JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 15, No. 3, May-June 1992

High-Accuracy Attitude Determination for the X-Ray Satellite ROSAT

T. Rupp and G. Schneiders
Deutsche Forschungsanstalt für Luft- und Raumfahrt, German Space Operations Center
Oberpfaffenhofen, D-8031 Germany

The ROSAT mission requires highly accurate attitude data. Therefore, an attitude determination procedure has been established at the German Space Operations Center (GSOC) using star camera measurements and gyro data. The latter replaces the model in a modified Kalman filter. A quaternion representation of the attitude is used. A fiducial light star system monitors the relative motion between telescope axis and star cameras. The reference is a star catalog for the epoch 2000.0. Results of first flight data demonstrate the capability of the post facto altitude determination system to obtain attitude accuracies of a few arcseconds. The first year of the ROSAT mission has shown that the results presented in this paper are representative for the performance of the two operational spacecraft modes "scan" and "pointing" that are described here.

I. Introduction

THE ROSAT spacecraft was launched into a circular orbit of 580-km attitude with an inclination of 53 deg by a Delta II launch vehicle on June 1, 1990. The scientific payload of the ROSAT spacecraft consists of a large x-ray telescope and a smaller extreme ultraviolet telescope, pointed in the same direction. The main telescope contains of a fourfold mirror system with an 83-cm aperture having three focal plane instruments. Two instruments are image position sensitive proportional counters (PSPC 0.1—2 keV) providing a field of view of 2 deg. The third focal instrument is a high resolution imager (HRI) with a resolution of about 3 arcsec.

The primary objective of the mission is to perform the first all-sky x-ray survey. During a six-month survey phase, which started on July 30, the PSPCs began scanning the whole sky in 2-deg stripes. It can be expected that about 100,000 x-ray sources will be discovered and the locations of the sources determined to an accuracy of 30 arcsec or better. After completion of this scan phase, the instruments are used for detailed investigations of selected targets. This pointing phase, which will then last up to 2½ years, will be open for guest observers. The x-ray sources will be located within the HRI to an accuracy of a few arcseconds.

The quality of the final attitude solution significantly influences the success of the ROSAT mission. Special effort was, therefore, put on obtaining the best attitude solution possible.

The ROSAT Scientific Data Center (RSDC) is the Max-Planck-Institut für Extraterrestrische Physik in Garching near Munich. The German Space Operation Center (GSOC) in Oberpfaffenhofen near Munich is responsible for all spacecraft operations, both for the satellite systems and the scientific payload.

II. Mission Phases

The ROSAT mission is split into three parts. A so-called premeasuring phase during the first two months prepares the satellite for its two main mission phases, scan and pointing:

Checkout	Duration: 15 days
Calibration	Duration: 24 days
Miniscan	Duration: 5 days
Minipointing	Duration: 14 days

Thomas Rupp was born in Burgkunstadt, Germany, in 1960. He studied mathematics and economics at the University of Bayreuth and received the diploma degree in 1984. He joined the German Aerospace Research Establishment (DLR) as a scientist in 1985 and belongs to the staff of the Space Flight Dynamics Section of the German Space Operations Center (GSOC) in Oberpfaffenhofen near Munich. He is responsible for the attitude determination and control of the ROSAT (Roentgen Satellite) spacecraft. Currently, he is working on the ATMOS (Atmospheric and Environmental Research Satellite) project as a member of the coordination team.

Gottfried Schneiders studied mathematics and physics at the University of Heidelberg and Freiburg, Germany. He received the diploma degree in 1975. In 1977 he joined the German Aerospace Research Establishment (DLR), where he was responsible for orbit and attitude calculations of many different sounding rocket missions and satellite projects. In 1990 he joined the Remote Sensing Application Section of DLR.

Presented as Paper 90-3494 at the AIAA Guidance, Navigation, and Control Conference, Portland, OR, Aug. 20-22, 1990; received March 13, 1991; revision received July 18, 1991; accepted for publication July 19, 1991.

Scan	Duration: 189 days
Pointing 1	Duration: 180 days

III. Attitude Sensors

The Attitude Measurement and Control Subsystem (AMCS) of the three-axis stabilized ROSAT has two types of attitude sensors that are currently used for the post facto attitude reconstruction.

Gyro Package

The gyro package contains three orthogonal measurement axes aligned with the ROSAT reference system and a fourth redundant measurement axis in the direction of $-x$, y, z with equal angular separation to these axes. Two types of output are provided, an incremental output with a resolution of 4/3 arcsec and an analog output with a resolution of 0.0065 arcsec. The alignment error of the gyro axes was minimized during ground assembly and, therefore, has an insignificant influence on the performance of the AMCS. The actual maximum drift rate was expected to be less than 0.5 arcsec/s untrimmed.

Results of the initial gyro drift calibration are as follows:

X-Gyro Bias: $+0.062$ arcsec/s
Y-Gyro Bias: -0.062 arcsec/s
Z-Gyro Bias: $+0.050$ arcsec/s
S-Gyro Bias: not yet compensated

In addition to the drift correction, a scale factor compensation had to be performed for the *x*-gyro incremental output. The ROSAT *x*-axis gyro was corrected by a factor of 1.002, which equates to an error of 0.2%.

Two Star Tracker Cameras

The two star tracker cameras are offset from the telescope axis by 3 deg and located 90 deg apart. The Change Coupled Device (CCD)-chip consists of 385 × 288 pixels. The field of view is 5.9 × 4.4 deg, and every pixel thus covers 55 × 55 arcsec. The origin of the camera coordinate system is the center of the array. The array axes are defined as *y* axis in the scan direction, *x* axis perpendicular to the scan direction (parallel to the ROSAT *x* axis), and *z* axis perpendicular to the array.

In the pointing mode, the image of a star is smeared over 3 × 3 pixels, and the star camera electronics calculate the center of the star image using an interpolation method, which takes into account the line spread function of the star image as a function of star color and position within the field of view. The response function within a pixel is a function of the star color. In the scan mode, the star image is smeared over several rows of the detector array. The length of the image depends on the scan velocity. Analogous to the pointing mode, an onboard interpolation is used to calculate the star position on the array.

Geometrical errors in the positioning of the CCD pixels are directly reflected in the interpolated star positions. In addition, since the absorption in the electrode structure is wavelength dependent, there is a color error in the aperture of the CCD.

