STAR TRACKER/GYRO CALIBRATION AND ATTITUDE RECONSTRUCTION FOR THE SCIENTIFIC SATELLITE ODIN - IN FLIGHT RESULTS

Jacobsson B (1), Nylund M (1), Olsson T (1), Vandermarcq O (2), Vinterhav E (1)
(1) Swedish Space Corporation, P.O. Box 4207, SE-171 04 Solna, Sweden
(2) CNES, 18 Avenue Edouard Belin, 31041 Toulouse Cedex 4, France
e-mail: torbjorn.olsson@ssc.se / Fax +46 8 98 70 69
e-mail: olivier.vandermarcq@cnes.fr

ABSTRACT

The small satellite Odin, launched February 20, 2001, combines two different scientific disciplines, astronomy and atmospheric research. It has a 3-axis stabilised, zero momentum, attitude control system that operates in two different modes, an inertial pointing astronomy mode and an atmospheric mode providing pointing/scanning of the Earth limb. The absolute pointing requirements at the attitude control sub-system level is 8 arcseconds in inertial pointing mode and 1 arcminute in Earth scanning mode, requirements that after the commissioning phase has been fulfilled with margin.

This article presents the basic principles and methods for the on ground Attitude Reconstruction S/W and the principles and methods for the Calibration S/W. The operational aspects are emphasised.

The Calibration S/W is responsible for estimation of biases, scale factors and alignment parameters for the prime sensors - the two medium field-of-view Star trackers and the three 2-axis DTG (dynamically tuned gyroscope) gyro packages. In-flight results are presented; the one year in-orbit has given valuable insights into the stability and consistency in the calibration parameters.

INTRODUCTION

The Odin satellite combines two scientific disciplines on a single spacecraft: astronomy in studies of star formation and aeronomy the mechanisms behind the depletion of the ozone layer in the atmosphere. Odin was developed by Swedish Space Corporation (SSC), on the behalf of the Swedish National Space Board and the space agencies of France, Canada and Finland and was launched from the Svobodny Cosmodrome in february the 20th 2001 with a Start-1 launching vehicle. Odin orbits the earth in a sun-synchronous orbit, presently at an altitude of 594 km.

The daily operations of Odin is carried out by SSC from Esrange, Kiruna in the north of Sweden.[1] The high latitude of the ground station (69°N) makes it ideal for satellites with polar orbits as Odin. There are about 11 passages with radio contact, each of them 3-11 minutes, per day. The Odin mission control is situated in SSC:s office in Solna, Stockholm. Here the feasibility of the scientific observations are technically validated.

Mission Overview

Both scientific missions, aeronomy and astronomy, are studying the same molecules and, in many cases the same radiate transitions. Therefore only one main instrument is required: A radiometer system consisting of five submm and mm heterodyne receivers fed by a 1.1 metre telescope. The telescope is fixed and mounted on the spacecraft body. For the aeronomy mission Odin also carries an optical slit spectrograph developed in Canada, OSIRIS (Optical Spectrograph and InfraRed Imaging System). This instrument is used to detect aerosol layers and abundance of some molecules in the atmosphere.

The Odin science team, consisting of scientists from Sweden, France, Canada and Finland have defined the scientific goals. These goals have established the requirements of the Odin attitude control system. In astronomy the satellite is commanded so the telescope line-of-sight is the direction of a fix point in the sky (inertial pointing). This means that the instruments are occulted by the earth in part of the orbit (approximately one third), this is depicted in Figure 2. In aeronomy the line-of-sight is in the tangent of the earth limb, i.e. the attitude of the satellite is continuously altered, this is depicted in Figure 3.

These pointing tasks are accomplished by a 3-axis stabilised attitude control system (ACS) with an inertial reference. The ACS on Odin was developed by SSC.[2]

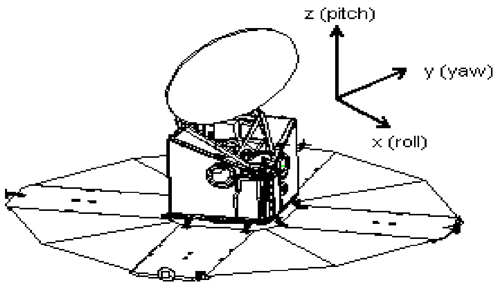

Figure 1. The Odin Satellite.

