Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF) Calibration Of The Upper Atmosphere Research Satellite (UARS) Sensors*

N93-24733

S39-19

154737

p. 9

J. Hashmall
COMPUTER SCIENCES CORPORATION (CSC)

J. Garrick
GODDARD SPACE FLIGHT CENTER (GSFC)

ABSTRACT

Flight Dynamics Facility (FDF) responsibilities for calibration of Upper Atmosphere Research Satellite (UARS) sensors included alignment calibration of the fixed-head star trackers (FHSTs) and the fine Sun sensor (FSS), determination of misalignments and scale factors for the inertial reference units (IRUs), determination of biases for the three-axis magnetometers (TAMs) and Earth sensor assemblies (ESAs), determination of gimbal misalignments of the Solar/Stellar Pointing Platform (SSPP), and field-of-view calibration for the FSSs mounted both on the Modular Attitude Control System (MACS) and on the SSPP. The calibrations, which used a combination of new and established algorithms, gave excellent results.

Alignment calibration results markedly improved the accuracy of both ground and onboard Computer (OBC) attitude determination. IRU calibration results allowed UARS to identify stars in the period immediately after yaw maneuvers, removing the delay required for the OBC to reacquire its fine pointing attitude mode. SSPP calibration considerably improved the pointing accuracy of the attached science instrument package.

This paper presents a summary of the methods used and the results of all FDF UARS sensor calibration.

* This work was supported by the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center (GSFC), Greenbelt, Maryland, Contract NAS 5-31500.

PRECEDING PAGE BLANK NOT FILMED

PAGE 564 INTENTIONALLY BLANK

1. INTRODUCTION

The Upper Atmosphere Research Satellite (UARS) was launched on September 12, 1992, aboard the Space Shuttle Discovery on a mission to investigate the chemistry of the Earth's upper atmosphere. It was equipped with a variety of sensors, most of which would be aimed at the edge of the atmosphere, at precise heights above the surface. To achieve the required science instrument pointing precision, the UARS attitude knowledge was required to have a small uncertainty—less than 60 arcseconds (3σ).

UARS uses two fixed-head star trackers (FHSTs) as primary attitude sensors. It propagates attitudes using two inertial reference units (IRUs) (primary and backup channels on each axis). It also has one fine Sun sensor (FSS) with a 64-degree square field of view (FOV) as a backup fine attitude sensor, and a second FSS with a 4-degree square FOV, mounted on the Solar/Stellar Pointing Platform (SSPP) as a reference sensor for the science instruments mounted on that platform. For coarse attitude sensors it has two three-axis magnetometers (TAMs), two coarse Sun sensors (CSSs), and two Earth sensor assemblies (ESAs). These last are used primarily for acquiring Earth pointing attitude prior to fine pointing.

UARS travels in a near circular orbit with an inclination of about 57 degrees. Its attitude rotates at 1 revolution per orbit (RPO) about an axis approximately parallel to the orbit normal. Consequently, the UARS body maintains an attitude that is nearly fixed with respect to the Earth.

The UARS orbital plane precesses about 4 degrees a day, which has two effects of consequence for calibration. As the solar β angle (the angle between the Sun vector and the orbit normal) changes, the apparent path of the Sun through the FSS FOV changes, moving from below one edge (outside the FOV) to near the other. In addition, as the orbit plane precesses, the Sun moves from one side of the spacecraft to the other. At about 6-week intervals, UARS is commanded to yaw 180 degrees in order to maintain the Sun on one side of the spacecraft.

The Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF) helped satisfy the UARS attitude knowledge accuracy requirement by performing on-orbit calibration of the attitude sensors, and also supported the UARS mission with two other calibrations. The major on-orbit calibrations that were performed included

- Determination of the misalignments of the FHSTs and FSS and determination of the coefficients in the FSS FOV transfer function, which converts detected sensor counts to Sun position angles. Determination of the misalignments and FOV coefficients was intended to improve the spacecraft attitude accuracy.

- Determination of the IRU misalignments, scale factors, and biases. Determination of these values was intended to improve the propagation of UARS attitude through maneuvers, allowing the onboard computer (OBC) to converge on an attitude rapidly after maneuvers.

- Determination of the SSPP gimbal misalignments and FOV coefficients for the FSS mounted on the SSPP. Determination of these quantities was intended to improve the pointing accuracy of the science instruments mounted on the SSPP and coaligned with the platform FSS.

