. The estimation and control requirements for the attitude are 60 and 108 arcseconds (arcsec) (3 standard deviations ( $3\sigma$ )), respectively, for each axis.

An important parameter related to the orbit is the solar beta angle. The solar beta angle is the complement of the angle between the orbit normal vector and the Earth-to-Sun vector. The beta angle is constantly changing due to the combined motion of the UARS orbit precession and the Sun in the celestial sphere. The changing solar beta angle forces UARS to perform an attitude maneuver approximately monthly. The Sun must be kept in the hemisphere bounded by the X-Z plane and containing the solar array for power considerations and science instrument protection. As the beta angle passes through 0 deg, UARS must perform a yaw maneuver of 180 deg. UARS is said to be flying forward when its positive X-axis is aligned with its velocity vector and backward when its negative X-axis is aligned with its velocity vector.

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Engineering support for the mission is provided by a standard Multimission Modular Spacecraft (MMS) bus. The MMS, built by Fairchild Space Company, consists of a communications and data handling (C&DH), power, signal conditioning, propulsion, and attitude control subsystems. The Modular Attitude Control Subsystem (MACS) has Earth sensors, fine and coarse Sun sensors, magnetometers, fixed-head star trackers (FHSTs), and inertial reference units (IRUs (gyroscopes)) available for use in attitude estimation. The Earth sensors are Ithaco-manufactured Earth sensor assemblies (ESAs), which perform conical scans and sense the infrared horizon of the Earth; UARS has two ESAs. The coarse Sun sensors (CSSs) are manufactured by Adcole. These are backup sensors for safehold situations and are not analyzed in this paper. The pair of three-axis magnetometers (TAMs) are flux-gate units manufactured by Schoenstadt. Besides providing safehold attitude support, they give information used to adjust the FHST measurements. There are three fine Sun sensors (FSSs): one mounted on the MACS, called the MACS FSS, and two mounted on the Solar-Stellar Pointing Platform (SSPP), called platform Sun sensors (PSSs). These are two-axis digital sensors manufactured by Adcole. The SSPP provides pointing control for some of the science instruments. The FSS and the PSSs differ in that the FSS has a 64-by-64 deg field-of-view (FOV) and is a backup to the FHSTs, while the PSSs have only a 4-by-4 deg FOV and are used primarily to determine the pointing of the SSPP. The PSSs are also much more accurate than the FSSs. The two FHSTs manufactured by Ball Electro-Optics/Cryogenics Division (BECD) (Reference 2) are the primary attitude sensors. The onboard computer (OBC) normally computes attitudes and gyro rate biases using star observations from the FHSTs, along with rates determined by the Teledyne dry rotor inertial reference units (DRIRU IIs) (Reference 3) in a Kalman filter.

**Flight Dynamics Facility Support for UARS Attitude Sensors.** The Flight Dynamics Facility (FDF) at Goddard Space Flight Center (GSFC) provides orbit and attitude support for GSFC-managed space missions. FDF attitude support responsibilities for the UARS mission include

- Real-time and near real-time attitude monitoring
- Trend analysis of sensor and onboard attitude determination performance
- Production of definitive attitudes as requested by the scientist
- Attitude and high-gain antenna contact predictions
- Attitude sensor calibration/alignment
- Science and mission planning aids

The software systems used by FDF to provide this support are the attitude determination system (ADS), the calibration and attitude validation systems, and several utilities that run exclusively in batch (noninteractive) mode. Most of the software is part of the Multimission Three-Axis Stabilized Spacecraft (MTASS) Flight Dynamics Support System (FDSS), which was developed by Computer Sciences Corporation (CSC) under a GSFC-managed National Aeronautics and Space Administration (NASA) contract (Reference 5). The MTASS system provides functions that are common to three-axis stabilized spacecraft support. (It is currently used to support two other operational missions: the Extreme Ultraviolet Explorer (EUVE) and the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) missions; several upcoming missions also plan to use parts of the MTASS system for their attitude support.)

The ADS processes the spacecraft telemetry sequentially through a mission-unique telemetry processing subsystem and mission-independent data adjustment, star identification, and attitude determination subsystem. The onboard-determined attitude can then be compared to that computed by the ADS; the differences are a measure of OBC attitude determination and control accuracy. The definitive attitude determination system (DADS) is designed to create a file containing 24 hours of UARS attitude from ADS solutions in the event of OBC attitude estimation problems. So far this has actually been needed only once.