The systematic star position error in the *x* and *y* directions for real stars was expected to be less than 2 arcsec for the pointing mode and less than 10 arcsec for the scan mode. The mounting angle errors were expected to be less than 5 arcmin around each of the star tracker camera axes. Some calibration results to these systematic errors will be mentioned later. Noise equivalent angles (equal to the sum of star sensor and electronic errors, which are considered to be random) are less than 1 arcsec (pointing) and less than 5 arcsec (scan).

IV. Modified Kalman Filter

The algorithm for the ROSAT post facto attitude reconstitution is based on a Kalman filter technique. In general, a Kalman filter consists of a state dynamic model, normally described by a set of linear differential equations, and a set of linear measurement equations. For ROSAT, the state modeling was replaced because onboard measurements of satellite rotation rates are available. The measurements are made by rate integrating gyros, and so they contain the sum of all torques acting on the spacecraft. Hence, force model errors in the integrated satellite state exist only to the extent that the measurements of the satellite rates contain errors.

When integrating only the spacecraft kinematic equations, it is more convenient to work with a quaternion representation of spacecraft orientation rather than with Euler angles. In the quaternion formulation, the Space Craft (S/C) attitude matrix (direction cosine matrix) can be computed without the need of any sine/cosine calculations. Since ROSAT utilizes quaternions in the onboard processing and in the telemetry data stream, it is natural to use quaternions in ground-based processing to produce refined attitude state estimates.[1]

The quaternions that are calculated on board (accuracy of some arcmin) serve for initialization of the Kalman filter and as an approximate attitude path for processing the star camera and gyro measurements.

V. Star Tracker Camera Calibration Procedures

In contrast to the gyro package, it is necessary to calibrate the star tracker camera mounting angles with respect to the x-ray telescope boresighting axis for which the final attitude solution is required. These calibration procedures are the so-called "boresighting procedure" and "fiducial light star filter."

Further, a correction of the star tracker cameras' measurements affected by biases is performed within the post facto attitude determination software in pointing mode by using bias correction tables provided by the RSDC.

Boresighting Procedure

The on-orbit alignment or boresighting procedure determines the absolute misalignment between the three x-ray detectors and the star tracker cameras caused by mounting errors on ground and launch shift. The basic requirement to determine a three-axis misalignment between two systems is the existence of two star measurements in each of the two systems. But as the fields of view (FOV) of the x-ray sensors are very small, it is not realistic to assume two x-ray targets of high radiance in the FOV of the sensors at the same time; therefore a chosen target in the star tracker camera FOV and the x-ray sensor FOV is measured at several different places within the FOV.[2]

The result of the boresighting procedure performed at day $L + 17$ between PSPC 1 and star tracker camera 1, relative to the nominal alignment, is as follows:

1) misalignment around star tracker camera 1 *x* axis: 254 arcsec
2) misalignment around star tracker camera 1 *y* axis: 50 arcsec
3) misalignment around star tracker camera 1 *z* axis: arcsec to be determined

Because the star tracker camera *z* axis looks in the same direction as the x-ray telescope boresighting axis, a significant value for the *z* axis misalignment cannot be determined.

From these misalignments and the relative alignment between the two star tracker cameras, determined directly by optical stars in both cameras, we obtain immediately the misalignment of star tracker camera 2 to PSPC 1:

1) misalignment around star tracker camera 2 *x* axis: 4 arcsec
2) misalignment around star tracker camera 2 *y* axis: 320 arcsec
3) misalignment around star tracker camera 2 *z* axis: arcsec to be determined

The misalignments of star tracker camera 2 were later improved by a least squares algorithm to obtain full consistency between the two star tracker cameras' mountings.

Fiducial Light Star Filter System

The fiducial light star system (FLS) determines the relative alignment between the three x-ray detectors and the two star tracker cameras. It is measuring the dynamical part of the misalignments caused by the thermal distortions and the anomalies during one orbit during sun and eclipse phases. The nondynamical parts of the misalignments, caused by mounting errors and launch shift, have already been determined by the boresighting procedure.[3]

The FLS provides relative position measurements of up to five artificial stars. The sources (LEDs) of these artificial stars are located in the focal plane of the x-ray sensors and are directed via an optical path to the star cameras. The star cameras measure successively all visible artificial stars. The number and positions of these stars depend on the x-ray sensor. Three of the five existing LEDs belong to the HRI, the other ones to the PSPC. The mapped stars within the FOVs of the star cameras are illustrated in Fig. 1. Each of the five stars normally is tracked for 12 s in the sequence 1, 2, 3, 4, 5. The measurements are placed within the telemetry stream. In those phases where the stars 1 and 2 or 3, 4, and 5 are not visible, the related telemetry data are ignored.

So the thermal deflections caused by periodical change of sunlight and eclipse phases can be determined. This is done in two steps. First, the artificial stars of the FLS are measured on board by the star cameras as described earlier. These measurements are then input to a ground Kalman filter program that computes the time-dependent direction cosine matrices for the two star cameras, representing the misalignment between the star camera coordinate systems and the fiducial light coordinate system. These direction cosine matrices combined with the misalignments of the boresighting procedure and the star camera measurements of the real stars are input for the post facto attitude determination program.

For each of the star tracker cameras, the state equation of the Kalman filter consists of three misalignment angles δx, δy, and δz, which describe the deviations around x, y, and z axes respective to their nominal mounting angles. Further, the state vector is extended by the time derivations of these three misalignment angles. The systematic error (= bias) on the fiducial light star measurements is less than 1 arcsec in pointing mode and less than 2 arcsec in scan mode in both (x and y) components. The random error (= noise) is less than 0.5 and 5.0 arcsec, respectively.

Of course, the positions of the fiducial light stars could be calibrated before launch only against the star tracker cameras' mounting errors on the ground. So, as the initial result of the fiducial light star filter, we obtain the sum of launch shift and thermal distortions, which is then the deviation to these calibrated positions.

Figures 2 and 3 show the performance of the fiducial light star filter for PSPC 1 for star tracker camera 1 in pointing mode. Especially from the x and y misalignments, we can see the sine of the thermal distortions over one orbit period of about 90 min (Fig. 2). The amplitude is about 2 arcsec. Unfortunately, the fiducial light stars are located near the star tracker cameras' z axis, so the estimation of the z misalignment is degraded by the strong influence of bias and noise (Fig. 3).