In addition, biases for the ESA and TAMs were determined, but the values determined in these calibrations were small enough that the impact of their use was considered unimportant to the mission and the values have not yet been transmitted to the spacecraft.

2. ALIGNMENT CALIBRATION

Alignment calibration is intended to determine the true pointing directions of the attitude sensors. Sensor alignments are determined before launch, but removal of gravitational load and vibrations during launch shift the alignments, making it necessary to redetermine sensor alignments on orbit.

The alignment calibrations were performed using Shuster's algorithm with a postprocessing step added to minimize variation of the mean OBC attitude. The methods used do not require accurate attitude knowledge to yield accurate alignments.

Shuster's algorithm minimizes a loss function that contains two types of terms. The first type represents differences in the angles between simultaneously measured observation vectors and the angles between corresponding reference vectors. The second type represents differences between modeled alignments and those measured before launch. This second term allows determination of the three degrees of freedom that cannot be resolved using sensor data alone. The method resolves these indeterminate degrees of freedom by minimizing these terms.

After launch, the UARS scientific instruments were calibrated by the UARS scientists using the OBC attitude as a reference. The scientists requested that when the FDF calibration values were uplinked, the OBC attitude should change as little as possible so that the science instrument calibration would remain valid. To accommodate the scientists, an algorithm was developed to maintain a reference frame that would not change as the alignments were changed.

The UARS OBC attitude is determined using a Kalman filter with FHST data as attitude input. Data are used alternately from the two FHSTs, with the FHST selected changing frequently compared to the time constant of the Kalman filter. On the average, the attitude reference is the mean of the two FHST boresights. At any time, however, the OBC attitude will deviate from this toward the direction of misalignment of the particular FHST currently used as a reference. During periods when few stars appear in the FHSTs, the deviation will be especially evident because it is more likely that there will be no observations in one of the trackers for a considerable period of time.

To minimize the deviations from the true attitude while keeping the mean attitude independent of calibration, the following three orthonormal vectors were established as the basis of a mean boresight reference frame defined by the nominal FHST boresights:

$$\hat{X} = \frac{\vec{B}_1 + \vec{B}_2}{|\vec{B}_1 + \vec{B}_2|} \qquad \hat{Y} = \frac{\vec{B}_1 \times \vec{B}_2}{\vec{B}_1 \times \vec{B}_2} \qquad \hat{Z} = \hat{X} \times \hat{Y} \tag{2}$$

where $\vec{B}_1$ and $\vec{B}_2$ represent the FHST boresight vectors in the nominal body frame.

A matrix **M** is constructed with the rows composed of the three vectors:

$$M = \begin{bmatrix} \vec{X}^T \\ \vec{Y}^T \\ \vec{Z}^T \end{bmatrix} \tag{3}$$

M transforms vectors in the nominal body frame to corresponding vectors in the mean boresight frame.

Any subsequent FHST alignment calibration generates misalignment matrixes and corresponding misaligned boresight vectors $\vec{B}'_1$ and $\vec{B}'_2$. A new matrix **M'** can be constructed from these vectors using equations 1 and 2. The matrix which transforms **M'** into **M** was determined and used to correct the misalignments of all sensors so that their mean FHST frame remained invariant.

Three periods of data were used for alignment calibration of the FHSTs and FSS. Each period started when the Sun entered the FSS FOV in one orbit and ended when the Sun left the FSS FOV in the next orbit. Initially, data were used from shortly after deployment, when the solar β angle resulted in the path of the Sun through the FSS FOV being near its edge.

Before alignment calibration results were accepted, data became available from a period about 3 weeks after deployment, at which time the Sun passed near the center of the FSS FOV. Use of data from this period was expected to improve the FSS alignment accuracy because the FSS FOV transfer function is significantly less accurate at the edges of the FOV than at its center. For this reason, about three orbits (320 minutes) of data from this period were processed for calibration. As anticipated, this second calibration yielded FHST misalignments that were almost identical to the first, but yielded somewhat improved FSS misalignments. The new misalignment matrixes were chosen as the calibration baseline and transmitted to the OBC.

FHST alignments were determined first, followed by determination of FSS alignments using artificially high weights to the FHST observations so that their misalignments would not be altered by the addition of FSS data. The resulting misalignments were transformed to maintain an invariant mean boresight.