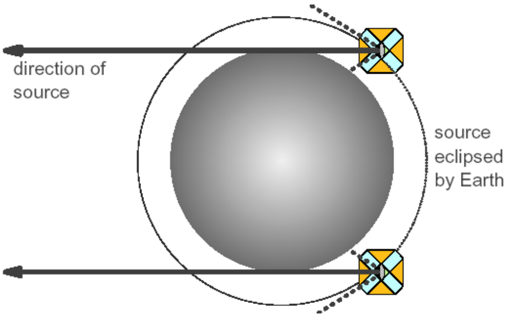

Figure 2. Astro staring geometry.

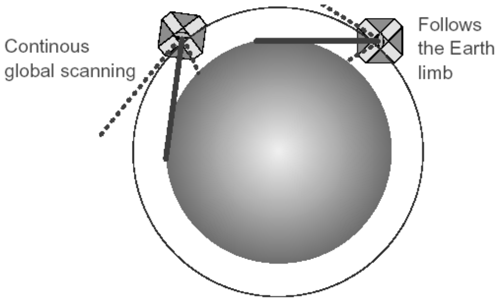

Figure 3. Aero limb following geometry.

ATTITUDE RECONSTRUCTION AND ST CALIBRATION

Purpose

The purpose of the attitude reconstruction software is:

- Primarily to provide the scientists with the data that define the attitude the S/C platform during the mission in both cases aeronomy and astronomy,
- To monitor the performance and consistency between the prime attitude sensors : star trackers and gyros,
- To provide a monitoring capacity of the measurements delivered by Sun sensors and magnetometers,
- To monitor the pointing accuracy of the S/C

The purpose of the ST calibration software is :

- primarily to estimate the relative misorientation between the two Star Trackers (ST) optical heads (OH)
- secondly to estimate the residual scale factors of the OH.

The calibration is necessary to improve the precision of the reconstructed attitude and reach the pointing requirements; it is also necessary for the onboard ACS system to work properly during the mission when both STs are used.

Attitude reconstruction principles

The attitude of the S/C platform is reconstructed based upon the star trackers and the gyros measurements that are downloaded.

The attitude of the platform is defined with respect to (wrt) an inertial coordinate frame that is a transformation of FK5 system at the current date. The attitude is represented by quaternions.

A Kalman filter estimates 6 parameters corresponding to the 3-axis attitude and gyros drift errors estimated in the S/C control frame. The filter is classically based on :

- a state model which represents the relation between the kinematics of the attitude and the gyro measurement
- an observation model which represents the relation between the ST measurements and the attitude of the platform.

The principle of the filter is to compute sequentially the attitude that makes the observation model of ST measurements match with real measurements. It is an optimal filtering process, were the observations are linearised around the estimated attitude.

Observation model

The ST provides for each of the measured stars (a maximum of 3), the tangents (z1,z2) of two angles that define the direction of the star wrt the ST coordinate frame.

The linearised observation model for one star measurement can be written with the form:

$$\Delta Z_{ST} = \begin{bmatrix} \Delta z1 \\ \Delta z2 \end{bmatrix} = \begin{bmatrix} 0 & 1 & z2 \\ -1 & 0 & -z1 \end{bmatrix} \Delta\theta_{ST}$$

were $\Delta\theta_{ST}$ represents a small variation of the ST attitude defined by a vector of the components of the rotations around the x,y,z axis of the ST.

If the attitude variation is defined in the S/C system, the observation model of the attitude variation becomes:

$$\begin{bmatrix} \Delta z1 \\ \Delta z2 \end{bmatrix} = \begin{bmatrix} 0 & 1 & z2 \\ -1 & 0 & -z1 \end{bmatrix} P_{ST} \Delta\theta_{SC}$$

$$\Delta Z_{ST} = H_{ST} \Delta\theta_{SC}$$

were P_{ST} is the transformation matrix between the ST and the SC frame and $\Delta\theta_{SC}$ represents a small attitude variation in the S/C frame.

Attitude determination error analysis

The results of a simplified error analysis based on the linear observation model and optimal filtering are provided below.

