Real-Time Attitude Determination and Gyro Calibration*

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ABSTRACT

We present results for two real-time filters prototyped for the Compton Gamma Ray Observatory (GRO), the Extreme Ultraviolet Explorer (EUVE), the Cosmic Background Explorer (COBE), and the next generation of Geostationary Operational Environmental Satellites (GOES). Both real and simulated data were used to solve for attitude and gyro biases. These filters promise advantages over single-frame and batch methods for missions like GOES, where startup and transfer-orbit operations require quick knowledge of attitude and gyro biases.

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1. INTRODUCTION

Mishaps of the distant past have prevented sequential filters from becoming part of the operational ground support systems in the Flight Dynamics Facility (FDF). Experience gained over the past few years with prototype filters for several spacecraft, however, bolsters the conviction that sequential filters have a place in real-time attitude and gyro bias estimation in the FDF.

Two very different filters, filter QUEST and the Real-Time Sequential Filter (RTSF), both show themselves to be reliable alternatives to the original single-frame QUEST for real-time systems. As long as attitude is continuously observable, divergence does not appear to be a problem, and the filters work over a wide range of tuning parameter values.

This article provides an account of recent attitude and gyro bias filtering experience using data from COBE, GOES, GRO, and EUVE. The filters perform well and provide attitude and gyro bias solutions in less time than would be necessary to obtain a batch estimate.

2. FILTER QUEST

Filter QUEST is a sequential version of the q-algorithm as implemented in the widely used QUEST software (Reference 1). The q-algorithm only estimates attitude, but for the sake of accuracy, it is almost essential that gyro biases be estimated as well. In order to make filter QUEST satisfy the demand for gyro biases, a bias filter was added to run in parallel with the attitude filter.

The bias filter takes the attitude predicted using gyro measurements $\bar{q}(-)$ and compares it to the attitude updated using sensor measurements $\bar{q}(+)$. First, the difference between the two attitude quaternions is computed:

$$\Delta\bar{q} = \begin{bmatrix} \Delta q_1 \\ \Delta q_2 \\ \Delta q_3 \\ \Delta q_4 \end{bmatrix} = \begin{bmatrix} q(-)_4 & q(-)_3 & -q(-)_2 & q(-)_1 \\ -q(-)_3 & q(-)_4 & q(-)_1 & q(-)_2 \\ q(-)_2 & -q(-)_1 & q(-)_4 & q(-)_3 \\ -q(-)_1 & -q(-)_2 & -q(-)_3 & q(-)_4 \end{bmatrix} \begin{bmatrix} -q(+)_1 \\ -q(+)_2 \\ -q(+)_3 \\ q(+)_4 \end{bmatrix} \tag{1}$$

Then, this difference is transformed into a rotation vector $\Delta\vec{a}$ and divided by the time step Δt to provide an observation of the gyro bias $\Delta\vec{b}$:

$$\Delta\vec{a} = \frac{2\,\text{atan2}\left(\sqrt{\Delta q_1^2 + \Delta q_2^2 + \Delta q_3^2}, \Delta q_4\right)}{\sqrt{\Delta q_1^2 + \Delta q_2^2 + \Delta q_3^2}} \begin{bmatrix} \Delta q_1 \\ \Delta q_2 \\ \Delta q_3 \end{bmatrix} \tag{2}$$

These observations are averaged using the same fading memory parameter, α, as is used for the attitude (Reference 2). The fading memory parameter is a scalar between 0 and 1.

$$\vec{b}_n = \vec{b}_{n-1} + (1 - \alpha)\frac{\Delta\vec{a}_n}{\Delta t} \tag{3}$$

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The enhanced filter QUEST was originally applied to COBE where the spin (X-axis) gyro bias is of primary concern. The COBE Fine Attitude Determination System (FADS) found the X-axis gyro bias to be 14.4 degrees per hour (deg/hr) for these data. Figure 1 through Figure 3 show the filter QUEST bias solutions for different values of α. An initial bias value of 0 deg/hr was used. Figure 1 shows that α equal to 0.9 is too low to filter out sensor noise. In Figure 2, the bias converges to within 1 deg/hr of the FADS bias in only 6 minutes. Setting α to 0.999 as in Figure 3 further reduces the noise but slows convergence.

Figure 4 differs from the preceding figures in that the initial bias is close to the correct value. Filter QUEST with α equal to 0.999 shows variation in the estimated bias. The COBE X-axis gyro is known to be temperature sensitive, and the enhanced filter QUEST may be useful in studying this sensitivity.

The COBE solutions were obtained by replacing the standard QUEST subroutines in the Coarse Attitude Determination Subsystem (CADS) with the new filter QUEST subroutines. All the data were synchronized in the Data Adjuster Subsystem (DA), and every data point was processed. The filter is updated every half-second.