There are six calibration systems. The FHST/Earth sensor/FSS calibration system (FEFCAL) computes alignments according to an attitude-independent method developed by Shuster, Chitre, and Niebur (Reference 8) and later refined by Shuster and Bierman (Reference 9). Gyro biases and the gyro scale factor/misalignment matrix are computed by the IRU calibration system (IRUCAL) using an algorithm developed by Davenport and documented by Keat (Reference 10). The

TAM calibration system (TAMCAL) computes the biases and TAM scale factor/misalignment matrix based on an algorithm developed by Lerner and Shuster (Reference 11). The FSS field of view system (FSSFOV) calculates the nine parameters required for the Adcole FSS; both the MACS FSS and the PSSs can be calibrated. Finally, the SSPP gimbals can be calibrated using SSPPCAL. Each system uses processed telemetry and/or the adjusted data. Calibration results are typically confirmed by before and after comparisons of sensor residuals in the coarse/fine attitude determination system (CFADS). Following verification, the calibration results may be made available for processing in the ADS and for uplink to the spacecraft.

The attitude verification system (ATTVAL) compares Euler angles for any two attitudes. Operationally, the OBC determined attitude is compared to the ADS-determined attitude. Statistics for the differences in the Euler angles are displayed for the analyst's interpretation.

**Attitude Data Trending and Problem Analysis.** The Attitude task processes 2 hours of data three times each week and trends the results over the life of the mission. The ground ADS uses star tracker data and gyro rates in a batch least-squares algorithm to determine the attitude and the gyro biases (assumed constant over the 2-hour interval). Values that are trended include sensor root-mean-square (RMS) residuals, which are computed from a comparison of the observed vectors to the reference vectors; the onboard versus ADS attitude comparison results; the ground-based (ADS-computed) gyro bias correction; and the TAM bias correction. Parameters from the planning aids software, such as star density, are also trended for use in analysis.

Plots of these data are examined for anomalies; however, the causes must be carefully discerned because anomalies can result from operational errors as easily as from real problems with the attitude sensors or may result from the ill behavior of another component of the system. It is important to recognize that the residuals are based on the ground processing because the sensor alignments are updated more frequently on the ground than onboard the spacecraft. To accomplish the proper validation of the OBC attitude, the most accurate sensor calibration is used in the ground processing to account for potential shifts in the sensor performance over time. Updates in the ground sensor parameters are often visible in the plot of the sensor residuals discussed later in the paper.

## Fixed Head Star Trackers

The primary sensors used for attitude determination by the UARS spacecraft are the FHSTs. In addition to this function, they are used to produce high-quality attitudes that are used to perform gyro calibrations and to evaluate calibrations of the coarser sensors. Correct calibration of the FHSTs is, therefore, considered of utmost importance to the mission.

These sensors search for, detect, and track stars as they pass through an 8-by-8 deg FOV. By focusing light from the star being tracked on the photocathode of an image dissector tube, the position and intensity of the star can be determined. The UARS FHSTs can track stars from magnitude 2.0 to 5.7. They are mounted on the MACS with approximately a 76-deg angle between boresights. The digital resolution of the sensors is 7.78 arcsec with a manufacturer's specified accuracy of 10 arcsec inside an 8-deg circular central FOV. Star positions are given as the distance from the center of the FOV in two orthogonal directions referred to as H and V. The parameters are converted to a unit vector in the data adjustment process.

For UARS, one of the Ball FHSTs (designated FHST1) is experiencing scale factor drift. The scale factor is a counts-to-degrees conversion factor that is applied to the two star position parameters H and V in the data adjustment process. Changes in this scale factor had been seen in previous missions and was, therefore, anticipated for the UARS FHSTs. An apparent rotation of the FHST about its boresight accompanies this drift and is believed to result from the same source (Reference 12).

An analysis utility, developed by Joseph Hashmall and William Davis of CSC, determined new scale factors for the trackers. This utility performs a least-squares fit of the horizontal and vertical position errors. The slope of this linear fit is then used as a multiplicative correction factor for the nominal scale factor value to eliminate these position errors.

## Methods

The star tracker residuals are trended as discussed previously, and plots are generated. New alignments and scale factors are computed and the ground processing of the tracker observations updated to the new values as needed. In addition, the onboard parameters are updated but less frequently, based on FDF recommendations as to when the onboard attitude determination is becoming too inaccurate. Due to the scale factor drift of FHST1, the FHST1 alignment is being updated much more frequently than is normally expected.