Figures 4 and 5 show the performance in scan mode. The estimated trajectories are not as smooth as in the pointing mode, but the oscillations are synchronous to the orbit periods. The amplitude remains nearly unchanged.

VI. Star Catalog

The coordinate system in which the attitude of the telescope axis has to be determined is the inertial equatorial system of the epoch 2000.0. A star catalog derived from a SKYMAP catalog with star positions for this epoch is used as the reference. Only those stars from the SKYMAP catalog are selected for the reference catalog, which fulfill the following criteria:

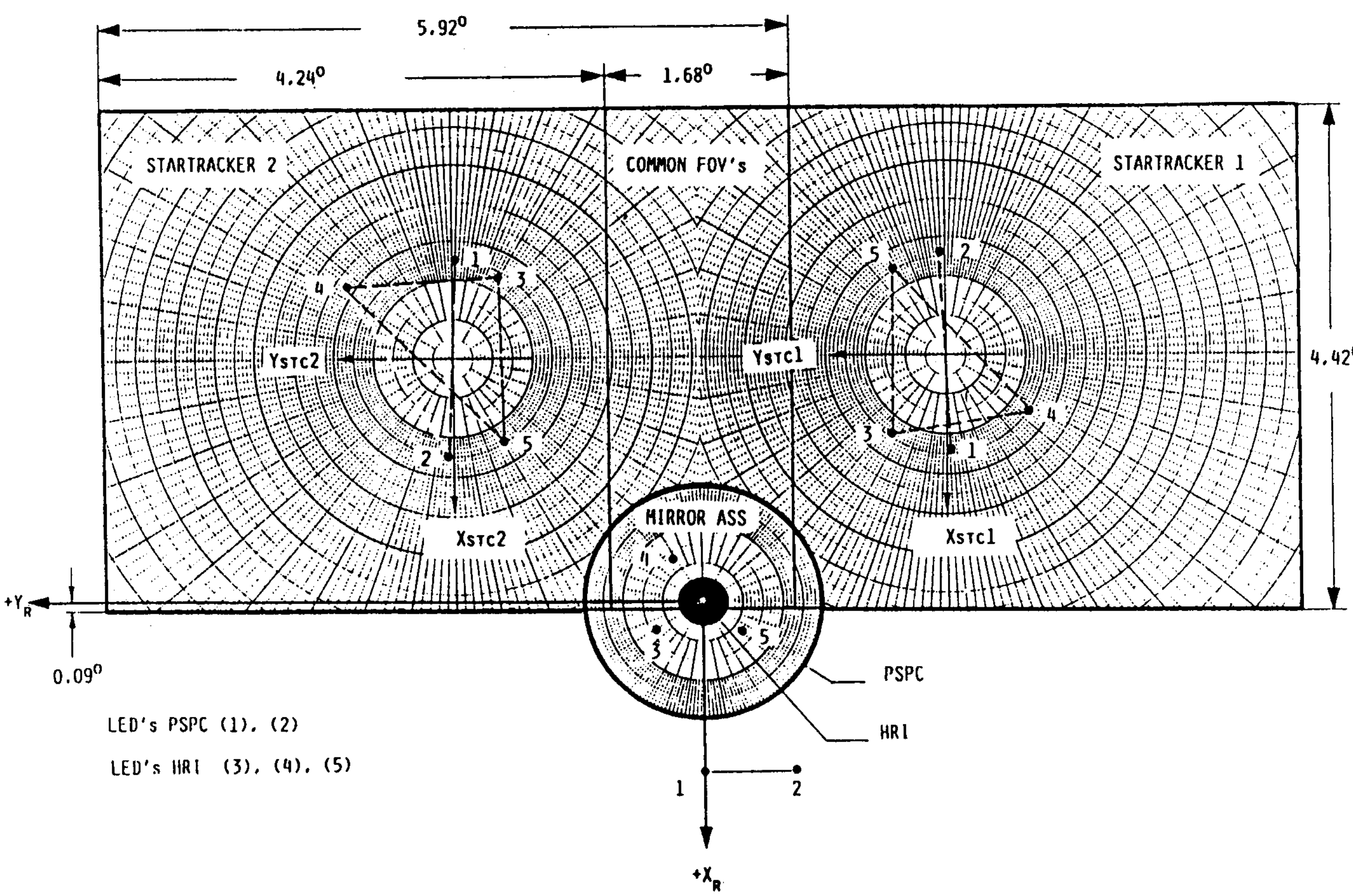

Fig. 1 Fiducial light star configuration.