Filter QUEST has also been tested with simulated data for GOES. In this case, the standard QUEST routines were replaced with their filter counterparts in the Real-Time Attitude Determination System (RTADS). There, at most one data point can be processed for every 8 seconds (sec) of data, and the different data types may come from any time in that interval. These attributes of RTADS are clearly undesirable, but there has not yet been time to change them.

Nonetheless, Figure 5 shows the filter QUEST roll and pitch bias solutions converging over the course of 15 minutes (yaw is similar). The data were simulated to reproduce that expected during the GOES transfer orbit but without systematic errors other than gyro biases. The filter was started from initial estimates of 0 deg/hr and was given an α value of 0.9999, which should slow the convergence. There are initial transients and oscillations in the bias solutions, but even with the less than ideal RTADS preprocessing and a fairly short data span, biases approach the batch estimated values. The filter solutions are within 10% for yaw, 30% for pitch, and 40% for roll.

3. RTSF

The RTSF is a scaled-down version of the extended Kalman filter originally prototyped for the Earth Radiation Budget Satellite (ERBS) (References 3 and 4). Whereas the 37-component state vector of the ERBS filter included various sensor misalignments and scale factors, the RTSF estimates a 7-component state vector consisting of the attitude quaternion and the three components of the gyro bias (Reference 5). The objective of the present study is to evaluate the RTSF in a real-time situation with its attendant data processing problems. To this end, we integrated the RTSF into current real-time attitude determination software and evaluated it using real telemetry data from GRO and simulated data from EUVE.

The theory of the filter has been presented elsewhere (References 3 and 4) and will not be repeated here, except to note that the GRO RTSF updates the attitude quaternion using a multiplicative method. Thus, if (ϕ, Ω, μ) are three small Euler angles representing corrections to the attitude estimate, the corresponding correction to the quaternion is specified by

$$\delta \vec{q} = \begin{bmatrix} \phi/2 \\ \Omega/2 \\ \mu/2 \\ 1 \end{bmatrix} \tag{4}$$
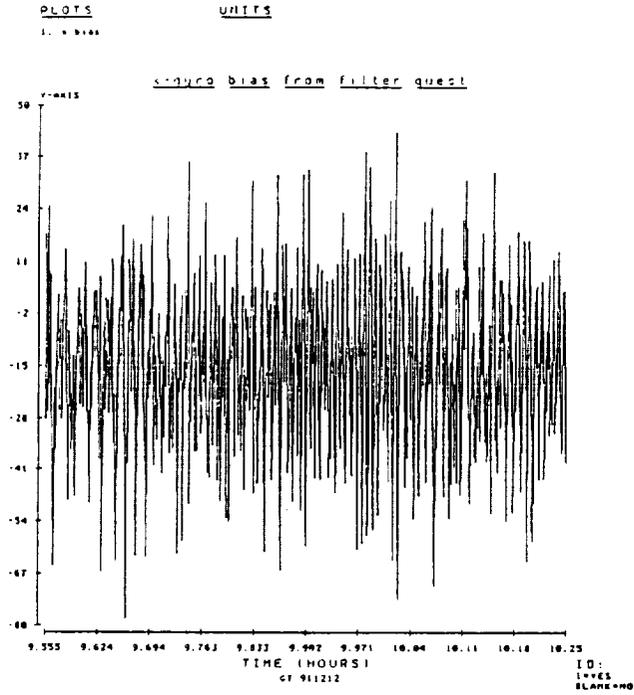
Figure 1. Filter QUEST Gyro Bias Fading Memory Equal to 0.9
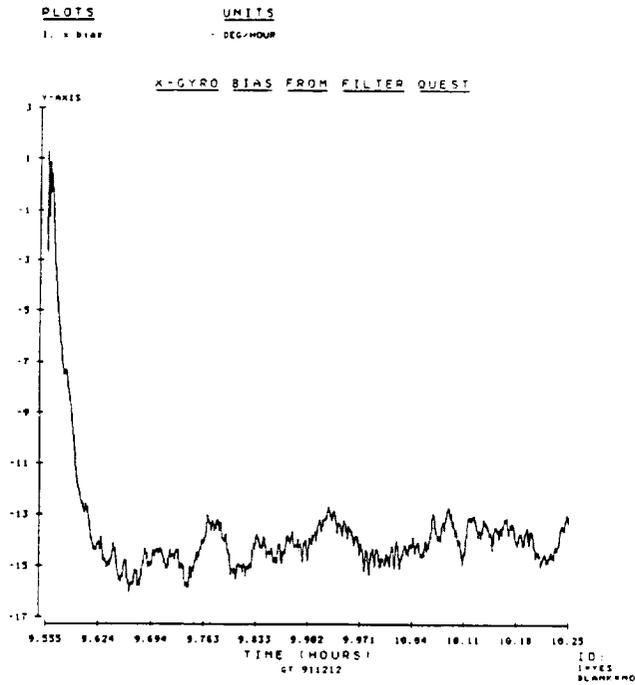
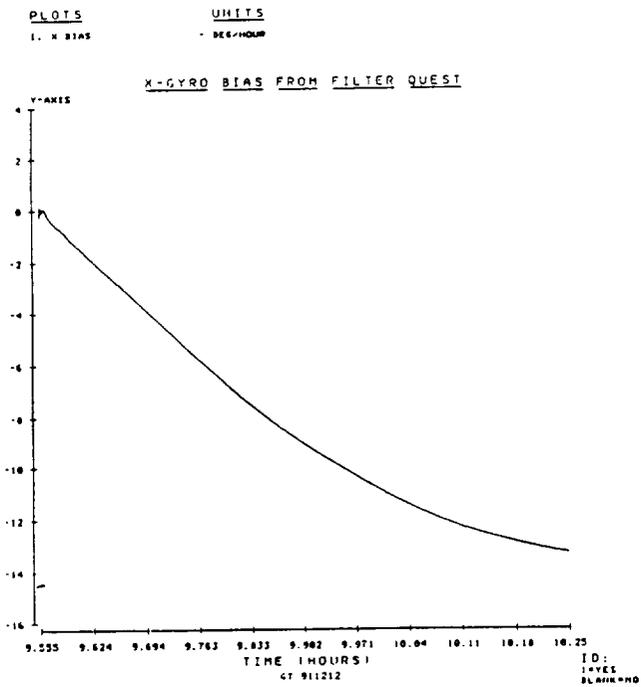**Figure 2. Filter QUEST Gyro Bias Fading Memory Equal to 0.99**