The results from optimal estimation based on the ΔZ observations can be written with the form:

$$\Delta\hat{\theta} = \left(H^T R^{-1} H\right)^{-1} H^T R^{-1} \Delta Z = H^* \Delta Z$$

We consider now that the ST measurements (*z1,z2*) are corrupted and that the distribution of the measurement errors is normal and centred with a covariance matrix represented by the matrix R:

$$R = \begin{bmatrix} \sigma_{ST}^2 & 0 \\ 0 & \sigma_{ST}^2 \end{bmatrix}$$

In that case, the distribution of the estimation error based on optimal filtering is also normal and centred and the covariance of the error is :

$$Cov = \sigma_{ST}^2 \left(H^T H\right)^{-1}$$

This allows us to obtain analytical expression of the 1σ standard deviation of the reconstructed attitude error in some "academic" cases.

Case 1: ST1 and ST2 are both measuring one star centred on the line of sight (LOS). In that case:

$$H = \begin{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \times P_{ST1} \\ \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \times P_{ST2} \end{bmatrix}$$

and the expression of the covariance matrix of the attitude estimation error is given in the S/C coordinate frame by:

$$Att\_Cov = \frac{\sigma_{ST}{}^2}{2} \begin{bmatrix} 1/\sin^2\alpha & 0 & 0 \\ 0 & 1/\cos^2\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

were α represents the separation angle between the line of sight (LOS) of the STs and the SC x-axis.

With α=20° (Figure 4), the standard deviation for the attitude around the SC x-axis is degraded by a factor of 3 compared with the attitude error around the z-axis; the degradation around y-axis is small (factor 1.1). Assuming a standard deviation of the ST measurement error of 3arcsec, we obtain the following the typical uncertainties for the estimated attitude:

SC axis	$\sigma_{\theta SC}$ (arcsec)
X	6
Y	2
Z	2

Table 1.

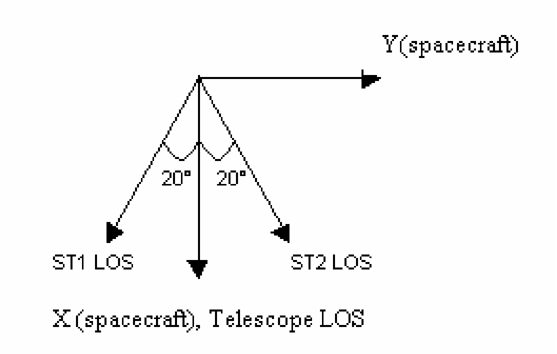

Figure 4. A schematic geometry for the star trackers and the telescope. The Z spacecraft axis completes the Cartesian system and thus points out from the paper.

Case 2: ST1 is measuring 2 stars, no star measured by ST2. If we assume the directions of the 2 measured stars S1 and S2 are such that:

- *z1*(S1) = *z1*(S2) = 0
- *z2*(S1) = -*z2*(S2) = z

The observation model matrix becomes :

$$H = \begin{bmatrix} 0 & 1 & z \\ -1 & 0 & 0 \\ 0 & 1 & -z \\ -1 & 0 & 0 \end{bmatrix} \times P_{ST1}$$

In that case, the covariance of the attitude error is :

$$Att\_Cov = \frac{\sigma_{ST}{}^2}{2} \begin{bmatrix} 1+\left(1/z^2-1\right)\cos^2\alpha & -\left(1/z^2-1\right)\sin\alpha\cos\alpha & 0 \\ -\left(1/z^2-1\right)\sin\alpha\cos\alpha & 1+\left(1/z^2-1\right)\sin^2\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

From this expression and taking a separation angle of 6° between the stars, we obtain a factor of 18 (resp. 7) between the uncertainty that can be expected around the z and the uncertainty around the x (resp. y) axis. We observe also the coupling between x and y SC-axis due to the (α) separation between the ST LOS and the x-axis of the S/C control frame.

Assuming that in general, the standard deviation of the ST measurement error is 3arcsec, we obtain the following uncertainties for the estimated attitude:

SC axis	$\sigma_{\theta SC}$ (arcsec)
X	38
Y	14
Z	2

Table 2.

ST relative calibration principle

The estimation of the attitude will be biased when the observation errors are not centred (non-zero mean value). This is the case here, since the a priori knowledge of the real in-flight orientations of the STs is known with poor accuracy.

The ST calibration consists essentially in estimating the parameters that define the in-flight orientation of the STs.