## Results

Figure 1 shows a steady increase of FHST1 residuals (from flight days 450 to 679), which appeared to correspond to the pitch axis attitude residuals shown in Figure 3. The FHST residuals shown are the difference between the observed vectors and the reference vector if the ground attitude is assumed to be true. This gives a measure of sensor and ground determined attitude accuracies. Figure 2, however, shows that the residuals for the FHST2 observations did not have a systematic change over time, which indicated that the problem was endemic to FHST1 rather than in the ground attitude determination. Both scale factors for FHST1 were also shown to be changing nearly monotonically, as can be seen in Figure 4. An analysis by Lee (Reference 13) proved that this scale factor drift could cause the pitch axis errors evident in Figure 3.

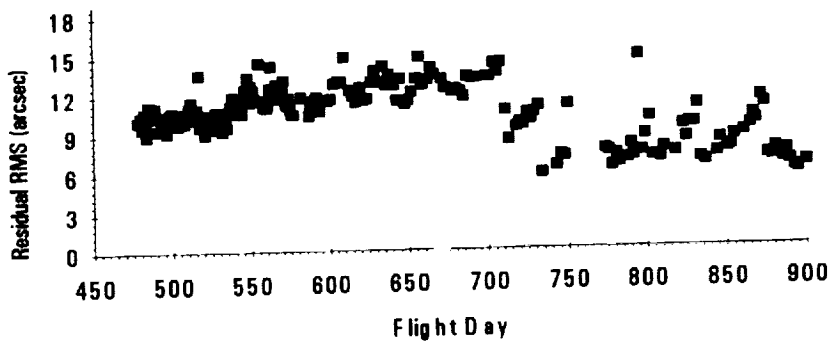


Figure 1. FHST1 RMS Residual (arcsec)

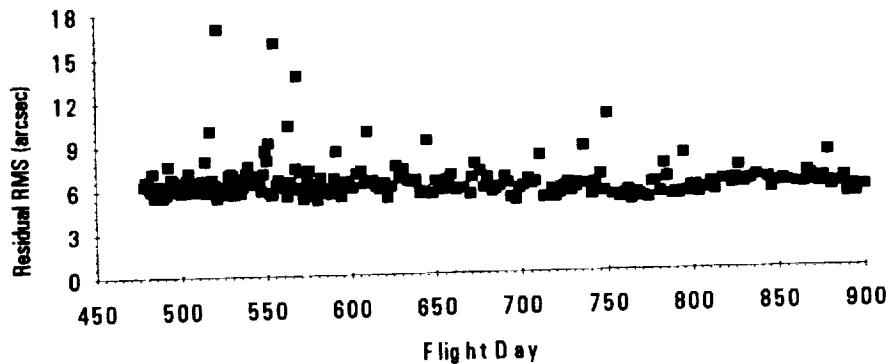


Figure 2. FHST2 RMS Residual (arcsec)

