ATTITUDE DETERMINATION & CONTROL FOR THE X-RAY SATELLITE ROSAT

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ABSTRACT

This paper describes the approach for operations of the ROSAT Attitude Measurement and Control Subsystem (AMCS). The S/C is three-axis stabilized using reaction wheels,gyros and imaging star cameras as main attitude devices. According to the mission timeline AMCS operations must be supplied on ground. A large number of commands in the areas of orbit/ephemeris data, star catalogues, scan and pointing catalog is required. For post facto attitude determination star camera measurements and gyro data are used, the latter replace the model in a Kalmanfilter. A quaternion representation of the attitude is used. A fiducial light system monitors the relative motion between telescope axis and star cameras. The reference will be a star catalog for the epoch 2000.0.

Keywords: High-Accuracy Pointing,Imaging Star Cameras (with CCD), Onboard Star Catalog, Fiducial ·ght Stars, Kalmanfilter,Boresighting

1. Introduction

The ROSAT spacecraft comprises a three-axis stabilized satellite supporting a large X-ray telescope (83 cm aperture) of Wolter type with a carrousel focal plane assembly carrying two imaging proportional counters (PSPC) and one high resolution imaging detector (HRI). The main telescope will be supplemented by a XUV wide field camera. The main goal of the mission is to perform the first all-sky survey with an imaging X-ray telescope during a half year scan over the sky. After the survey detailed investigations of selected sources will be made in a pointing mode of at least one year duration.

ROSAT is a cooperative project between Germany (BMFT), the United States (NASA) and the United Kingdom (SERC). Germany will develop ROSAT and conduct the operations, the US will provide the launcher and the HRI, and the UK will build the XUV camera. Main contractor for ROSAT is the German company DORNIER. The spacecraft of 2500 kg weight is scheduled to be launched in 1991 with the Space Shuttle (or in 1988/89 with an Atlas Centaur vehicle), into a circular orbit of 475 km altitude inclined at 57 degrees.

GSOC (German Space Operations Center) will be responsible for mission operations. It will provide all tracking, telemetry, command and data processing capabilities to support the mission, with additional facilities to provide interfaces with NASA ground stations in the event of contingency operations. The use of a single ground station (Weilheim, FRG) in the nominal case will lead to a daily visibility pattern of 5-6 short consecutive contacts of approx. 6 minutes duration, each separated by 1.5 hours, followed by an invisibility period of approx. 16 hours. The collected data are stored onboard on tape recorders and are sent to ground during contacts at a rate of 1 MBit/sec, parallel to the realtime telemetry.

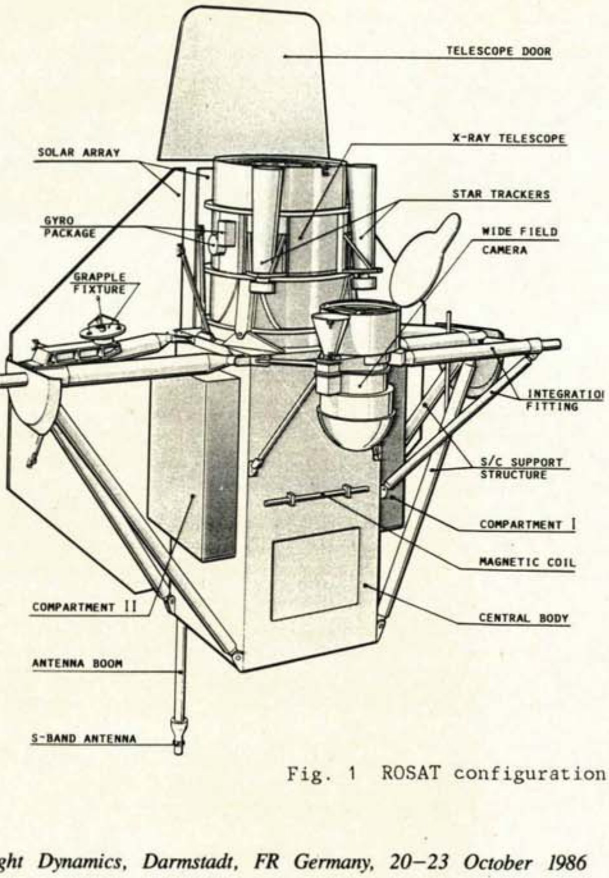

Fig. 1 ROSAT configuration

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The quality of the final attitude solution will significantly influence the success of the ROSAT mission. Special effort is therefore put on obtaining the best attitude solution possible.