The calibration procedure is achieved in 3 steps:

1) estimate of the orientation parameters
2) validate the new estimates
3) update the onboard and on-ground attitude determination and reconstruction functions with the new orientation parameters

The estimation of the orientation of STs is performed on-ground with a Kalman filtering of the STs and gyros measurements that are telemetry downloaded. Compared with the attitude reconstruction process, the ST calibration implements an extended observation model. It benefits also from specific attitude profile and guide star selection in order to minimize the effects of the STs short term errors.

Observation model

We add new parameters in the observation to take into account the knowledge error of the orientation (let's call this the misorientation) of the STs called $\Delta\theta_{ST1}$, $\Delta\theta_{ST2}$ that are defined in the S/C frame:

$$\Delta Z_{ST1} = H_{ST1} \times \Delta\theta_{SC} + H_{ST1} \times \Delta\theta_{ST1}$$
$$\Delta Z_{ST2} = H_{ST2} \times \Delta\theta_{SC} + H_{ST2} \times \Delta\theta_{ST2}$$

By decomposing the individual misorientations of ST1 and ST2 with common and relative components, we write:

$$\Delta\theta_{ST1} = \Delta\theta_{STcom} + \Delta\theta_{STrel}$$
$$\Delta\theta_{ST2} = \Delta\theta_{STcom} - \Delta\theta_{STrel}$$

The observation becomes:

$$\Delta Z_{ST1} = H_{ST1} \times (\Delta\theta_{SC} + \Delta\theta_{STcom}) + H_{ST1} \times \Delta\theta_{STrel}$$
$$\Delta Z_{ST2} = H_{ST2} \times (\Delta\theta_{SC} + \Delta\theta_{STcom}) - H_{ST2} \times \Delta\theta_{STrel}$$

The STs cannot themselves provide the information needed to distinguish the effect of a common misorientation of both STs, from an effect of attitude knowledge error. Due to the fact that the calibration is performed at the platform level only, payload being excluded, the common misorientation is excluded from the ST calibration; only relative misorientation is taken into account and estimated. We write:

$$\Delta Z_{ST1} = H_{ST1} \times \Delta\theta_{SC} + H_{ST1} \times \Delta\theta_{STrel}$$
$$\Delta Z_{ST2} = H_{ST2} \times \Delta\theta_{SC} - H_{ST2} \times \Delta\theta_{STrel}$$

Error analysis

We analyse the effect of a relative misorientation between the STs on the attitude knowledge error. A bias in the estimated attitude will result from a misorientation of the STs:

$$\Delta\hat{\theta}_{SC} = H^{*} \begin{bmatrix} H_{ST1} \\ -H_{ST2} \end{bmatrix} \Delta\theta_{STrel}$$

Case 3: ST1 and ST2 are each measuring one star (like in case 1) located in the center of the field of view (FOV).

In that case, the mean deviation of the estimated attitude from the case where the observations are not biased by the misorientation is :

$$\Delta\hat{\theta}_{SC} = \frac{1}{2} \begin{bmatrix} 0 & \cot an(\alpha) & 0 \\ \tan(\alpha) & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \Delta\theta_{STrel}$$

Numerically:

$$\Delta\hat{\theta}_{SC} = \frac{1}{2} \begin{bmatrix} 0 & 2.75 & 0 \\ 0.36 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \Delta\theta_{STrel}$$

We can notice that in this case, were both STs are used:

- a relative misorientation between the ST around the SC z-axis has no effect on the attitude;
- a deviation of the attitude around the S/C x-axis results from a ST relative misorientation around the SC y-axis with a factor of amplification of 1.4
- the deviation around SC y-axis results from a ST relative misorientation around SC x-axis with a factor of 0.18.

In the case below, we define the uncertainty that can be expected in the estimation of the relative alignment. Based on the observation model were we include the noise η on the measurement:

$$\Delta Z_{ST1} = H_{ST1} \times \Delta\theta_{SC} + H_{ST1} \times \Delta\theta_{STrel} + \eta_1$$
$$\Delta Z_{ST2} = H_{ST2} \times \Delta\theta_{SC} - H_{ST2} \times \Delta\theta_{STrel} + \eta_2$$

we now include the relative misorientation in the parameters to be estimated. The global observation matrix becomes:

$$H = \begin{bmatrix} H_{ST1} & H_{ST1} \\ H_{ST2} & -H_{ST2} \end{bmatrix} \text{with a state vector } X = \begin{bmatrix} \Delta\theta_{SC} \\ \Delta\theta_{STrel} \end{bmatrix}$$

Case 4: ST1 and ST2 are each measuring two stars.