X-GYRO BIAS FROM FILTER QUEST

Figure 3.   Filter QUEST Gyro Bias Fading Memory Equal to 0.999
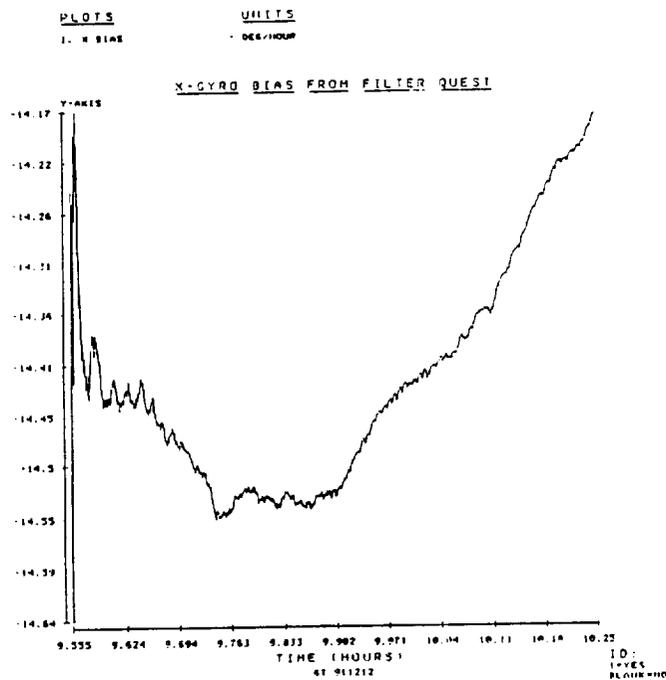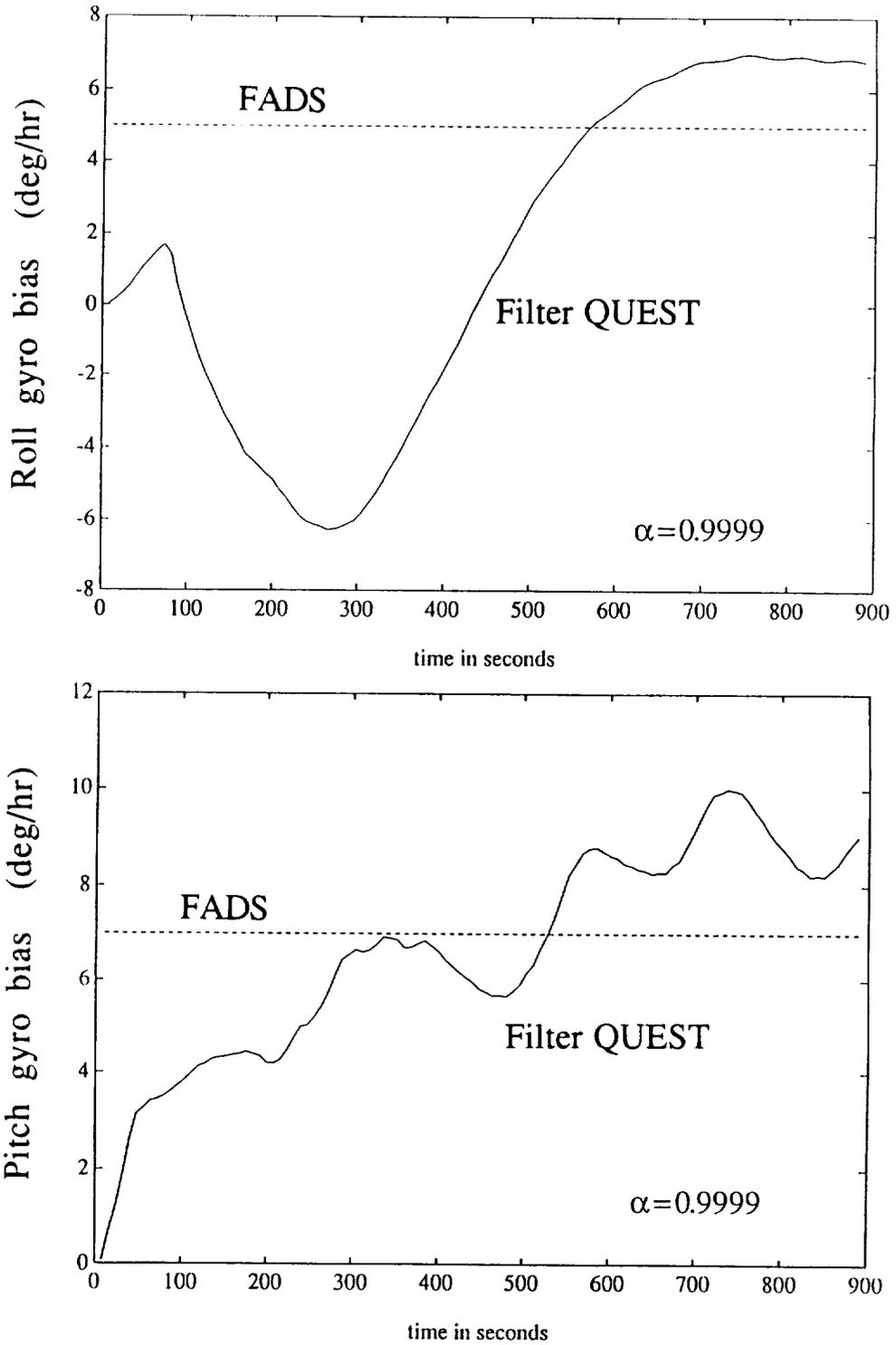
X-GYRO BIAS FROM FILTER QUEST