2. The Attitude Measurement and Control Subsystem (AMCS)

The AMCS is a digital control system based on an onboard computer. It uses a strapdown system (which is updated by star camera measurements) and quaternion notation. It is provided by MBB as subcontractor.

The satellite has a solar array fixed to the spacecraft structure. The array must be oriented to within ± 15 degrees of the perpendicular to the sun direction. This leads to the constraint that the inertial attitude (i.e. the observable part of the sky) is coupled with the apparent motion of the sun (~ 1 deg/day).

The following attitude control accuracies are required:

- deviation of telescope axis from commanded attitude:
  - 8 arcmin during scan
  - 3 arcmin during pointing
- rate limits in pointing mode: 5 arcsec/sec

Attitude determination to arcsec accuracy will be achieved by a so-called 'post-fact attitude determination' on ground, using gyro and star camera data.

2.1 Subsystem Devices

The spacecraft is equipped with the following attitude devices:

- Attitude Measurement and Control Data System (AMCD):
  a redundant microcomputer-based digital processing system with the following main tasks:
  - acquisition of sensor data
  - attitude determination
  - execution of control algorithms
  - generation of actuator commands
  - command processing and distribution of telemetry
  - star catalogue management
  - time tag control
  - status check of components
  - failure detection and management
- Two imaging Star Cameras:
  for stellar reference to update strapdown system, equipped with CCD devices.
  Field of View: 4.4° x 5.9°
  Sensitivity: + 6.5 mag to 0.0 mag
  Accuracy: ≤ 2 arcsec for pointing
  Update period: 1 sec
  Tracking capacity: 3 real stars,
  1 fiducial light star
  (artificial star in focal plane of the detectors to provide relative position measurements between detectors and the star cameras to monitor launch shift and thermal distortions)

  The CCD-chip consists of 385 x 288 pixels, and every pixel thus covers 55 x 55 arcsec.
  In the pointing mode the image of a star is smeared over 3 x 3 pixels and the star camera electronics calculates the center of the star image, using an interpolation method taking into account line spread function of star image as a function of star colour and position within the field of view and the response function within a pixel as a function of the star colour.
  In the scan mode the star image is smeared over several rows of the detector array.The length of this image depends on the scan velocity. Analogous to the pointing mode an on-board interpolation is used to calculate the star position on the array.
  Geometrical errors in the positioning of the CCD pixels will be directly reflected in the interpolated star positions. In addition, since the absorption in the electrode structure is wavelength-dependent, there will be a colour error in the aperture of the CCD.
- Four rate-integrating Gyros:
  for rate sensing as input to the strapdown system; 3 orthogonal measurement axes and a 4th redundant measurement axis.
  Scale factor: 4/3 arcsec
  Drift: ≤ 0.01 deg/hour in 24 hours
- Four Reaction Wheels:
  for attitude maneuvers; axes oriented to achieve unrestricted torque vector direction in case of failure of any one of the four wheels.
  Momentum capacity: ± 25 Nms
  Torque capacity: 0.2 Nm

2.2 AMCD Operating Modes

- Safe Mode:
  provide survival capability to avoid loss of spacecraft in an AMCS emergency and/or spacecraft malfunction situation. It shall cover the following requirements:
  -insensitive against radiation induced bit flips
  -independant of eclipse or sunlit phases
  -maintain two-axis solar oriented attitude
  -avoid transition of telescope axis through sun
  Attitude devices used: sun sensors, gyros, magnetometer
- Standby Mode:
  provide coarse attitude control and rate stabilization, reaction wheel desaturation, star acquisition to derive inertial attitude on ground
- Normal Mode:
  covers the normal operations scan and pointing
  -scan at rates between 3 arcmin/sec and 5 arcmin/sec
  -scan reversal

-inertially fixed pointing to selected targets
-slewing: automatic time-tagged performance of up to 24 targets during the periods without contact, 180° slewing within 15 minutes

- Degraded Mode:
to reconfigure the AMCS in case of equipment failure or abnormal behaviour of the subsystem in orbit. A RAM capacity is provided to load modified program tasks/modes

- Checkout Mode:
a special mode to check the subsystem on the RMS of the shuttle. In case of grave malfunctions during checkout, ROSAT would be stowed back in the orbiter's cargo bay and brought back to Earth

3. Ground Support Requirements

A mission planning facility will establish the ROSAT mission timeline according to:

- observation requests

- instrumental, astronomical and spacecraft constraints

This timeline, optimizing the available observation time, will be the base for the AMCS operations, requiring commanding and telemetry analysis.