With a separation angle of 6° in each couple of stars, the numerical expression of the covariance matrix is:

$$Cov = \sigma_{ST}^{2} \begin{bmatrix} C1 & -C2 \\ -C2 & C1 \end{bmatrix}$$

$$\text{with } C1 = \begin{bmatrix} 80.4 & 0 & 0 \\ 0 & 10.9 & 0 \\ 0 & 0 & 0.25 \end{bmatrix}, C2 = \begin{bmatrix} 0 & 29.2 & 0 \\ 29.2 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

C1 provides the standard deviation (1σ) for the attitude estimation error and for the estimation error of the relative misorientation between the STs expressed in the SC frame:

SC axis	$\sigma_{\theta SC}$ $\sigma_{\theta ST}$
X	9.0 x σ_{ST}
Y	3.3 x σ_{ST}
Z	0.5 x σ_{ST}

Table 3.

Conclusion of the error analysis

The simplified error analysis provide the theoretical performance of the reconstructed attitude and ST calibration that can be expected. The attitude error is composed with

1) a short term "noise" component mainly derived from ST measurement error
2) a bias component mainly coming from the knowledge error about the ST orientation

The noise component will be further reduced (not developed in this paper) thanks to the Kalman filtering of the STs + gyros measurements, while the bias component cannot.

The following tables summarizes the results, assuming that the standard deviation for the ST measurement error is 3 arcsec.

One can expect the standard deviation of the reconstructed attitude error – short term error - to be :

SC axis	ST1 + ST2	ST1 alone
X	6 arcsec	38 arcsec
Y	2 arcsec	14 arcsec
Z	2 arcsec	2 arcsec

Table 4.

One can expect a systematic shift of the attitude error due to the ST misorientation ($\Delta\theta_{STrel}$) to be:

SC axis	ST1 + ST2	ST1 alone
X	1.4 x $\Delta\theta_{STrel}(2)$	1 x $\Delta\theta_{STrel}(1)$
Y	0.18 x $\Delta\theta_{STrel}(1)$	1 x $\Delta\theta_{STrel}(2)$
Z	0	1 x $\Delta\theta_{STrel}(3)$

Table 5.

One can expect the ST calibration to reduce the relative misalignement of ST in the range (1σ) :

SC axis	$\Delta\theta_{STrel}$ *(arcsec)*
X	$\Delta\theta_{STrel}(1)= 27$
Y	$\Delta\theta_{STrel}(2)=10$
Z	$\Delta\theta_{STrel}(3)=1.5$

Table 6.

The Attitude reconstruction and Star tracker calibration software.

The attitude reconstruction and ST calibration functions have been implemented in a Matlab single package in order to share a maximum of subfunctions. The core process consists in a Kalman filtering of the gyros and ST measurements that are included in the telemetry. The user is assisted in the retrieval of telemetry and other input data files. He has the capacity to monitor the progress and the behaviour of the processing. A number of plots can be displayed which provide a capacity for deep analysis.

The attitude reconstruction software outputs in one file the information necessary for the scientists to know the position and velocity of the satellite, the attitude of the platform and during aeronomy mission, the geodetic coordinates of the line of sight of the payload instrument. The sampled data (1.06s) are time tagged both with UT and relative orbit time.

A few features are listed below.

Attitude initialisation

The attitude is initialised at the first point in the telemetry flow of data where a star identification procedure succeeds. This first star identification uses the raw attitude information down-loaded from on-board computer and at least the measurements for 2 tracked stars. A Quest algorithm is then used to refine the attitude estimate and define initial covariance of the attitude estimation error.

Forward-Backward processing

A forward-backward Kalman pass on the data allows to remove a large part of the transition effects due to the filter initialisation. It allows also to process the telemetry file from the very first format whatever the availability of ST measurements at this first format.

Stellar correction

The J2000.0 inertial star coordinates provided by the star catalogue are compensated with the precession and nutation of the current date and by the annual aberration and aberration due to SC relative motion around the Earth.

Star identification

A star identification procedure is implemented which transforms the directions of the measured stars in the inertial coordinate frame and perform a matching with the catalogue referenced stars that are close.