Figure 4.   Filter QUEST Gyro Bias Good a Priori Bias—Memory 0.999

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Transfer orbit

Figure 5.   GOES Filter QUEST Gyro Bias

and the quaternion is updated through:

$$\vec{q}_{k+1}(+) = \vec{q}_{k+1}(-)\delta\vec{q}^{-1} \qquad (5)$$

GRO is an inertially fixed spacecraft. The attitude hardware consists of: two fine Sun sensors (FSS); two three-axis magnetometers (TAM); two fixed-head star trackers (FHST); and an inertial reference unit containing three two-axis gyroscopes. Although the onboard computer (OBC) uses the full sensor complement, the GRO RTSF does not process the more accurate FHST data; thus, we take here the OBC's attitude estimate as the truth model. A different scheme was used to evaluate the RTSF gyro bias estimation, since (1) the OBC's estimates of the biases were not readily available in telemetry, and (2) batch estimates showed that the real biases were comparable to the noise in the RTSF estimates (0.5 to 1.0 deg/hr). Biases were introduced into the gyro rates before they were input to the filter, and these were taken as the truth model. (Several different combinations of simulated biases were used, ranging in magnitude from 1 to 60 deg/hr). The attitude matrix for inertial-to-body transformation is described here by a 1-2-3 Euler angle sequence about the body X, Y, and Z axes, respectively, and the respective Euler angles are denoted roll, pitch, and yaw.

We present here the RTSF results using real telemetry data from GRO spanning a roll maneuver on April 9, 1991. The maneuver lasted about 2200 sec, during which only the roll gyro rate is nonzero and is maintained at about 0.06 deg/sec. The initial and final OBC estimates of the attitude Euler angles are, respectively, (146.27, 17.54, -11.00) and (-96.85, -17.96, -10.26) deg.

Figure 6 shows the roll angle estimated by the RTSF. We see that, starting from an a priori roll estimate of 120 deg, the RTSF converges to the OBC estimate in about 1500 sec (75 filter updates). It then varies about the OBC estimate with an error of about 2 deg. For this set of data, the FSS boresight was very close to the roll axis, so that the roll estimate is obtained essentially from TAM data alone. Thus, we attribute the relatively large error in the RTSF estimates as being due to the coarseness of the TAM data.