3.1 Commanding

The situation of the control center is characterized by an AMCS subsystem which requires relativ much support from ground and by short contacts during which a large number of commands have to be sent (for AMCS max. 1100 commands per day, mainly star coordinates). A lot of the commands must be time-tagged.

The AMCS requires commands in the following areas:

- orbit/ephemeris data in mean-of-2000.0 coordinates:
for onboard attitude control, spacecraft-earth/sun aspect angle calculations, eclipse and magnetic field calculations

- commands for scan control:
mode initialization, scan axis direction, scan rate and direction, initial scan angle

- star catalogue for scan:
inertial coordinates (unit vectors) and instrumental magnitudes for approx. 500 stars in a strip 7 degrees wide from pole to pole of ecliptic, perpendicular to the direction of the scan axis. The positions will be given in mean-of-2000.0 coordinates corrected for proper motion and parallaxe. The correction for aberration will be applied during the attitude determination. The catalogue must be updated every two days because of the apparent motion of the sun (scan axis motion coupled to sun motion). The catalogue is derived from a master catalogue of 250 000 stars. The stars extracted must meet the following criteria:
  - no variability
  - position accuracy better 1 arcsec
  - instrumental magnitude between 0 mag and 6.5 mag
  - no neighbour stars < 0.05 degree distance with magnitude difference < 4 mag

- commands for pointing control:
mode initialization, begin time of slew, inertial attitude of targets (quaternion notation)

- star catalogue for pointing:
up to 6 reference stars per target, selection criteria as above

- star camera control commands

- maneuver independant commands:
device power and status commands, error limits, biases and misalignments, RAM load, memory dump

- Three Magnetic Coils:
for unloading of the wheels, each coil carries two redundant windings.
Dipole momentum capacity per coil: 350 Am^2

- A three-axis Fluxgate Magnetometer:
to measure the Earth's magnetic field so that the coils can be energized correctly.
Measurement range: ± 50 A/m
Bias error: < 0.5 A/m
Linear error: < 5 %

- A set of three Coarse Sun Sensors:
to control sun pointing, mainly as safety devices. Two oriented in direction of -x-axis (nominal sun direction), one in +x-direction. Together they provide a 4π sterad field of view.
Zero bias error: < 0.2°
Accuracy between ±17° FOV: < 1°

3.2 Telemetry

The short contacts allow only a quicklook of the status and behaviour of the satellite. The realtime telemetry must be automatically compared with predicts to check if the spacecraft is in a nominal status. A pass protocol must be generated by the telemetry processor. The telemetry of the long invisibility periods, stored onboard and replayed (dumped) during the contacts, must also be processed and analized to have a complete history of the spacecraft for attitude determination, AMCS performance analysis and status reports. Special provision will have to be made for estimation of gyro drift, star camera/telescope misalignment and star camera performance.

4. ROSMAC - the Data Management System for ROSAT Attitude Control

To fulfill the requirements of the previous section, a data management and processing system will be established to generate and analize the required data.

ROSMAC will be the interface between the mission planning system and the command system for attitude related commands. A second task is the generation of predicts for the telemetry processor and for the performance analysis software.