The determined angular deviations of the sensor boresights are summarized in Table 1.

Table 1. Determined Misalignment Magnitude of Sensor "Boresights"

SENSOR	MISALIGNMENT (ARC-SECONDS)
FHST1	62
FHST2	62
FSS	417

The large value of the FSS boresight shift was realistic. This sensor's alignment had been measured before launch, but the sensor had subsequently been removed from the spacecraft and remounted without redetermining the alignment.

The principal validation of the misalignment calibration was achieved by computing fine attitude solutions using sensor data with and without application of the determined misalignments. The attitude solutions were taken for periods of about one orbit with times different from the times of the data used for calibration. In FSS validation, the weight of the FSS observations was set to a small value so the attitudes determined were exclusively FHST based.

Residuals between observed and reference sensor observation vectors from the two solutions were compared. For all three sensors the results were as expected: the mean of the observation residuals moved toward zero and the dispersion about the mean decreased.

These validation results are summarized in Table 2.

An attempt was also made to verify that attitudes determined after calibration and rotated to maintain an invariant mean boresight frame would not change, on the average, from the attitudes computed with uncalibrated sensors. To achieve this goal, attitudes were calculated for a one-orbit period using the same sensor data but using the pre- and postcalibration alignments. These attitudes were compared at epoch and at 5-second intervals throughout the orbit. Table 3 presents the RMS attitude change at 5-second intervals, the attitude change at epoch, and the maximum attitude change found.

Table 2. Sensor Residuals Before and After Calibration

CASE	RMS RESIDUAL (ARC-SECONDS)		
SENSOR	FHST1	FHST2	FSS
PRELAUNCH ALIGNMENTS	26.8	25.27	250
FDF ALIGNMENTS	6.17	6.35	32.8

Table 3. Attitude Change Due To Calibration (arc-seconds)

	YAW	ROLL	PITCH
RMS CHANGE	14	13	6
CHANGE AT EPOCH	11	5	3
MAXIMUM CHANGE	25	20	13

When the misalignments were uplinked to the OBC the results were dramatic. Neither the flight operations team (FOT) nor the project scientists detected any attitude shift, but the OBC attitude sensor residuals decreased by an order of magnitude. The attitude pointing knowledge improved from barely meeting requirements to exceeding them by about a factor of 3.

3. IRU CALIBRATION

Calibration of the UARS IRUs was intended to allow precise propagation of attitudes during intervals when no attitude sensor measurements are available and therefore minimize differences between calculated OBC attitudes and true values. Calibration consists of determining a bias vector $\vec{b}$ and a matrix G. The corrected rate vector, $\vec{\omega}_{c'}$, is related to the observed rate vector, $\vec{\omega}_{o'}$, by

$$\vec{\omega}_c = G\,(\vec{\omega}_o - \vec{b}) \qquad (4)$$

Because the IRUs three axes behave as separate rate sensors, their misalignments are independent. It follows that the G matrix need not be orthogonal. It is also customary to multiply each column of the G matrix by an independent scale factor, so the G matrix need not be normal.

During periods with spacecraft motions at constant angular velocities, errors in the alignment cannot be separated from biases. The misalignment projects components of each axis' constant angular velocity onto other axes, resulting in a constant contribution to the other axes' biases. Both the OBC and ground attitude determination systems solve for IRU biases along with attitudes, so as long as the spacecraft has negligible angular acceleration, IRU misalignments result in very small attitude errors.

In order to separate biases from misalignments and scale factors, data for calibration must include maneuvers during which the rates about the axes change. Ideally, at least three maneuvers would be used, each containing an acceleration about one of the axes and an eventual return to the original velocity. Maneuvers in which the spacecraft slews by 90 degrees around a single body axis should yield the best results.

Because of UARS mission constraints, no pitch maneuvers were performed. Data for calibration were taken during a normal mission yaw maneuver (180 degrees) and a special roll maneuver in which the spacecraft was rolled by 10 degrees, and after a period at this attitude, rolled back to its nominal attitude. During both maneuvers the pitch rate was maintained at its nominal 1 RPO value. IRU calibration was performed using intervals of data, each starting just before a maneuver and ending just after. The roll forward and roll back were treated as separate maneuvers. In addition, intervals of data containing no maneuvers were used. In all, more than 600 minutes of IRU data were used for calibration.