The orientation of the FSS does not pose a problem for estimating yaw and, as shown in Figure 7, we see that the RTSF errors are now less than 0.5 deg. Note also the spikes in the estimate at about 7000 and 7500 sec; inspection of the data shows that abnormally large gyro data were received at those points. However, the filter recovers very quickly after the anomalies. Another interesting feature is the effect of the covariance matrix on the convergence rate of the RTSF. Whereas the a priori covariance matrix used to generate Figure 6 was large, the a priori matrix used to obtain the data of Figure 7 was the converged matrix obtained at the end of the run of Figure 6. Starting from an a priori value of –20 deg, the RTSF's yaw estimate now converges within 500 sec (about 25 updates).

An example of the GRO RTSF's gyro bias estimation is presented in Figure 8. We see that, until the start of the maneuver, the RTSF recovers the true yaw bias of +2.4 deg/hr with an error of about 0.5 deg/hour. There is substantial noise during the maneuver—about 3.6 deg/hr or 0.001 deg/sec. We attribute this to a combination of an effective yaw component of the rate due to errors in the attitude estimate and greater noise in the high-rate gyro data during the maneuver.

The EUVE sensor complement consists of two FHSTs, an FSS, two coarse Sun sensors, and two triaxial magnetometers. The EUVE RTSF performs real-time star identification by a direct match method enhanced by an attitude-independent dot-product check between the star and Sun vectors.

Shortly after orbit insertion, EUVE will be spun up to 1.3 revolutions per orbit to allow its FHSTs to scan for acquisition stars. As stars move through the FHST fields of view, the filter solution shows discontinuities (Figures 9 and 10) due to small misalignments and biases in the simulated sensors. (The Kalman filter only

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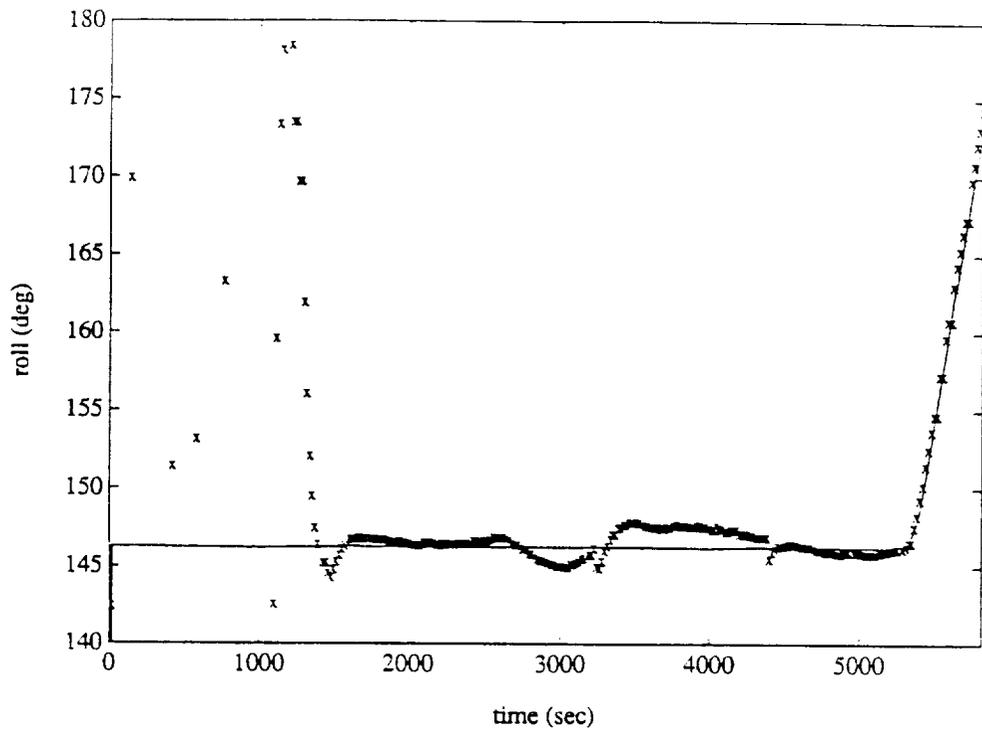
Figure 6. Estimates of the roll (Euler) angle. Solid line represents the OBC estimate, and 'x' represents the RTSF estimates. The a priori roll estimate was +120 deg.
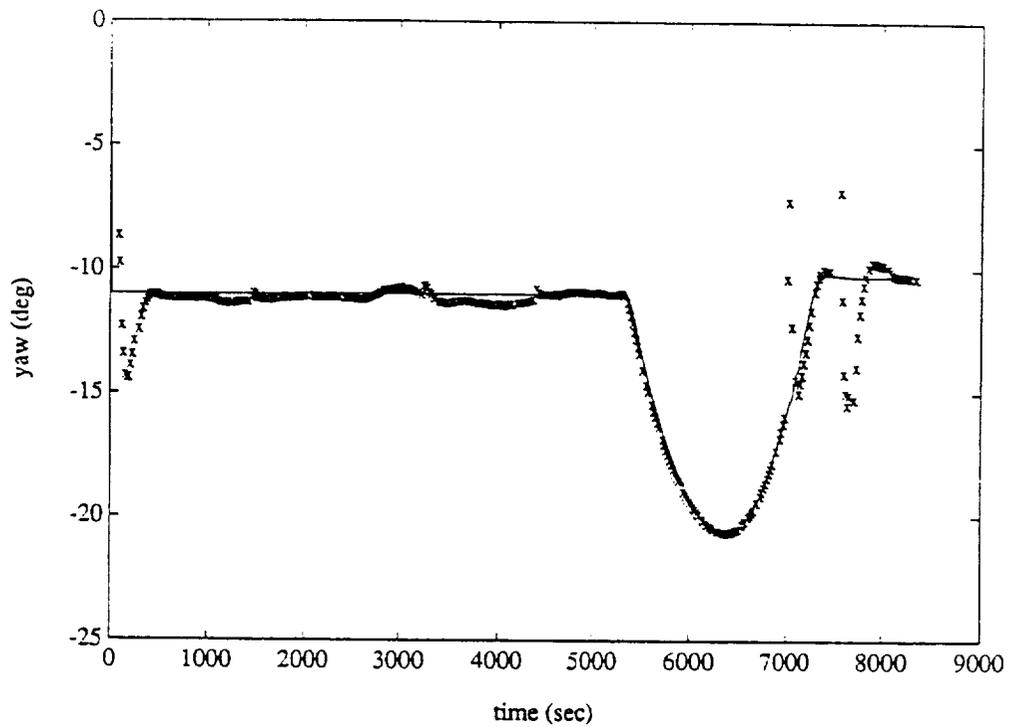