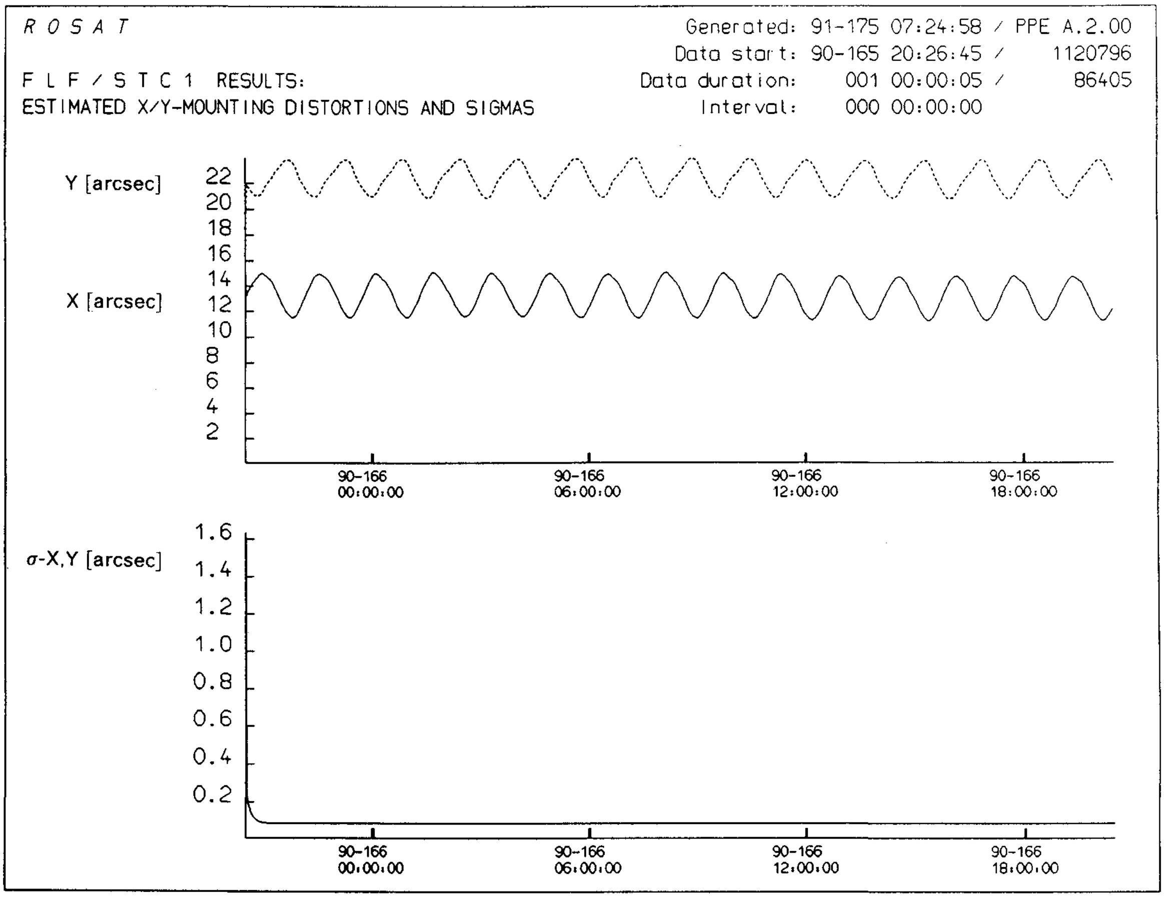

Fig. 2 STC1/Pointing: *x/y*-axis misalignments and corresponding standard deviations (sigmas).

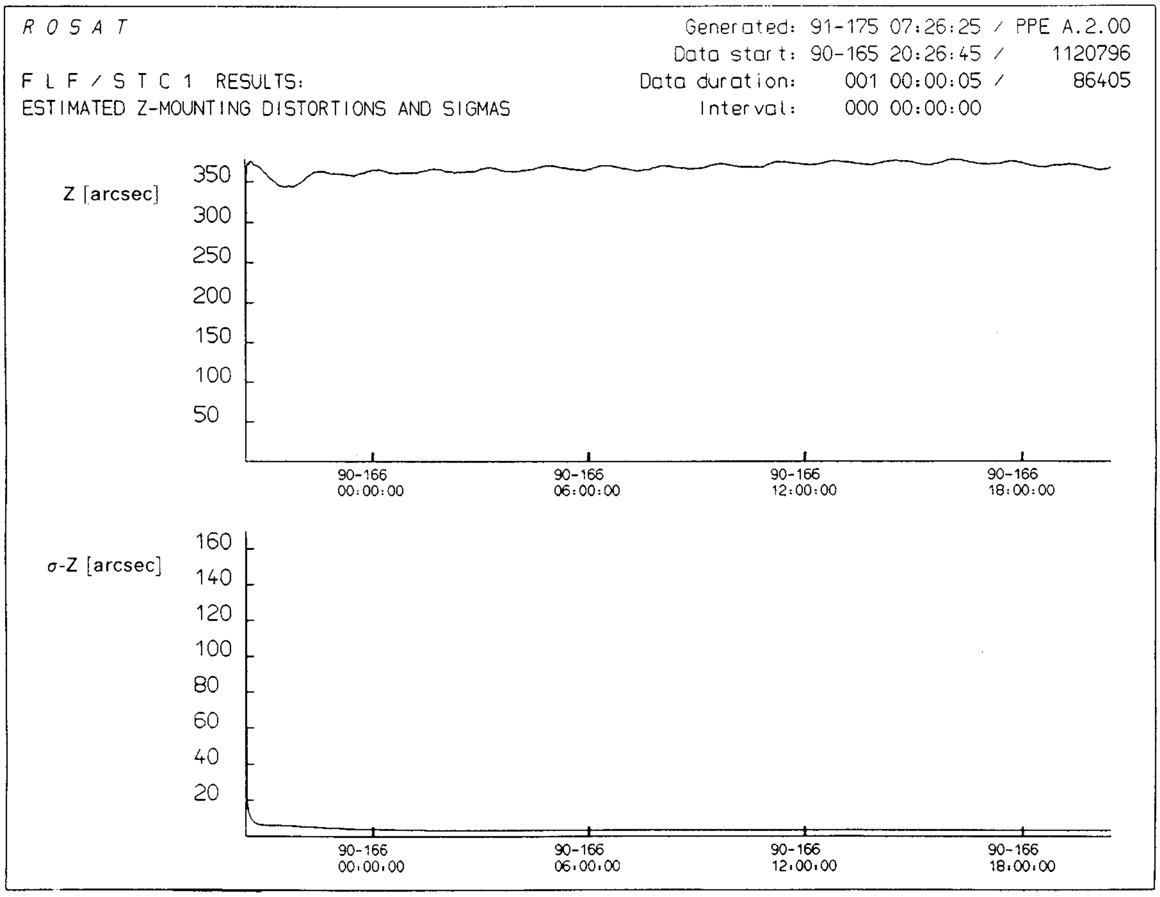

Fig. 3 STC1/Pointing: *z*-axis misalignments and corresponding standard deviations (sigmas).