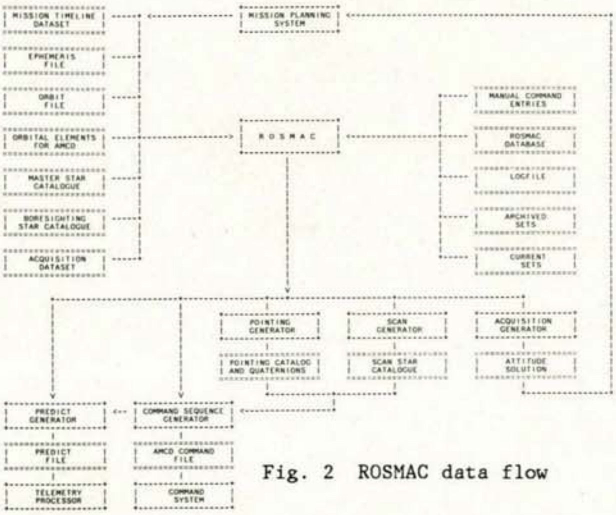

Fig. 2 ROSMAC data flow

5. COORD. SYSTEMS FOR ATTITUDE DETERMINATION

- Inertial Equatorial System (epoch 2000.0)

Origin: Centre of earth
x-axis directed towards the vernal equinox
z-axis directed along the axis of the earth
y-axis completes the right hand system

- The ROSAT system

Origin: Centre of the mass of ROSAT
-x-axis normal to the solar generator array
z-axis along the telescope axis
y-axis completes the right hand system

- The Star Camera Systems

Rotated 45 deg. about ROSAT z axis, and then 3 deg. around the resulting x axis.

- The Gyro Reference Coordinate System

Nominally parallel to the Rosat system but with x,y,z not necessarily corresponding to those of the Rosat system.

- The Fiducial Light Coordinate System

This system is the coordinate system in which 5 artificial stars (the fiducial lights of PSPC and HRI, see also later) are defined as unit vectors. Nominally it is identical with the ROSAT system. Deviations are measured by the fiducial light system (FLS).

- The X-ray Reference Coordinate System

Nominally parallel to the Rosat system. The deviation from it will be estimated by in-orbit calibration by comparision of measured celestial objects visible within the star camera and the x-ray sensors.

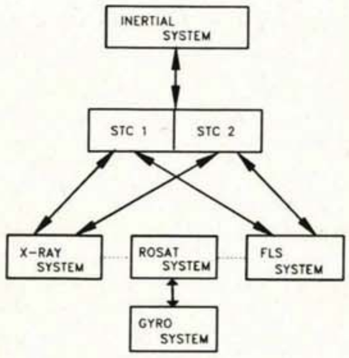

Fig. 3 Coordinate Systems

6. MODIFIED KALMANFILTER

The 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 non-linear differential equations and a set of non-linear measurement equations.
For ROSAT the state modelling is replaced, because on-board measurements of satellite rotation rates are available. Such measurements contain the integration of all torques acting on the spacecraft. Force model errors in the integrated satellite state will then exist only to the extent that the measurements of the satellite rates contain errors. The measurements are made by rate integrating gyros, which are subject to mounting errors and slowly varying biases, as well as errors characterized as either measurement or bias noise.
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. Since ROSAT utilizes quaternions in the on-board processing , it is natural to use quaternions in ground-based processing to produce refined attitude state estimates. In the Kalman filter framework one has to consider the propagation of state errors over the interval for which above integration is made. For ROSAT the quaternion error δq is expressed not as the arithmetic difference between the true and the estimated quaternion but as the quaternion which must be composed with the estimated quaternion q' in order to obtain the true quaternion q.

$$q = \delta q \times q'$$

Since the incremental quaternion corresponds to a small rotation, the fourth component will be close to unity and, hence, all the attitude information of interest is contained in the three vector components. There are four gyro measurements from which the three rotation rate components can be computed. The gyro measurements may be biased, as well as containing high frequency or noise errors. A state vector therefore defined by the vector components of the incremental quaternion and the drift-bias vector will provide a nonredundant representation of the state error. With this state vector

$$X = [\ \delta q\ ,\ b\ ]$$

one can now consider the propagation of both the attitude state and gyro measurement errors.

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

7. IN-FLIGHT MISALIGNMENT MEASUREMENTS

The main task of the operations for the misalignment measurements is the determination of the misalignments between the x-ray coordinate system and the star camera systems. Two parts have to be distinguished:

- the measurements with help of the 'On Orbit Alignment' or 'Boresighting'
- the measurements with a 'Fiducial Light System'

The boresighting determines the mutual alignment between the three x-ray detectors and the star sensors. It is considered as a constant offset until for example another boresighting is done. The dynamical part of the misalignments caused by the thermal deflections during one orbit with sun and eclipse phases is measured with help of the fiducial light system. It provides relative position measurements of up to five artificial stars. The sources (LED's) of these artificial stars are located in the x-ray sensor and directed via an optical path to the star cameras. The fiducial light measurements are used to improve the accuracy of the mounting angles of the starcameras; the boresighting provides a transformation matrix from the fiducial light coordinate system to the x-ray system.