Figure 7. Estimates of the yaw (Euler) angle. Notation is that of Figure 6. The a priori yaw estimate was –20 deg.

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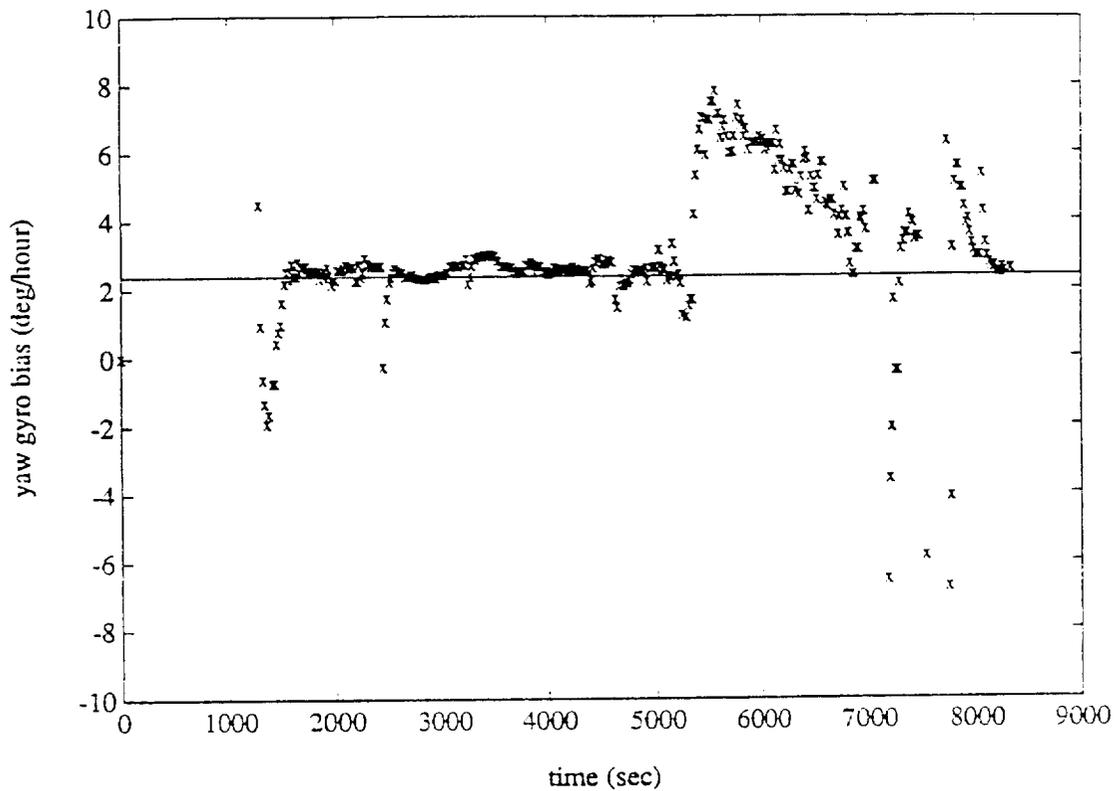
Figure 8. RTSF estimates ('x') of the gyro bias along the yaw axis. The horizontal line represents the bias of +2.4 deg/hr included in the gyro data input to the RTSF. The a priori bias estimate was 0.0 deg/hr.