The calibration algorithm requires an accurate attitude at the start and end of each calibration interval. These attitudes were determined using FHST data in the periods before and after each maneuver while the spacecraft angular velocities were constant. The epochs of each attitude solution were set at an end of one of the calibration intervals.

If IRU data are used to propagate the spacecraft attitude from an epoch at the start of each interval to one at the end, the difference between the propagated attitude at the second epoch and the attitude determined at the same epoch from sensor data will depend chiefly on the errors in IRU misalignments, scale factors, and biases. The calibration software determines the least-squares minimum deviation of these attitudes over a number of such intervals. Note that for the least-squares process each interval corresponds to only three observations – one for each axis – so that for the small number of maneuvers used, the solution is not much more than minimally determined.

The results of the IRU calibration are shown in Table 4. In this table, the change in direction of each IRU axis and the scale factor corresponding to the axis are given.

Calibration results were validated by determining the accuracy of propagation for the second normal mission yaw maneuver – a maneuver that was not used in the calibration itself. Data from before and after but not during this maneuver were processed to produce accurate attitudes with epochs immediately before and after the maneuver. The attitudes were then propagated through the maneuver using pre- and postcalibration IRU parameters. The attitude differences between the attitude solutions and the propagated attitudes are shown in Table 5.

The mission consequences of IRU calibration were significant. At the end of the first scheduled yaw maneuver, the spacecraft attitude (propagated onboard from premaneuver solutions) was sufficiently far from the actual attitude (> 0.2 degree) that the OBC could not identify stars. The spacecraft dropped out of fine pointing mode and had to use the ESAs to establish sufficient attitude accuracy to resume normal operations. The IRU calibration parameters were uplinked before the second scheduled yaw maneuver, and fine pointing was never lost throughout the maneuver.

Table 4. Changes of IRU Parameters Due To Calibration

AXIS	POSTCALIBRATION SCALE FACTORS (UNITLESS)	ALIGNMENT CHANGE (ARC-SECONDS)
X	0.999818	79.7
Y	0.999144	88.5
Z	0.999057	310.8

Table 5. Propagation Errors (degrees)

AXIS	BEFORE CALIBRATION	AFTER CALIBRATION
YAW	0.087	0.010
ROLL	0.132	0.044
PITCH	0.081	0.045
TOTAL (RSS)	0.178	0.065

4. SSPP CALIBRATION

Several of the scientific instruments on UARS are mounted on the SSPP. This platform is attached to the spacecraft through two nominally orthogonal gimbals, which are normally rotated to follow the Sun. The platform may also be driven to track a star. An FSS (called the platform Sun sensor – PSS) is mounted on the SSPP, and the scientific instruments are aligned relative to it.

The alignment of the platform was parameterized and solved as two misalignment matrixes and an intergimbal misalignment angle. The matrixes, $M_{\beta S}$ and $M_{M\alpha}$, represent misalignments from the PSS boresight to the β (or outer) gimbal and from the α (or inner) gimbal to the body frame. The intergimbal angle,

γ, is the rotation of the β gimbal axis from the α gimbal axis about an axis perpendicular to both. Since the α and β gimbals are nominally aligned (at index) to rotate about the Y- and X-axes respectively, the intergimbal rotation is about the Z-axis.

An observed Sun vector, $\hat{S}_{obs}$, may be transformed into GCI, by

$$\hat{S}_{gci} = AM_{M\alpha}M_2(\alpha)M_3(\gamma)M_1(\beta)M_{\beta S}\hat{S}_{obs} \tag{5}$$

where A is the attitude matrix and $M_2(\alpha)$, $M_1(\beta)$, and $M_3(\gamma)$ are rotation angles about single euler axes by the angles α, β, and γ. $M_{\beta S}$ and $M_{M\alpha}$ are represented as functions of two misalignment vectors, $\vec{\delta}$ and $\vec{\varepsilon}$ by:

$$M_{\beta S} \text{ or } M_{M\alpha} = I\cos(\theta) + (1 - \cos(\theta))\,\hat{\theta}\hat{\theta}^T - \sin(\theta)[\theta] \tag{6}$$

where I is an identity matrix and

$$\vec{\theta} = \vec{\varepsilon} \text{ or } \vec{\delta}$$

$$\theta = |\vec{\theta}|$$

$$\hat{\theta} = \frac{\vec{\theta}}{|\vec{\theta}|}$$

$$[\theta] = \begin{bmatrix} 0 & -\theta_z & \theta_y \\ \theta_z & 0 & -\theta_x \\ -\theta_y & \theta_x & 0 \end{bmatrix}$$