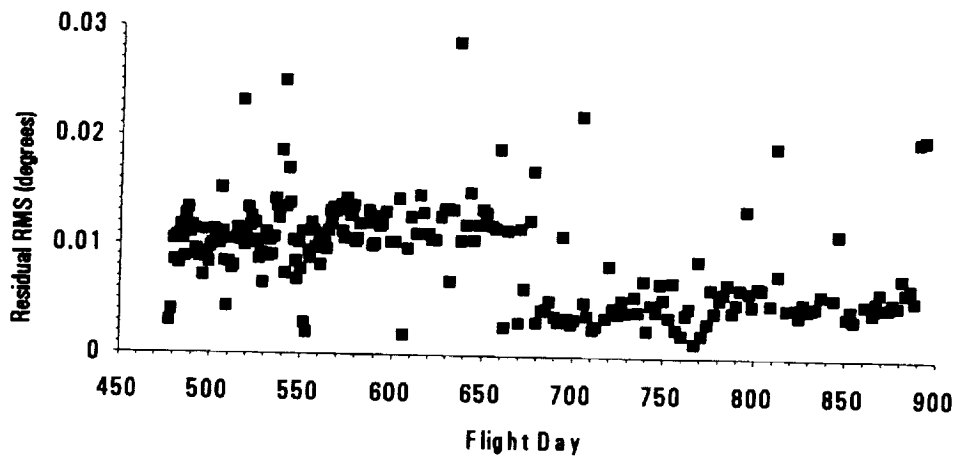


Figure 3. Errors in Pitch Axis Euler Angle

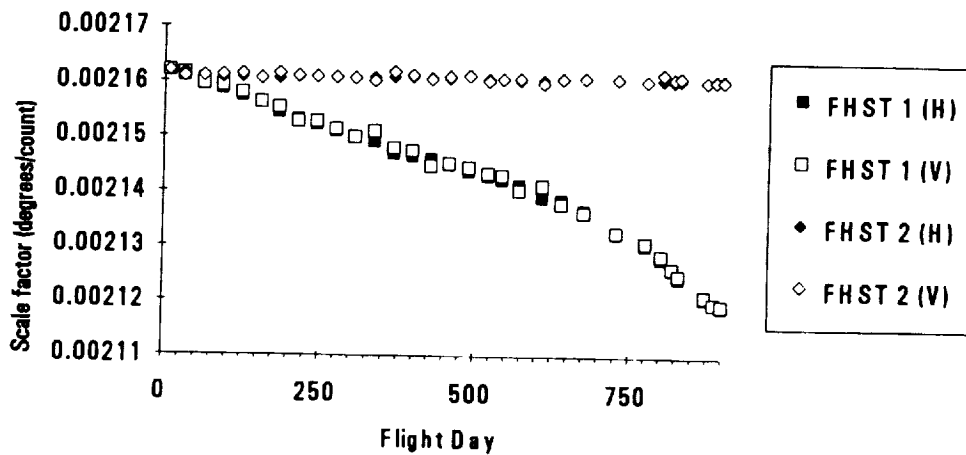


Figure 4. FHST1 Scale Factors Changing with the Flight Day

On flight day 679 (July 21, 1993), new H and V scale factors computed by the FDF were uplinked to UARS by the FOT for use in the onboard computations. This corrected the OBC-computed pitch attitude, as can be seen in Figure 3. This was followed by an uplink of the FHST1 alignment calibration on flight day 709. The alignment and scale factor calibrations were also updated in the ground system on day 709. This resulted in the reduction of the star observation residuals illustrated in Figure 1.

Based on the apparently more rapid degradation of FHST1 seen in Figure 3, the Attitude Operations task began to perform scale factor updates and alignment updates in the ground system more frequently. Figure 1 shows a decrease in FHST1 sensor residuals each time the scale factor was updated on the ground (flight days 817 and 888). Using the current scale factors and alignments in the ground system reveals the attitude error due to use of outdated FHST information in the OBC computations. The operations analysts can then determine when the onboard calibrations need to be updated by comparing the residuals to the OBC attitude estimation requirements.

The success of the corrections made on flight days 679 and 709 along with the increased monitoring has resulted in subsequent uplinks of FHST scale factors and alignments. The procedure is to uplink the scale factors, confirm their corrections by reviewing playback data, and then uplink the alignments a few days later. Uplinks occurred again on flight days 814 and 817. The corrections from these uplinks are not as obvious in the pitch residuals as from the first uplink because the error had not been allowed to grow as large.

## Fine Sun Sensors

The FSS provides two-axis Sun direction information with respect to the sensor axes as FOV parameters  $\alpha$  and  $\beta$ . The sensor consists of two orthogonally mounted single-axis sensor units. Each unit contains two reticles: one coarse and one fine. The reticles are composed of two thin fused silica plates separated by a fused silica spacer. Reticle patterns are located on the insides of the plates. Silicon photocell arrays are located below each reticle, which are used to provide the angle data (Reference 7). The overall accuracy of the FSS is specified to be within 60 arcsec within a 60-deg circular FOV, and 120 arcsec outside the 30-deg FOV.

The FSS residuals were seen to be steadily increasing, prompting calibration of the FSS alignments.

## Methods

The UARS FSS alignment is calibrated using the same Shuster algorithm and at the same time as the FHSTs. The FSS is also calibrated for FOV variations. The FOVCAL system uses the Levenberg-Marquardt method (Reference 13) to solve a nonlinear least-squares model for the calibration coefficients. These coefficients are used in constants in a transfer function to convert the counts to the FOV parameters  $\alpha$  and  $\beta$ . The current operational transfer function was provided by Adcole.

## Results

The UARS FSS alignments have been updated onboard and in the ground system each time the FHST alignments have been uplinked. Figure 5 shows that the RMS residuals for the FSS dropped almost in half due to the new alignment uplink that occurred on flight day 708. However, with the next calibration uplink on flight day 817, the FSS residuals increased back to near the original levels. This indicates that the alignment may be inaccurate. A new FSS alignment was put in the ground system on flight day 888 resulting in reduced residuals.