The procedure is first applied during the initialisation. It is also applied during the sequential process whenever a change or unconsistency are detected in the measured star pattern.

Data Acceptation

Before being accepted as input data to the Kalman filter, the star tracker measurements are tested against reconstructed measurements based on the current attitude estimate. The acceptance test uses a threshold level that takes into account the variance of the attitude computed by the Kalman filter and the uncertainties on the ST misorientation.

Star calibration

The estimation of the relative misorientation between the STs optical heads is achieved through a two steps Kalman sequential process.

The first step allows the attitude and the gyros drift to be estimated (as in the attitude reconstruction software). Independently from that, the residual scale factor of any optical head is updated through a sequential filter, whenever two stars are measured at least.

The second step is performed whenever both STs measure two stars at least each simultaneously. This step allows to estimate a relative misorientation for each optical head. It is there assumed that the residue between the obtained star tracker measurements and the expected ones are only dependent from the searched misorientations. The orientation parameters of one ST taken as the reference sensor (ST2) are kept unchanged. The estimated misorientations are differentiated and used to update the orientation parameters of the other ST (ST1).

IN FLIGHTS RESULTS

Star Tracker Calibration – Operation Principles

The ST calibration parameters, i.e. the alignment and the scale factors, have been continuously monitored during the Odin lifetime. Monitoring of the alignment parameters are made at “free orbits”, i.e. orbits in the transition between scientific disciplines where no observations are made and therefore are available for suitable calibration manoeuvres.

In the planning of ST calibration manoeuvres the following considerations are made:

- At least two tracked objects in each star tracker must be used in order to get fully determined estimator.
- Tracked objects with high magnitude and a large angular separation generally provide better estimation.
- The manoeuvres should be made so the tracked objects moves over the ST field-of-views in order to cancel out local residual errors on the charge-coupled device (CCD).

When processing the calibration data the following procedure are used:

- The tracked objects are investigated, to make sure there is no unexpected offsets in position compared to the Odin input catalogue.
- New calibration parameters are calculated with the ST calibration software.
- The new calibration parameters are evaluated against the old ones by re-performing the attitude reconstruction for a number of observation programs.
- If the improvement of the attitude reconstruction result is significant - the onboard and on-ground attitude determination and reconstruction functions are updated with the new parameters

In Figure 5 an example of an evaluation of an attitude reconstruction result is depicted Here a significant improvement on the innovations calculated from ST1 measurements can be observed. The high values on the x co-ordinates of the measurements in a) indicates a significant relative misalignment of the ST:s, which is almost cancelled with the new calibration parameters.

The error of the nominal alignment parameters, i.e. before in orbit calibration, was expected to be less than ± 0.1° for both star trackers. The misalignment of the nominal alignment parameters compared to the in-orbit calibrated parameters was found to be: [-0.02479° 0.1732° -0.0612°] in ST1 co-ordinate frame.

The mean alignment has shown to be very stable throughout the lifetime, although there have been periods with a small, but discernible bias: 5-10 arcsec. The short-time (diurnal) variations are less than 5 arcsec.

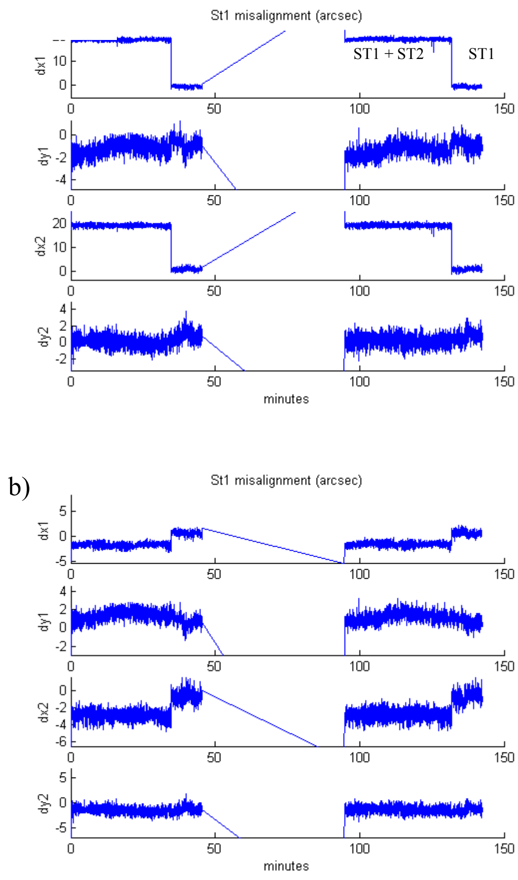

Figure 5. The innovations of ST1 measurements from reconstructed attitude for two tracked objects on star tracker1 are depicted a) Before the successful calibration b) After the successful calibration.