The gimbal rotation angles α and β, and information that can be converted into a Sun vector in the sensor frame are available from telemetry, the attitude can be computed from other sensor data (FHSTs), and the true Sun position can be obtained from known ephemerides, so the difference between observed and reference Sun vectors depends only on the unknown misalignment parameters $\vec{\delta}$, $\vec{\varepsilon}$, and γ. The calibration software minimizes the least-squares residuals with respect to a state vector containing the elements of the two misalignment vectors and the intergimbal misalignment angle.

Data for calibration were taken over a period of 15 days, using one orbit per day. The spacecraft solar β angle changed through most of its possible range during this period, so the data spanned almost the full range of gimbal angles.

Prelaunch analysis had shown that a large amount of data would be needed for resolving the partial correlations among the SSPP alignment parameters. Even with the large amount of data used, the parameter corresponding to a rotational misalignment around the β gimbal Z-axis could not be properly determined. This parameter correlates with a rotation about the PSS boresight. Since the PSS tracks the Sun, its boresight is always near the center of the FOV and rotations about it are not easily distinguished.

This problem was resolved by using additional data from a science instrument calibration maneuver (for SOLSTICE and SUSIM). During this maneuver, the PSS was slewed to follow a path where the Sun was tracked at a 1-degree offset from the center of the FOV. Several slews were performed so that the Sun position was maintained 1 degree on either side of both axes.

The seven alignment parameters and their uncertainties are presented in Table 6. This table also contains the RMS difference between Sun vectors, computed using these misalignments, and reference Sun vectors. The largest uncertainty is about the Z-axis of the β gimbal, but this uncertainty is greatly reduced from the value of 1.656 degrees obtained using all data except that from the maneuver.

Table 6. Comparison of SSPP Alignments

VARIABLE	VALUE ± UNCERTAINTY (DEG)
Rotation around α gimbal X-axis	-0.036 ± 0.001
Rotation around α gimbal Y-axis	-0.125 ± 0.005
Rotation around α gimbal Z-axis	0.072 ± 0.001
Rotation around β gimbal X-axis	-0.026 ± 0.001
Rotation around β gimbal Y-axis	0.030 ± 0.005
Rotation around β gimbal Z-axis	-0.035 ± 0.012
Intergimbal angle	0.001 ± 0.003
RMS Attitude Residuals (deg)	0.0048

The RMS error is an order of magnitude reduced from the value of 0.0535 degree obtained using prelaunch alignments.

Determination of the gimbal alignments greatly improved the pointing accuracy of the SSPP instruments. The improvement as a function of the two gimbal angles is shown in Figure 1.

5. FOV CALIBRATION

FOV calibration consists of determining the coefficients of the transfer function that converts the digitized FSS signal into angles. This function, supplied by the FSS manufacturer, is of the form

$$\phi = a_0 + \tan^{-1}\left(a_1 + a_2 N + a_3 \sin\left(a_4 N + a_5\right) + a_6 \sin\left(a_7 N + a_8\right)\right) \tag{7}$$

where ϕ is one of the desired angles (α or β), N is the digitized signal, and a_i is the set of coefficients. The axes are treated as entirely independent, and separate sets of coefficients are solved for each.

Calibration was performed both for the FSS mounted on the MACS and the PSS. These calibrations were performed only after the alignments had been determined. For the FSS, data from a period of about 2 weeks were needed to ensure that Sun observations from the entire FOV were used. For the PSS, since the PSS normally tracks the Sun, the only data that could be used were those from the SOLSTICE/SUSIM calibration maneuver described above.

The FSS FOV calibration resulted in coefficients that were only slightly changed from their ground-measured value. The sensor residuals determined using these coefficients were very slightly lower than those before calibration, and were not loaded into the OBC.