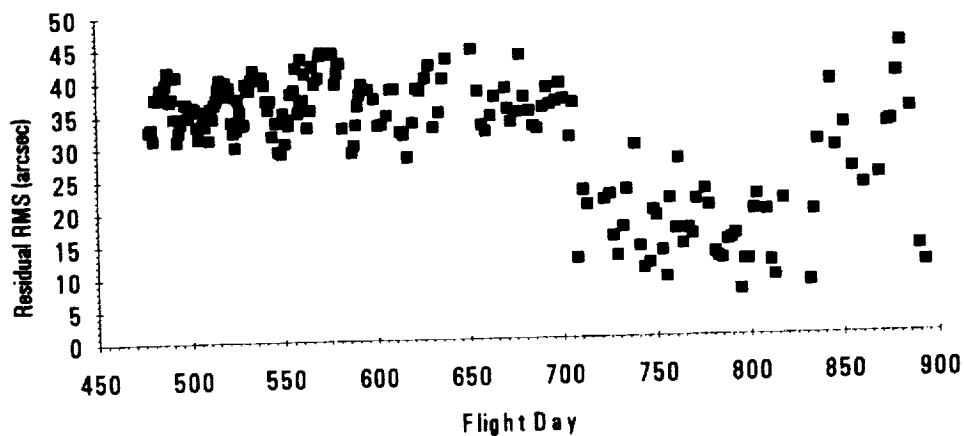


Figure 5. FSS Residuals

The calibration of the FOV coefficients has met with mixed success. The postlaunch on-orbit calibration of the FOV resulted in only a slight improvement over the prelaunch values. Systematic variations of residual magnitudes as a function of the sun's position in the FOV can still be observed even after the postlaunch calibration. As a result, the Sensor Studies task from FDF has undertaken an extensive analysis into this calibration problem (Reference 15).

The original transfer function defined for the FSS involves two equations (one for each axis  $\alpha$  and  $\beta$ ) with nine coefficients each to convert counts to position in the FOV. The Sensor Studies task developed equations with three additional constants for each axis. Initial analysis by the task shows a reduction in  $\alpha$  residuals from an RMS of 73 arcsec to 13, and a reduction in  $\beta$  residuals from 46 arcsec to 15 as reported by Hashmall (Reference 15). Investigation into the possible use of these new transfer function to improve FSS accuracy continues. These results are significant because of the possibility of using the FSS as a replacement for a degraded FHST to maintain the spacecraft attitude within accuracy requirements.

## Gyroscopes

UARS has one attitude rate sensor onboard consisting of a strap down gyro package that measures inertial vehicle rates about the sensor axes. The Teledyne DRIRU II consists of three gyroscopes, each with a spinning rotor mounted on two gimbals to provide two degrees of freedom and rate information along two body axes (two channel output) for a total of six channels of information. This allows the IRU to provide dual redundancy along each body axis. To maintain a null deflection on a given gimbal, a current is required to produce a magnetic torque that is proportional to the angular rate about the corresponding axis of that gimbal. This torque current is converted to a series of pulses, which are counted and reported as accumulated rotation angles. The torque current can also be differenced after small time intervals to generate analog rates.

The IRU can operate in two rate ranges. The high-rate mode allows for rates of up to 2.0 deg/sec; low-rate mode allows for rates of up to 400 arcsec/sec (0.11 deg/sec). The digital resolution of the IRU is 0.8 arcsec in the high-rate mode and 0.05 arcsec in low-rate mode. The specified angular rate bias stability for the DRIRU II is on the order of 0.0012 arcsec/sec over a period of 6 hours and 0.0008 arcsec/sec over a year (References 16 and 17).

ADS computes any unresolved body rates as a gyro bias correction in the state vector. The trends for gyro bias corrections from the CFADS state vector exhibited strong dependencies on UARS flight direction, as shown in Figure 6. A possible source of these bias corrections was a ground system timetagging error discovered through investigation of another problem seen in the ground system processing.

## Methods

The spacecraft angular rate vector is computed from the following equation:

$$\bar{\omega} = [A]([S]\bar{\Omega} - \bar{B})$$

where  $\bar{\omega}$  is the angular rate vector in body coordinates,  $[A]$  is an alignment matrix,  $[S]$  is a diagonal matrix that produces IRU scale factor adjustments,  $\bar{\Omega}$  is the raw unadjusted angular rate vector, and  $\bar{B}$  is a bias vector. The alignment part of the IRU calibration,  $[A]$ , consists of the unit vector of each of the three physical axes. This feature allows the measurement axes to be nonorthogonal. It also incorporates an overall rotation of all three axes. Such a matrix has six degrees of freedom. The transfer function part is parameterized by  $[S]$  and  $\bar{B}$ . The scale factor for each axis of the sensor and the alignment matrix are combined into a single 3-by-3 alignment/scale factor matrix,  $[G] = [A][S]$ . The angular rate vector is then given by

$$\bar{\omega} = [G]\bar{\Omega} - \bar{b}$$

where  $\bar{b} = [A]\bar{B}$ . All nine components of the G matrix can vary independently. Combined with a bias vector, a total of 12 degrees of freedom are to be determined. This is done using an algorithm described by Keat (Reference 10).