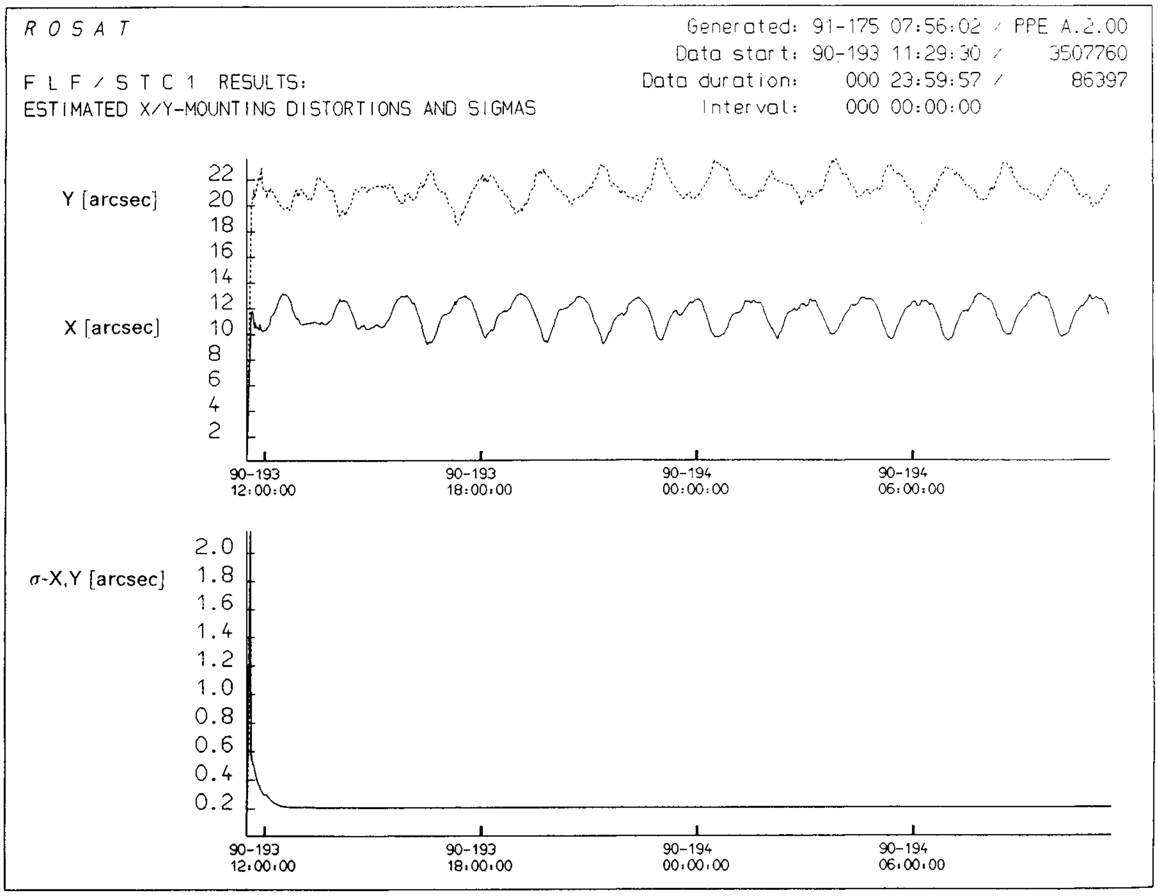

Fig. 4 STC1/Scan: *x/y*-axis misalignments and corresponding standard deviations (sigmas).

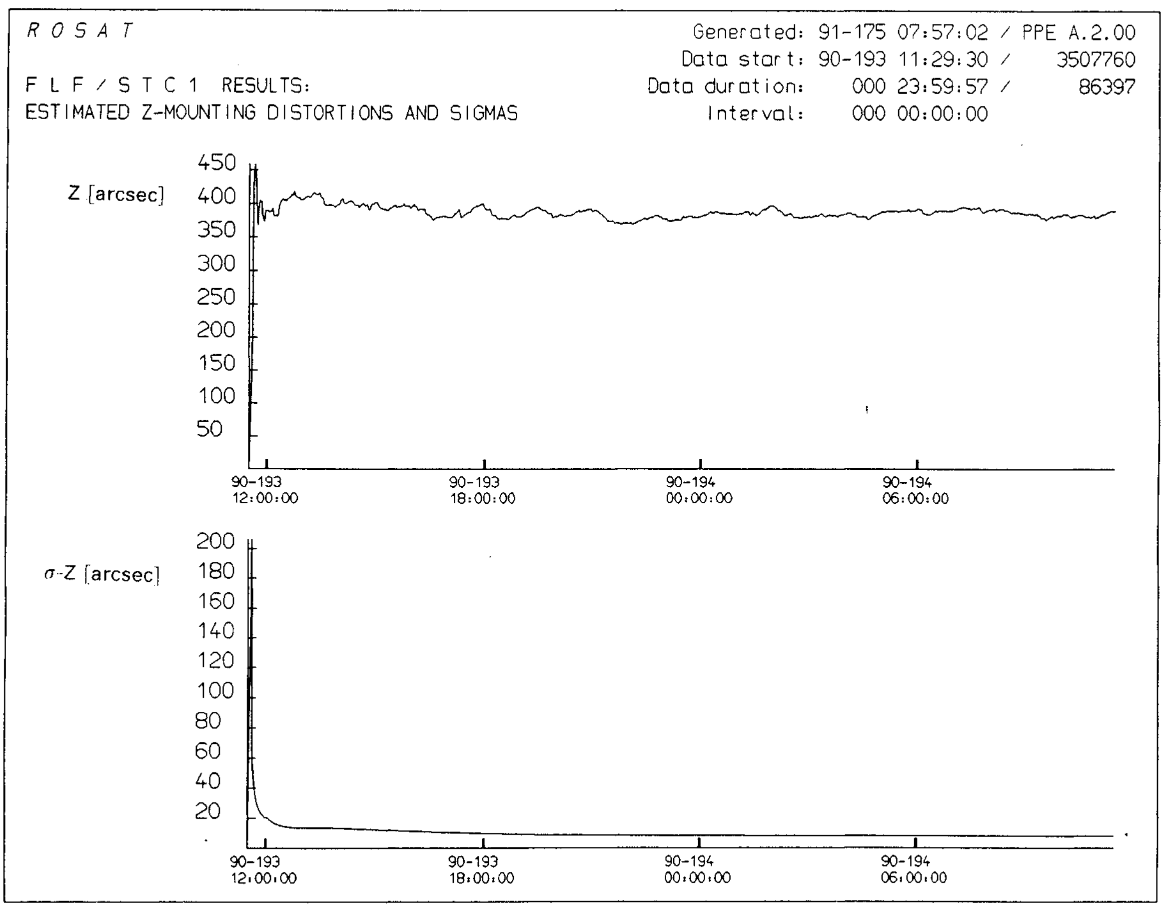

Fig. 5 STC1/Scan: *z*-axis misalignments and corresponding standard deviations (sigmas).