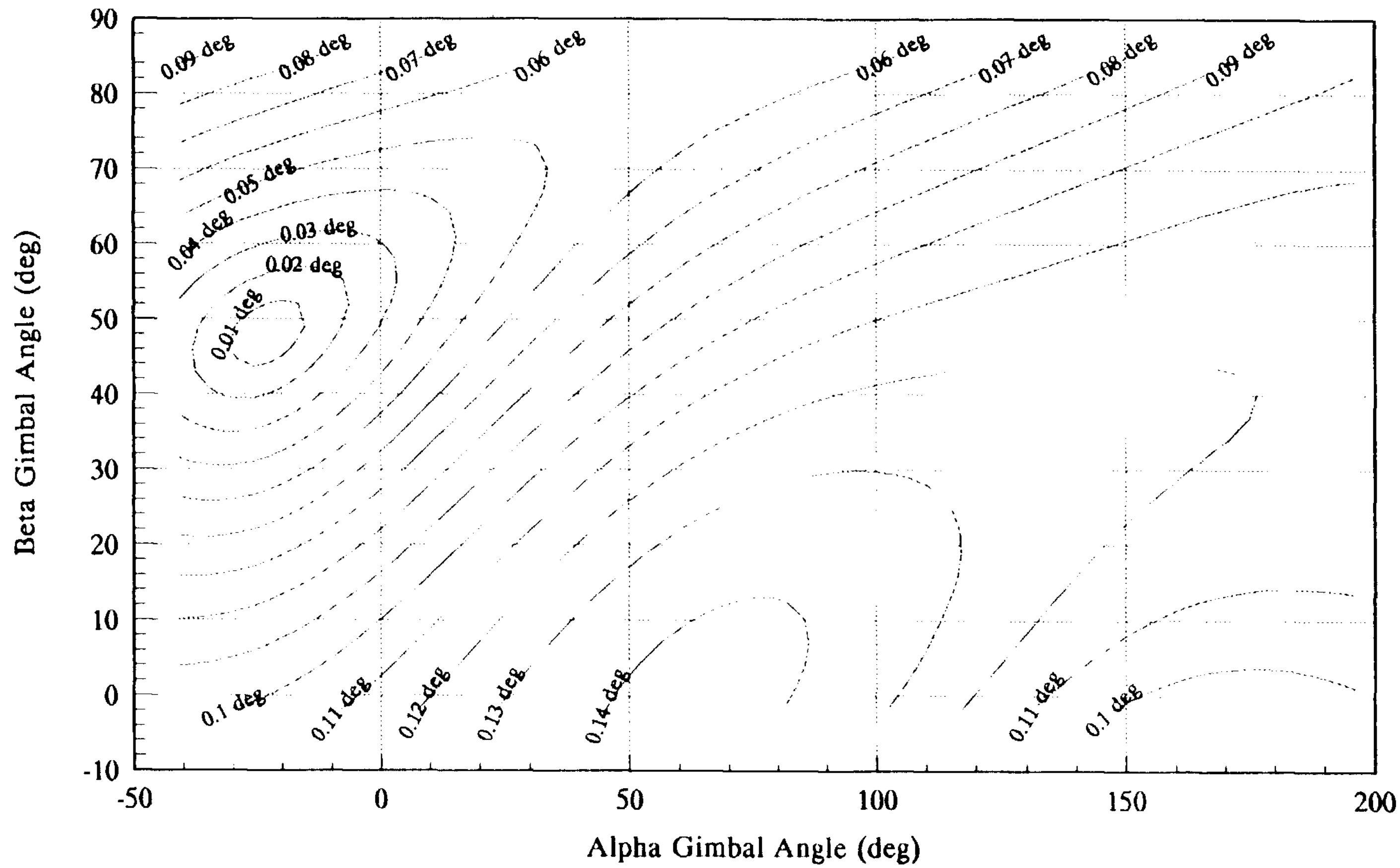
The PSS calibrations showed a somewhat larger change, and sensor residuals decreased from 12.2 to 8.8 arc-seconds for Sun measurements at the center of the FOV and from 15.0 to 12.2 arc-seconds for all measurements during the offset maneuver. These improvements were considered too small to merit uplink of the new coefficients.

6. CONCLUSIONS

Overall, the calibration of the UARS attitude sensors produced a marked increase in the accuracy of both ground- and OBC-determined attitudes. The pointing accuracy of the UARS science instruments was increased correspondingly, enhancing the attainable precision of scientific studies of upper atmosphere chemistry.

Over the life of the mission, the FDF will regularly monitor sensor calibration and is prepared to recalibrate any sensors that drift as the spacecraft ages.

UARS SSPP ALIGNMENT



Contour Plot of SSPP pointing error (deg) as a function of Gimbal Angle

Figure 1. SSPP Gimbal Alignment Corrections