7.1 Boresighting

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 field of views 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 thus is performed in another way. The chosen targets in the starsensor FOV and the x-ray sensor FOV are measured at two different places within the FOV. The resulting lines between these measurements are defining the 3-axis misalignment. The boresighting operation starts with the determination of the

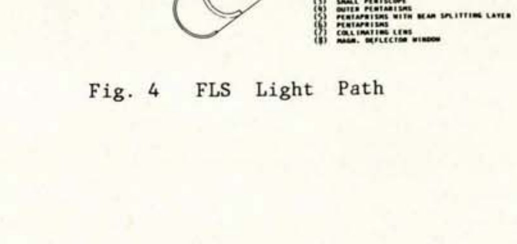

Fig. 4 FLS Light Path

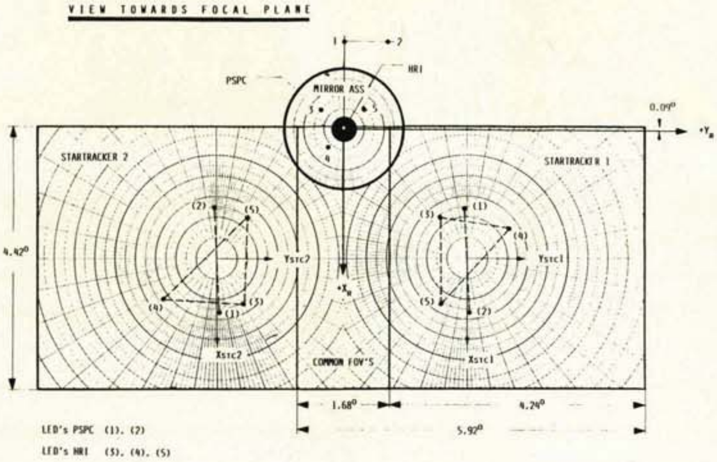

Fig. 5 Field of Views

target stars (visual and x-ray). The reference direction is defined by the inertial attitude of the x-ray source, which is positioned in the upper part of the FOV and then in the lower part of the FOV of the x-ray sensors. The same procedure must be done three times, for each x-ray sensor (HRI, PSPC1, PSPC2).

7.2 Fiducial Light System

With the help of the FLS the thermal deflections caused by periodical change of sunlight and eclipse phases can be determined. This is done in two steps. First the articficial stars of the FLS are measured on board by the star cameras. These measurements are then input to a filter program, which computes 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. The FLS can be operated on board with two telecommands, which specify the duration of the on-time of the LED's. All other operations run automatically. The star cameras measure sucessively all visible artificial stars. The number and location of these stars depend on the x-ray sensor actually placed in the focal plane. Of the five existing LED's three belong to the HRI and the other two to the PSPC. The light path and FOV's are