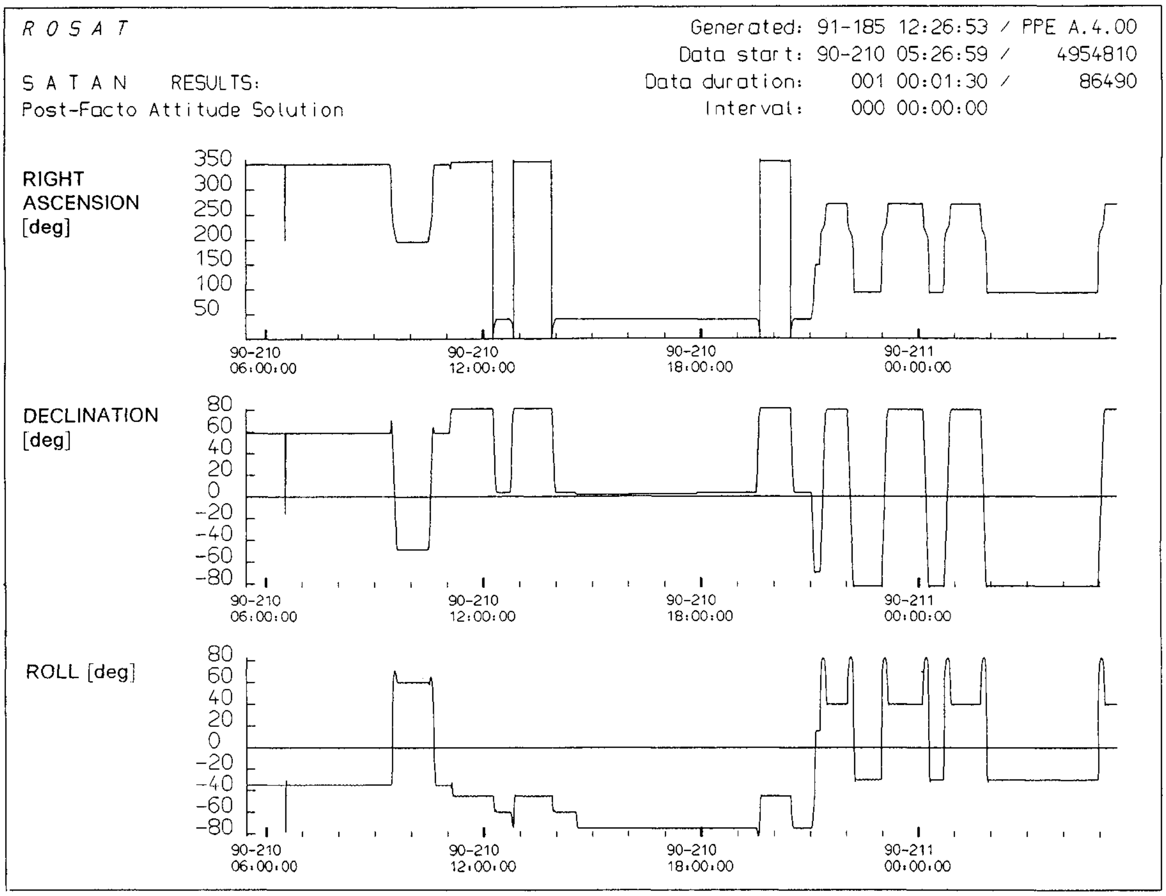

Fig. 6 Pointing mode: ROSAT attitude solution for day of year 210.

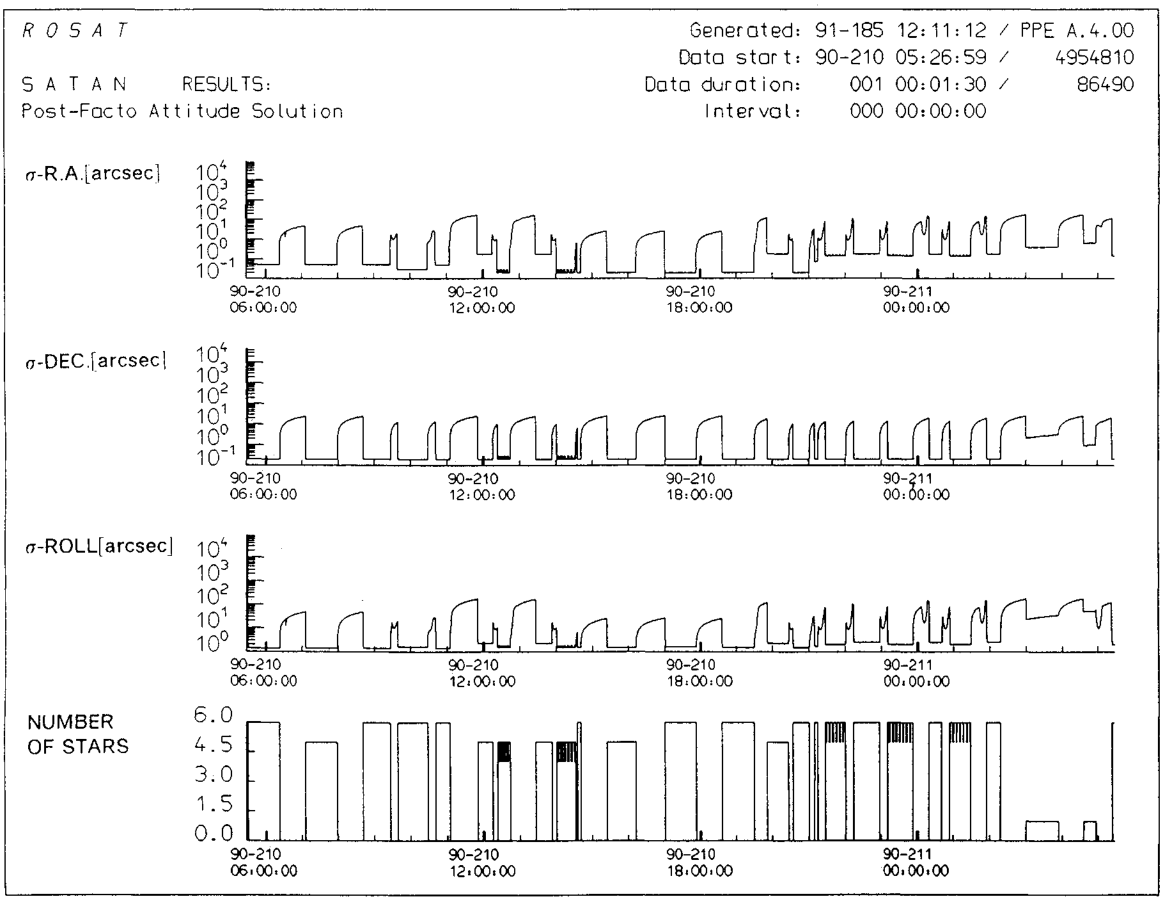

Fig. 7 Pointing mode: errors in ROSAT attitude solution for day of year 210 (sigmas), number of measured stars.