Observability in the gyro rates is required for all degrees of freedom solved for in the application of the gyro calibration algorithm. For the calibrations performed by the FDF, nine periods of data spanning three roll offset maneuvers and two yaw maneuvers were used for the gyro calibration. The yaw maneuvers rotate the spacecraft 180 deg. The roll offset maneuvers were first to -5 deg, remained at constant body rates for about 3 hours, then rotated to 5 deg, again remaining at constant body rates for about 3 hours, and finally rotated back to its initial orientation. Calibration was performed with the IRUs at low rate only. The accuracy of the results depends on the accuracy of the ground attitude solutions contained within the timespans of the data used. For this reason, the FHST alignment accuracy impacts the solved for gyro parameters. Additionally, in the ground ADS, the bias correction to the nominal calibration parameters is solved for, and this correction also depends on the star tracker alignments.

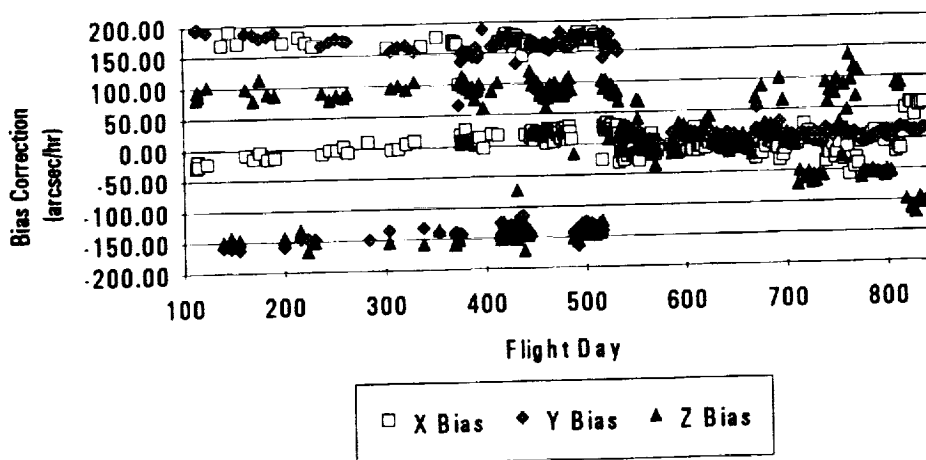
## Results

The most recent calibration accounts for the timetag error. The new calibration was introduced to the system on flight day-553, and the improvement is easily seen in Figure 6. Changes in the nominal spacecraft rotation rate due to yaw maneuvers can couple with inaccuracies in the gyro to star tracker alignment to appear as discontinuities on the bias correction plot. This is clearly seen for times previous to flight day 553. Table 1 shows the change in the gyro parameters from the prelaunch values to the current gyro alignment.

On flight day 709, the alignment for FHST1 was updated, and an increase can be seen in the Z component of the gyro bias corrections. Based on the FHST and FSS residuals, this most likely indicates that the gyro calibration was performed using a tracker alignment that had some inaccuracies. In general, the gyro bias corrections will respond to tracker performance changes (the actual alignment and scale factors change with time) and as to FHST1 alignment updates.

**Table 1. Change in IRU Alignment and Scale Factor Between Prelaunch and In-Flight Calibration**

Alignment Change in arcsec			Percent Change in Scale Factor		
X axis	Y axis	Z axis	X axis	Y axis	Z axis
117	103	109	-0.017	-0.103	-0.081



**Figure 6. UARS Gyro Bias Corrections Versus Flight Day**



## **Solar Stellar Pointing Platform (SSPP) and Platform Sun Sensors**

The SSPP provides pointing for three science instruments. This consists of pointing at the Sun during daytime portions of each orbit for solar observations and pointing toward selected bright stars for calibration during spacecraft night.

The SSPP subsystem includes a two-axis gimbal assembly with redundant drive motors and shaft encoders, a control electronics box, and associated control software in the OBC. The OBC can use data from the one of two PSSs for closed-loop Sun tracking. For star tracking, it is limited to using data derived from OBC attitude knowledge and platform gimbal position encoders. The OBC can also point the platform toward the Sun using onboard ephemerides and attitude knowledge.