EUVE: RTSF (with FHST)
Roll rate = 1.3 rpo
FSS biased
TAM misaligned & noisy
Discontinuities occur at new star identifications
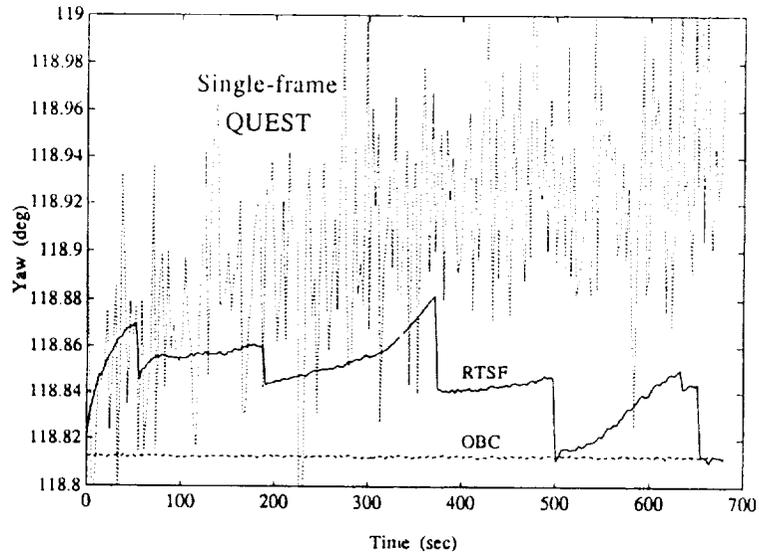
Figure 9. **EUVE yaw angle determined by RTSF and single-frame QUEST. The dashed line marked "OBC" is the true yaw angle.**

EUVE: RTSF (with FHST) Roll Gyro Bias
Roll rate = 1.3 rpo
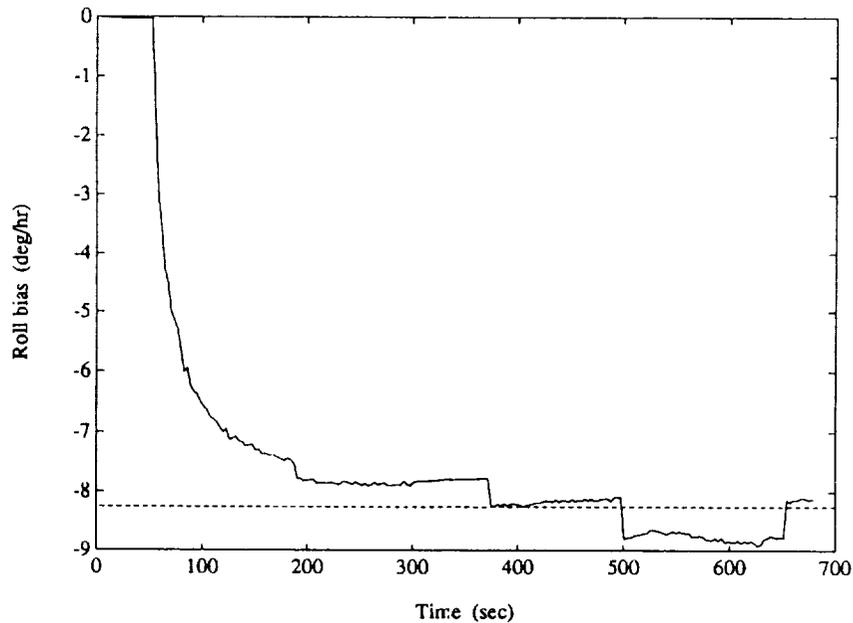
Figure 10. **EUVE RTSF solution for roll gyro bias. The dashed line indicates the true bias.**