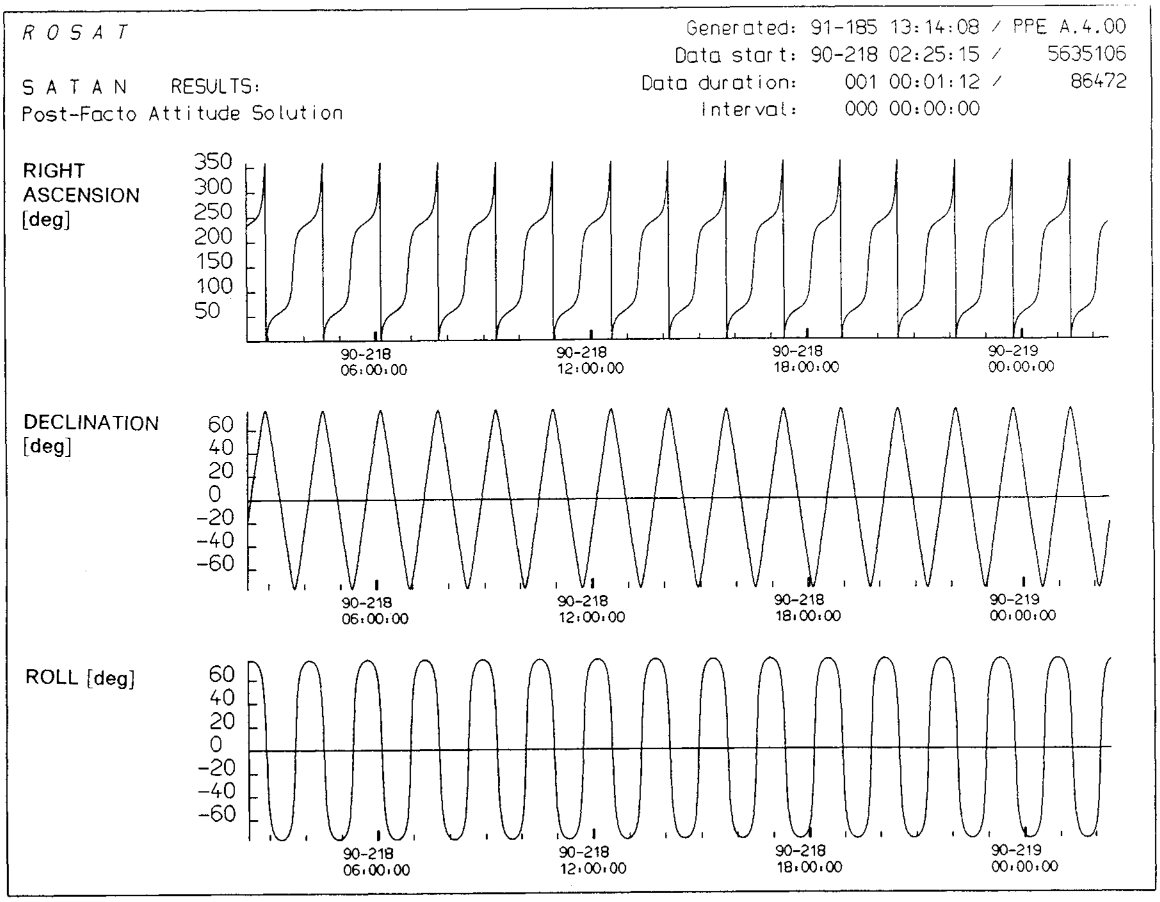

Fig. 8 Scan mode: ROSAT attitude solution for day of year 218.