Correct pointing of the SSPP is, therefore, dependent on gimbal angle and PSS calibrations, attitude knowledge, and sometimes ephemerides (Reference 1).

### **Method**

The PSS residuals had been approaching the 60 arcsec accuracy limit required for the SSPP science. To improve the PSS accuracy, a gimbal angle calibration was undertaken in November 1993. Unfortunately, this was shortly after the FHST1 alignment of flight day 817. This is the alignment that has not proven well in the sensor trending, and the SSPP results are based on this alignment. Therefore, the PSS calibration was not uplinked and will be redone for the more recent FHST1 alignment, which was proven. The results for this PSS calibration are presented to indicate the expected accuracy that can be achieved by updating the gimbal angle alignment parameters.

The PSS transfer function to convert from counts to the FOV parameters has the same form as the UARS FSS transfer function. The FDF has the capability to calibrate the PSS FOV transfer function; however, the PSS boresights are normally pointed directly at the Sun. Therefore, there has been no need to calibrate across the whole FOV, and no data are available for that purpose.

### **Results**

The initial validation was performed by observing PSS Sun observation residuals obtained using the old calibration parameters to those obtained with the new calibration. This validation was done on six segments of data from the actual calibration timespan, spread out to include three periods each of positive and negative solar beta angles. Timespans and residuals of for the initial validation are listed in Table 2 below. The old calibration solutions show residuals ranging from 18 to 48 arcsec, compared to the residuals from the new calibration, which range from 6 to 20 arcsec.

The calibration was then confirmed by examining residuals for contemporary data that were not used in the actual calibration. The results of this exercise shown in Table 3 confirm that the new calibration is an improvement over the old one.

Finally, data from the beginning of the mission were examined to determine if the errors in the gimbal angles were a result of calibration drift or procedure. The results from this analysis are shown in Table 4. The residuals for the beginning of mission data are comparable to the contemporaneous data, indicating that the improvement is due to calibration procedure. The calibration at the beginning of the mission was performed on data that included only negative beta angles because data for positive beta angles were not available at the time the calibration was needed. This analysis indicates that inclusion of data for one full period of both negative and positive solar beta angles is a better procedure for gimbal angle calibration.

**Table 2. Initial Validation Using Actual Calibration Timespans**

Greenwich Mean Time (YYMMDD.HHMM)	Solar Beta Angle (deg)	Old Calibration (arcsec)	New Calibration (arcsec)
931025.1831 - .1905	2.8	48	20
931106.2232 - .2309	40.0	31	7
931124.1730 - .1804	2.8	33	9
931126.0200 - .0250	-2.8	19	12
931218.1204 - .1256	-75.0	29	6
940104.2105 - .2140	-2.8	18	14

**Table 3. Validation Using Early Mission Data**

Greenwich Mean Time (YYMMDD.HHMM)	Solar Beta Angle (deg)	Old Calibration (arcsec)	New Calibration (arcsec)
911119.1200 - .1400	37.4	35	7
911225.1200 - .1400	-80.4	15	7

**Table 4. Calibration Validation Using Most Recent Data**

Greenwich Mean Time (YYMMDD.HHMM)	Solar Beta Angle (deg)	Old Calibration (arcsec)	New Calibration (arcsec)
931205.0300 - .0500	-40.0	26	5
931215.1130 - .1330	-80.0	37	13
931216.1930 - .2130	-40.0	38	16
940105.1000 - .1200	0.0	17	14
940110.1200 - .1400	18.0	34	6
940121.1200 - .1400	37.0	27	8
940120.1930 - .2130	18.0	31	7
940204.0900 - .1100	1.5	32	8

## Magnetometers

The type of TAM used on UARS consists of three mutually orthogonal, single-axis fluxgate magnetometers. These TAMs measure the strength and the direction of the Earth's magnetic field and can be used to compute magnetic torquing commands to control the spacecraft angular momentum. The magnetic torquing contributes to the ambient magnetic field at the TAM.

The TAMs on UARS are normally considered a backup sensor for safehold situations and do not require highly accurate calibrations. However, some unexplained trends in the magnetic field bias corrections computed by the ADS and the possibility that reasonable attitude accuracy could be provided by the TAMs provided the motivation to improve on the existing TAM calibrations.

## Methods

The calibration algorithm derived by Lerner and Shuster (Reference 11) determines the scale factor/misalignment matrix and biases and the coupling matrix for the influence of the magnetic torquer assembly (MTA) on the TAM. The misalignments, scale factors, and biases are used to convert TAM measurements in the true sensor frame into the MACS

frame and to compensate for static spacecraft magnetic fields. The coupling matrix compensates for the magnetic field due to the MTA.