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EUVE: RTSF (with FHST)
Inertial case
Attitude noise less than 15 arcsec (1-σ) on all axes
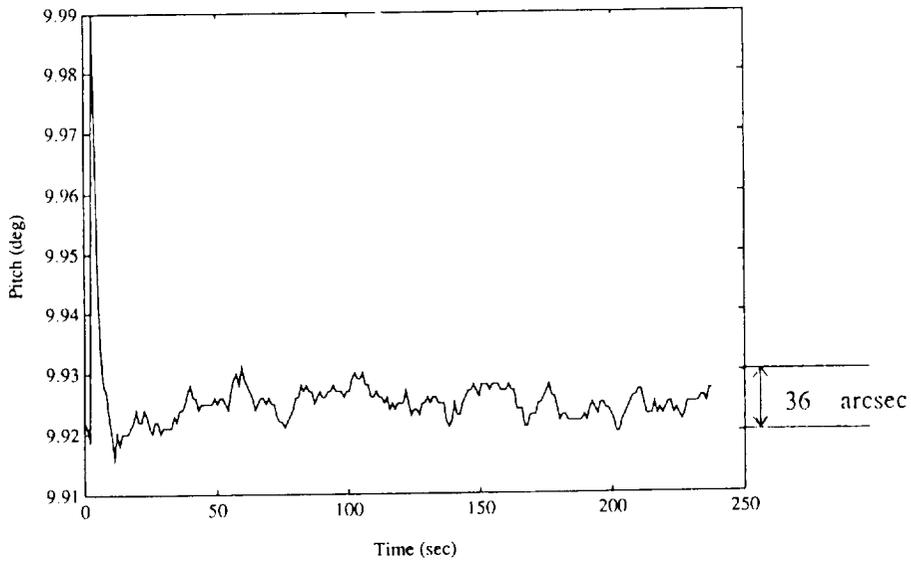
Figure 11. EUVE RTSF solution for pitch angle. True pitch is constant at 9.82 deg. FSS misalignment causes the 0.1-deg offset.

EUVE: RTSF (with FHST) Gyro Biases
Inertial case
Bias errors less than 0.2 deg/hr (1-σ) on all axes
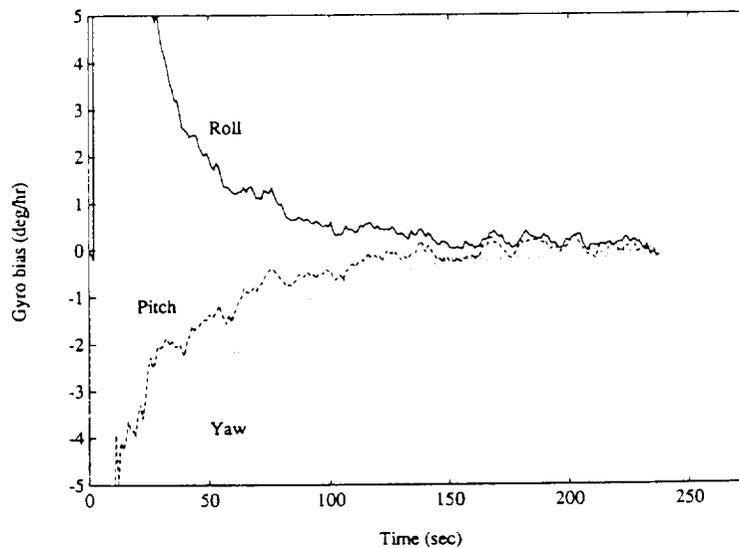
Figure 12. EUVE RTSF solution for the gyro biases. The true biases are all zero in this example.

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filters out random noise, not systematic errors). The discontinuities in attitude are under 0.04 deg. They can be greatly reduced by tuning the filter for a longer memory and increasing the sensor noise parameters to put less reliance on current incoming data. However, this leads to noisier solutions and longer bias convergence times.

Figure 11 and 12 show a case where EUVE is inertially pointing with the Sun in view of the FSS and an identified star in FHST-1. The attitude solution converges within 1 minute (the filter is updating once per second), with residual noise under 15 arcsec (1-σ). After 4 minutes, the gyro bias errors are under 0.2 deg/hr (1-σ) and still decreasing.

4. CONCLUSIONS

Adding a simple gyro bias estimator to filter QUEST gave COBE and GOES biases within 1 to 2 deg/hr of the batch estimator values. This filter proved stable under a wide range of memory length parameter values. Increasing the memory parameter slowed response and smoothed the time history but did not affect the final result. The COBE data used were all clean and synchronized. The GOES data were simulated and clean but not synchronized. Attitude was continuously observable for both spacecraft.

For the GRO RTSF, using real data provided a useful test of the filter's performance in a real-time situation. The attitude errors using FSS and TAM data depended upon Sun observability by the FSS and ranged from 0.5 to 2 deg; the gyro bias errors varied correspondingly between 0.5 and 20 deg/hr.

The GRO RTSF proved to be robust in the presence of gyro data anomalies. However, its solutions for roll angle and roll gyro bias are relatively noisy and slow to converge due to the limitation to only FSS and magnetometer measurements (the Sun being close to the roll axis). The inclusion of FHST data in the EUVE RTSF greatly improves the solutions. The EUVE RTSF solutions were subject to offsets and small discontinuities due to misalignments and biases. This problem is expected to affect the early stages of any mission until the full ground support system estimates these systematic errors.

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