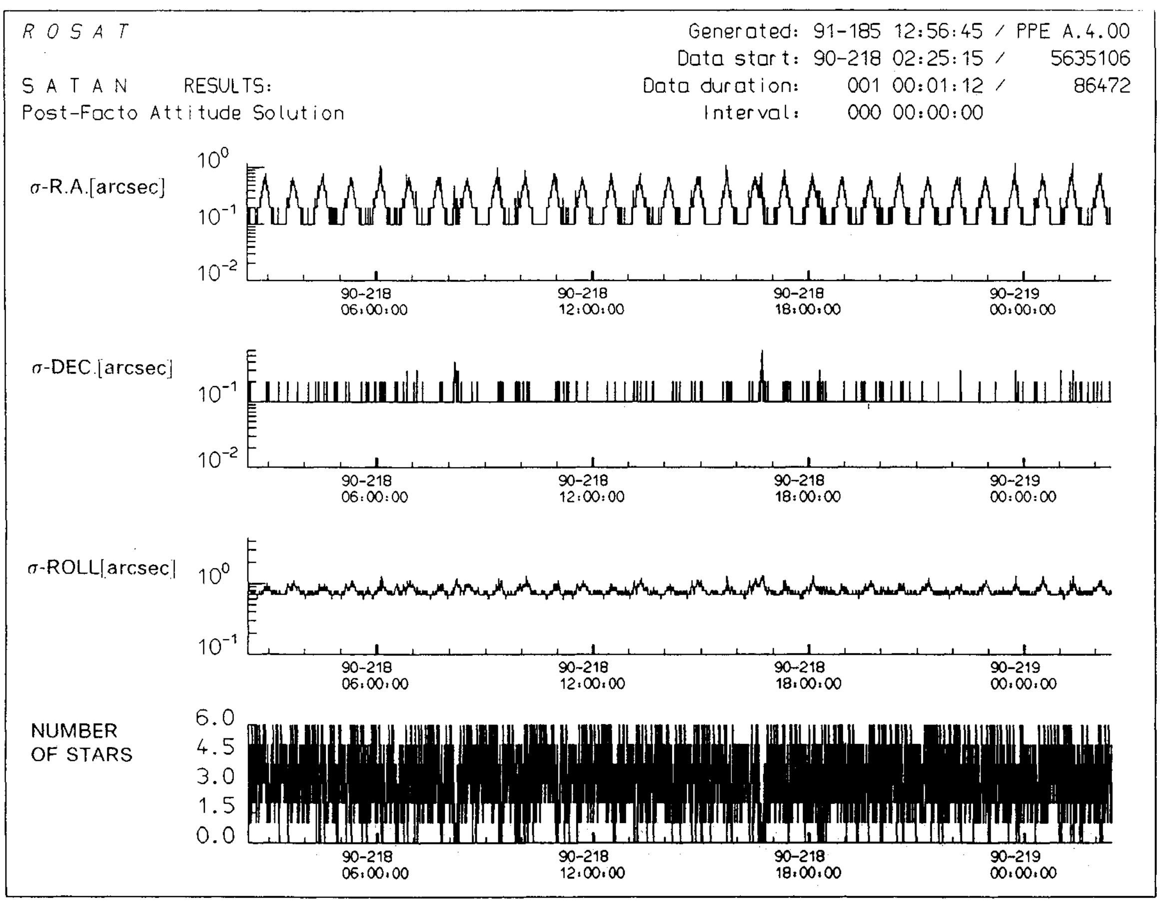

Fig. 9 Scan mode: errors in ROSAT attitude solution for day of year 218 (sigmas), number of measured stars.

1) They have no variable magnitude.
2) Their position accuracy is better than 1 arcsec.
3) Their magnitude is between 0 and 6.5 mag.
4) They have no bright neighbor closer than 0.1 deg.
5) They belong to the spectral classes A, B, F, G, K, and M.

This gives about 17,000 candidates. The positions of the SKYMAP stars are given for the epoch 2000.0. They are corrected for the proper motion and parallaxes for the mission time, and a conversion of the visual magnitude into instrumental magnitude of the star cameras is performed.[4]

VII. Post Facto Attitude Determination Procedure

After the fiducial light star measurements are processed to obtain the time varying mounting angles for the star cameras, they are input into the post facto attitude determination filter together with the star tracker camera and gyro measurements. This filter additionally needs orbit information to correct the stellar aberration and, of course, the star catalog for star identification purposes. The occurring star patterns are compared with the reference star catalog, and an output of this program is the attitude of the x-ray telescope coordinate system relative to the inertial system. Another output is used for the estimation of some parameters, such as the misalignment and biases of the star cameras and gyros. The concept, therefore, is to combine data from various time periods to best obtain an overall improvement in the rms for fitting attitude measurements with an algorithm based on least squares.[5,6]

VIII. Post Facto Results

Figures 6 and 7 show the performance of the post facto attitude determination procedure in pointing mode. In Fig. 7, curve 4, the number of measured stars is illustrated. Those time intervals where no stars occur can be related either to Earth blocks or to slews from one pointing target to another. Figure 6 then shows the attitude solution parametrized in right ascension, declination, and roll, related to the inertial 2000.0 coordinate system. From this attitude solution, we can see the duration of the pointings and the slews between the pointings.

The errors in the attitude solution are illustrated also in Fig. 7 and curves 1–3. They increase during Earth blocks and slews. The error in declination directly influences the pointing error, and the error in right ascension influences the pointing error by a cosine factor. The error in roll is larger than the errors in right ascension and declination by a factor of 10 because the star tracker cameras' measurements are made very close to their optical axes, which are tilted only by 3 deg to the telescope axis. The filter residuals are less than 5 arcsec in 90% of all cases.

Figures 8 and 9 show the performance of the post facto attitude determination procedure in scan mode. The attitude solution in Fig. 8 is represented by the expected three periodical (1.5 h) trajectories of right ascension, declination, and roll angle. The errors in Fig. 9 are more oscillating because of the worse performance in this mode. The number of measured stars is constantly changing because the scan rate of 4 arcmin/s brings new stars into the fields of view of the star tracker cameras. An average number of three measured stars can be expected. The filter residuals are less than 10 arcsec in 95% of all cases.

IX. Final Remarks

The ROSAT post facto attitude determination system meets the expected performance. In scan mode, the fiducial light star filter cannot improve significantly the quality of the attitude solution because the amplitude of the thermal distortions is comparatively much smaller than the systematic errors in the star tracker camera measurements, especially in this mode. The loss of star tracker camera 2 in September 1990 influences the accuracy of the attitude solution less but mainly causes star pattern identification problems because the average number of three measured stars decreases to one and one-half.

In pointing mode, however, this circumstance leads to a loss of attitude accuracy by a factor of $\sqrt{2}$ because the maximum number of six measured stars decreases to three measured stars.

References

[1]Lefferts, E. F., Markley, F. L., and Shuster, M. D., "Kalman Filtering for Spacecraft Attitude Estimation," *Journal of Guidance, Navigation, and Control,* Vol. 5, No. 5, 1982, pp. 417–429.

[2]Meier, H., and Rupe, U., "Proposal For On-Orbit Alignment," Dornier System Co., TN-202-2160 DS/023, Friedrichshafen, Germany, Nov. 1985.

[3]Porte. F., "ROSAT Fiducial Light Star Filter," Messerschmitt-Bölkow-Blohm Co., TN-RR51-66/86, Munich, Germany, June 1986.

[4]Bollner, M., "Star Identification Techniques Used For Attitude Determination and Control of the X-Ray Satellite ROSAT," AIAA Paper 87-2531, AIAA Guidance, Navigation, and Control Conference, Monterey, CA, Aug. 1987.

[5]Bollner, M., and Schneiders, G., "Attitude Determination and Control for the X-Ray Satellite ROSAT," *Proceedings of the Second International Symposium Spacecraft Flight Dynamics,* Darmstadt, Germany, SP-255, Oct. 1986, pp. 397–402.

[6]Rupp, T., and Schneiders, G., "High Precision Post-Facto Attitude Determination of the X-Ray Satellite ROSAT," Paper IAF-88-332, 39th Congress of International Astronautical Federation, Bangalore, India, Oct. 1988.