The TAMCAL utility uses the spacecraft ephemeris and an accurate Earth magnetic field model to compute a reference magnetic field vector each time sensor data are available. It converts the reference field into MACS coordinates using the spacecraft attitude at that time. It performs a least squares minimization of the difference between the measured and reference magnetic fields with reference to the parameters to be determined.

To compute the alignment and scale factor matrix, TAM calibration requires an FHST-determined attitude and adjusted TAM data. The OBC-computed attitude was considered to be sufficiently accurate. The calibration data were taken over a 12-hour span in which UARS performed a yaw maneuver to obtain good observability of the magnetic field. However, the MTA data were not available for analysis in the ground system. Therefore, the coupling matrix could not be determined.

## Results

The calibration was first examined by computing a fine attitude using the FHSTs and gyros in the ADS batch least squares algorithm, with the magnetometer measurements included in the processing but weighted so that they did not influence the attitude. This allows a good estimate of the residuals for the TAM measurements to be obtained. The variances and RMS residuals for the calibrated and nominally aligned and unbiased TAMs are in Table 5. These results show improvement for the calibration primarily in the spread of the residuals, as shown by the variances.

The attitude accuracy obtainable from the calibrations was then examined. The TAMs and gyros were used to compute attitudes that were then validated against the attitude obtained using the FHSTs. The RMS and maximum errors for the attitudes computed from the calibrated and nominally aligned and unbiased TAMs are in Table 6. TAM2 again shows the most improvement, but using the current calibration, it is not capable of determining the attitude as well as TAM1, as would be expected from the results shown in Table 5.

These results also indicate that the calibration was not significantly affected by magnetic torquer activity. This is probably due to the influence of the magnetic torquers being small.

**Table 5. Magnetometer Measurement Residuals and Variances**

Magnetometers	Variance (mG) for Spacecraft Axis			Residual RMS (mG)
	X axis	Y axis	Z axis	
TAM1, Nominal	23	8	27	3
TAM1, Calibrated	9	7	8	2
TAM2, Nominal	21	18	57	4
TAM2, Calibrated	17	8	26	3

**Table 6. Residuals From Magnetometer-Only Attitudes**

Magnetometer	Residual RMS, deg for Spacecraft Axis			Maximum residual, deg for Spacecraft Axis		
	X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis
TAM1, Nominal	0.5437	0.3030	0.6571	0.7920	-0.5569	1.033
TAM1, Calibrated	0.1958	0.0589	0.0767	0.2368	-0.0761	0.1166
TAM2, Nominal	1.0180	0.9175	2.2140	-1.623	1.792	3.010
TAM2, Calibrated	0.3170	0.1101	0.3113	0.6031	0.2153	0.5009

## Earth Sensors

Earth sensor data are received in telemetry as roll and pitch angles. These angles are computed onboard using a model based on a round Earth with UARS assumed to be flying at 600 km altitude. This model varies significantly with reality: the Earth is not perfectly round and UARS does not constantly fly at 600 km. Furthermore, the ESAs trigger on the infrared horizon of the Earth, which varies from the solid Earth horizon in a complex way. The ground system modeling for adjustment of ESA data currently accounts for Earth oblateness and non-nominal altitudes. It is being modified to account for radiance effects from the Earth's infrared horizon. A complete analysis of the ESA behavior will be performed and presented later in another paper after the ground system modeling is satisfactory.

## Conclusion

Monitoring attitude sensor data is critical for the success of the UARS mission. Maintaining a database of sensor and attitude data parameters derived from ground system processing is a valuable aid in monitoring long-term trends. The ground system must be kept as error free and as well calibrated as possible to properly reveal problems in the trends. The trend data must be carefully interpreted to derive the correct meaning.

The scale factor drift problem in FHST1 was revealed through the increasing residuals for the star observations. A corresponding trend was also seen in the OBC pitch axis attitude estimation error. FDF has devised procedures that are currently sufficient to compensate for this sensor problem. However, an FHST onboard the Gamma Ray Observatory (GRO) has exhibited erratic behavior in scale factor drift (Reference 18). The scale factor for this sensor increased rapidly, and then returned to a constant, stable value. The return to a constant value is encouraging, but FDF must carefully monitor the FHST for any rapid changes in the scale factor.

The results of the Sensor Studies task (Reference 15) may allow replacement of the FHST by the FSS should the FHST fail. The FDF will continue working to improve the attitude accuracy attainable from the UARS attitude sensors.

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