Gyro Calibration – Operation Principles

To characterise the gyro error sources and estimated the calibration parameters the following approach is used:

- A fix staring attitude are applied on the spacecraft in series of orbits. The staring attitude orbits are alternated with orbits containing manoeuvres around the gyro measurement axes.
- The fix staring orbits are analysed, to characterise the disturbances on the gyro output data, i.e. the accumulated angles data on the measurement axes.
- The data containing the manoeuvres are processed with the information from the analysis of the fix staring orbits.
- After synthesis of the data containing the manoeuvres, alignment parameters for the gyros are estimated.

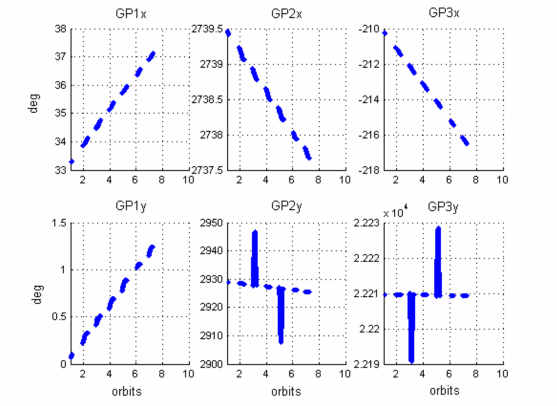

Figure 6. Accumulated angles from the gyros. The slopes of the graphs depicts the long term drifts. Orbit 3 and 5 containing an spacecraft z axis maneouvre.

In Figure 6 measurements for an series of calibrations orbits are depicted, where orbit no 3 and 5 contains manoeuvres around spacecraft Z axis (GP 2y and GP 3y measurement axes), the rest of the orbits contain fixed staring attitudes. The slope of the lines represents the gyro constant drift.

Analysis of the data from the gyro calibration has a surprise: A sinusoidal disturbance component in the gyro output; this is depicted in Figure 7. This component, with deterministic properties, is believed to depend on either internal thermal motions of the satellite structure or electromagnetic disturbance. The characteristics for the disturbance are similar for consecutive orbits, therefore it is assumed this disturbance can be modelled and used to extract the gyro output data.

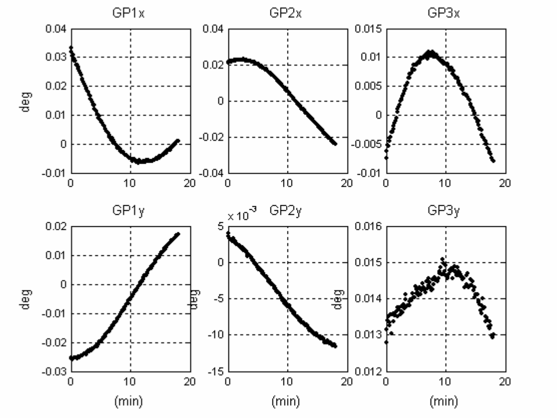

Figure 7. Remaining disturbance after removing long-term drift.

In addition there is a is a disturbance on the gyro output data when the magnetic coils are active. This disturbance is of the same magnitude as the ones depicted in Figure 7.

Since the time constants of the described disturbances are so long compared to the time resolution of attitude processing their impact on the overall ACS behaviour is negligible.

The error of the nominal alignment parameters, i.e. before in orbit calibration, was expected to be less than ± 0.1° for the gyros. The misalignment of the nominal alignment parameters compared to the in-orbit calibrated parameters was found to be in the order of 10 arcmin.

Attitude Reconstruction

Figure 8 and Figure 9 show the result of the attitude reconstruction of an astronomy staring observation with a calibrated ACS.

Figure 10 and Figure 11 show the result of the attitude reconstruction of an aeronomy limb scanning observation with a calibrated ACS.