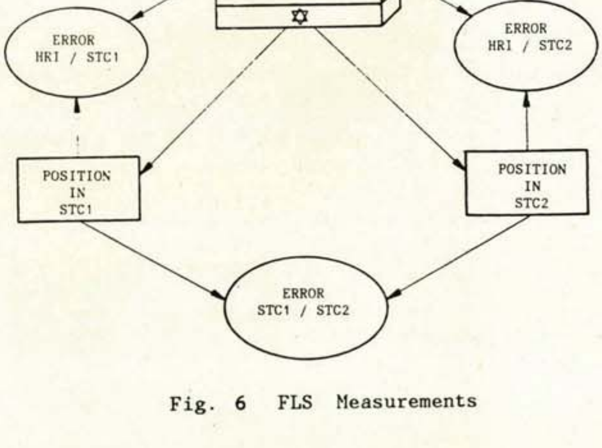

Fig. 6 FLS Measurements

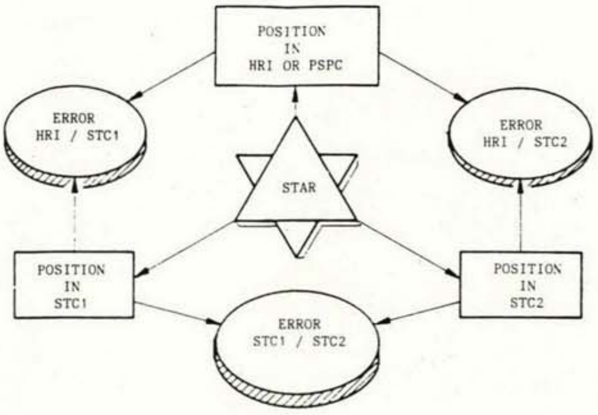

Fig. 7 Boresighting

shown in fig. 4 and 5. Each star normally is tracked for 12 seconds in the sequence 1,2,..5. The measurements are placed in the telemetry stream. In those phases, where the stars 1 and 2 or 3,4,5 are not visible the related telemetry data are ignored.

POST FACTO ATTITUDE DETERMINATION PROCESS

Fig. 8 shows the whole AD process. In a first data check of the telemetry which provides information about the AMCS performance a data quality file is produced. This file contains some parameters to drive the AD program, like measurement times, weighting factors for star camera measurements, gyro noise, etc. After preprocessing and calibrating the attitude measurements (star camera, gyro, on-board quaternions) the FLS measurements are processed by a filter to get the mounting angles for the star cameras as a function of time. These angles and the star camera measurements are the inputs for the AD program, which additionally needs orbit information to correct for the stellar abberation. Star patterns are compared with the reference star catalog, and an output of this program is the attitude of the fiducial light coordinate system relative to the inertial system. Another output is used for the estimation of some parameters like misalignment, biases of the star cameras and gyros. The concept is to combine data from various time periods to obtain the best overall improvement in the RMS of the fits of the attitude measurements with a so called external least square program.
Independently of the FLS a boresighting between the two star cameras is performed aperiodically, to estimate misalignments between the two star cameras, whenever a check of the FLS seems to be necessary. In case of no coincidence with FLS results a new boresighting between x-ray sensors and star cameras has to be executed.
In a last step the attitude of the telescope axis has to be transformed from the fiducial light system to the x-ray coordinate system by using matrices , obtained from the last boresighting.

9. Final Remarks

Because of extremely short station contact periods of a few minutes and a very high data rate of megabits per second the main problem will be to run the whole ROSAT TM/TC and data processing ground system, in which the post-facto attitude determination system is just a small part, with as little manual input as possible. To eliminate software errors and to train the operational personnel an AMCS simulator was built to provide the ground system with realistic telemetry data and to command a simulated spacecraft. One year before launch this test- and training period will start. For a few weeks after launch final checks of the on-board system of the real ROSAT and the ground system at GSOC will be made , before going into routine production of attitude and science data.

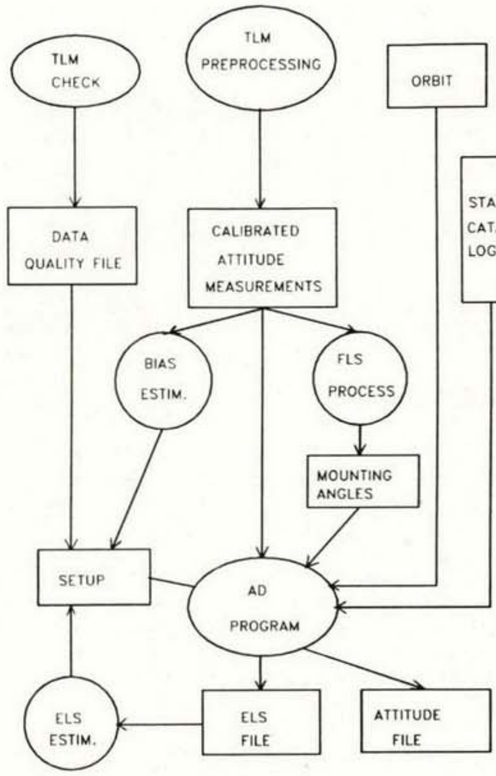

Fig. 8 Post-Facto AD Process

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