The standard deviations in Figure 9 and Figure 11, which are extracted from the reconstruction software, can be compared to the values from the error analysis in Table 4. Note, that in these case with several tracked stars the calculated standard deviation is even smaller than the one from the theoretical analysis. The smaller values of the standard deviation also stem from the fact the attitude reconstruction use gyro/ST measurements whereas the analysis only consider ST measurements.

The small visible offsets in Figure 8 when changing configuration from one to two star trackers and vice versa are effects from the small relative misalignment between the star trackers; compare the error analysis in Table 5. These are well within acceptable limits.

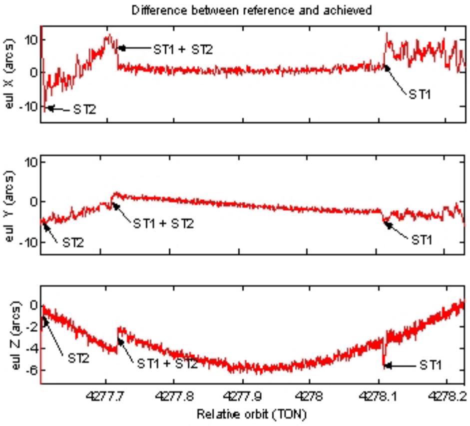

Figure 8. Attitude reconstruction from an staring observation. The diagram show the difference of a the reference attitude and the reconstructed attitude around the spacecraft axes, for the observation fraction of an orbit, ~60 min.

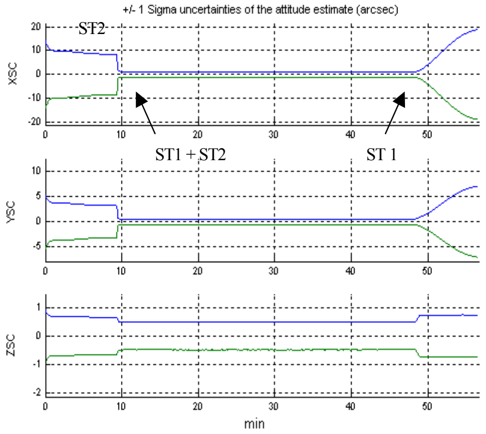

Figure 9. The standard deviation for a staring attitude reconstruction. Note how the standard deviation decreases when both ST are tracking and how it increases again when star ST2 is occulted.

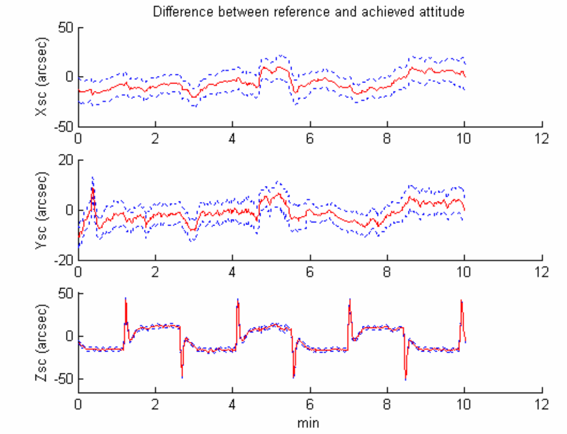

Figure 10. Reconstructed attitude in limb scanning. The scanning manoeuvres are around Zsc.

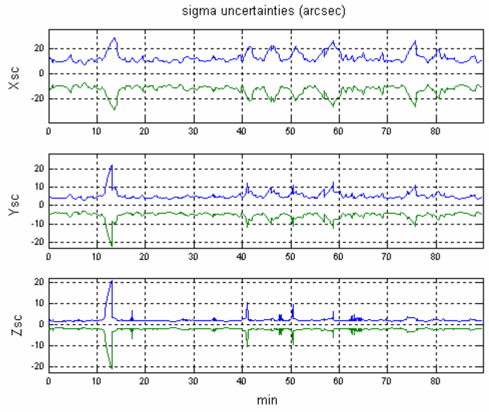

Figure 11. The standard deviation for a limb scanning attitude reconstruction.

CONCLUSION

To fulfill the pointing requirements - a few arcsecs - it is necessary to calibrate the prime sensors, star trackers and gyros. The calibration and attitude reconstruction software, developed for the Odin mission, have been proven to be accurate and robust. The in-flight behaviour of star trackers and gyros meets the requirements and allows the ACS to reach such high performance of pointing.

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