CONTINGENCY OPERATIONS DURING FAILURE OF INERTIAL ATTITUDE ACQUISITION DUE TO STAR TRACKER BLINDING FOR THREE-AXES-STABILIZED INTERPLANETARY SPACECRAFT

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ABSTRACT

The three interplanetary ESA missions Mars-Express, Rosetta and Venus-Express (launched 2003, 2004 and 2005 resp.) are three-axes stabilized spacecraft (s/c) that estimate their inertial attitude (i.e. the attitude of the s/c w.r.t. the inertial frame) using measurements from a redundant set of star trackers (STR). Each s/c is equipped with four reaction wheels, a reaction control system based on thrusters and a redundant set of ring laser gyroscopes (gyros).

The STR h/w layout of the three s/c is identical whereas there is a difference in the star pattern recognition algorithm of Rosetta which uses five neighbouring stars around a central star instead of star triads. The Rosetta algorithm has been implemented to cope with the presence of false stars which are expected to be seen during operations around the comet.

The attitude acquisition capability from lost in space is different also in terms of AOCMS: The survival mode of Rosetta which is entered upon STR failure is presented. The AOCMS of Mars- and Venus-Express manages temporary STR outages during sky occultation by the planet not even by using redundancy. Though, a blinding of both STR during cruise lasting for the order of days confronts the ground operators with the limits of the AOCMS design. The operations and analyses that have been planned and partially been performed to compensate for the outage of the STR are demonstrated for Mars-Express. The caution measures taken before Venus orbit insertion of Venus-Express are detailed.

1. INTRODUCTION

The autonomous acquisition and coarse attitude determination mode (AA&CAD) of the STR is entered upon start-up of the actions of the AOCMS that are performed when the s/c leaves safe mode. It is the back-up mode of the nominal STR mode, the autonomous tracking and fine attitude determination mode (AT&FAD). In AA&CAD the STR applies a star pattern recognition algorithm to an image of the full charge-coupled device (CCD) with 1024x1024 pixels. After a successful match of a pattern the attitude is determined and a star catalogue is tested against the complete list of objects in the field of view. Eventually this attitude represents the initial point for AT&FAD: On AOCMS level a Kalman filter uses the gyro measurements to predict the CCD image locations of max. nine tracked stars at time of STR measurement. At 2 Hz frequency the estimation vector consisting in the rotational degrees of freedom is corrected by the innovations resulting from the measured locations. *A posteriori* the estimation vector serves as an estimate as well for the gyro bias.

The quality of the CCD image and therefore the success of the coarse attitude determination is very sensitive against the radiation and dust environment (Rosetta) of the STR field of view.

2. THE MARS-EXPRESS EXPERIENCE

On October 28th 2003 an enormous coronal mass ejection swept past the Earth and Mars-Express - 1.4 AU away from the Sun and 0.53 AU away from the Earth - on its way to Mars. The s/c stayed in normal mode with its guidance based on Ephemeris, but the STR lost its stars completely and exited AT&FAD. After several minutes in stand-by mode the nominal STR entered AA&CAD and attempted the autonomous acquisition. After failure it returned to stand-by mode, waited and started another attempt. This sequence repeated during the next 32 hours. On ground command the redundant STR had been checked and showed the same behaviour. The gyro bias estimation was frozen by the AOCMS when AT&FAD was exited. Then the s/c maintained its attitude estimation by application of this gyro bias to the gyro measurements.

Tab. 1. Attitude determination: Errors to be considered

Type of error	Difference between	applicable with STR	applicable w/o STR
Orbit	True and determined orbit	No	Yes
Guidance	Commanded attitude and attitude aimed by ground	No	No
Control	Commanded and estimated attitude	No	Yes
Estimation	Estimated and true attitude	Yes	(Yes)
Alignment	Nominal and true HGA bore-sight	No	Yes
Calibration	Calibrated and true HGA bore-sight	No	Yes
Signal	Recorded and theoretical signal strength	No	Yes

If the gyro bias was unstable an estimation error would result that increases with time. The primary concern on a drifting attitude was the loss of the link via the high gain antenna (HGA). The communication to the Earth was established through the HGA in X-Band with a 3dB half cone angle of about 0.5 deg. Accounting for an absolute gyro bias of several tens of a degree per hour a total off-pointing by more than the 3dB half cone angle was expected to occur after about 1 day. This concern was aggravated by critical circumstances: The solar activity late October/early November 2003 consolidated on a high level due to a giant sunspot. In addition ESOC was just preparing Mars-Express for the trajectory correction manoeuvre planned for November 10th that put the s/c on collision course to Mars for Beagle 2 ejection.

An on ground determination of the attitude was needed. The difference between determined and nominal attitude divided by the time elapsed since the gyro bias estimation was frozen gives the average residual gyro bias that could be cancelled by ground:

$$bias_{residual} = \frac{\Delta\varphi \cdot \grave{e}_{\varphi}}{\Delta t} \qquad (1)$$

where:

$\Delta\varphi$ is the drift angle

$\grave{e}_{\varphi}$ is the drift axis unit vector

Δt is the elapsed time

2.1 The procedure

The knowledge of a direction in s/c frame that is fixed in a known reference frame reduces the attitude determination to the determination of the rotation angle around this direction. The Ephemeris guidance frame of the s/c is a frame in which the Earth direction is fixed. Its iner-

tial rate was app. 0.4 deg/day at that time - mainly due to the movement of the Earth. The Earth direction in s/c frame can be determined using slews around axes transversal to the nominal HGA bore-sight and a time correlated measurement of the strength of the antenna gain control signal at the ground station. The remaining rotational degree of freedom can be determined by the Sun acquisition sensors (SAS) mounted on the s/c body provided that rotations around the Earth direction cause substantial variation of the Sun direction in s/c frame. This requirement is fulfilled the better the closer the separation angle between Earth and Sun to 90 deg. Special attention must be paid to sources for errors in this procedure (see Tab. 1). The standard deviation of the nominal on board estimation process is 3 mdeg per estimation cycle. It will be demonstrated that, by contrast, the on ground determination of the Earth direction in s/c frame involves the errors indicated in the rightmost column.

2.2 Inertial Earth and Sun directions

The uncertainties in the direction of the Earth and the Sun in inertial frame are only due to the uncertainty of the position of the s/c. From planar geometry it follows that the orbit uncertainty translates into the uncertainty for the direction vector with the amplification factor:

$$\frac{\partial\varphi}{\partial\Delta} = \left(\frac{\partial\Delta}{\partial\varphi}\right)^{-1} = \left(r\frac{\partial\varphi}{\partial\varphi}\right)^{-1} = \frac{1}{r} \qquad (2)$$

where:

φ is the angle polar coordinate

Δ is the spatial variation along the angle polar coordinate local unit vector

r is the distance polar coordinate

The standard deviation of the orbit determination was 8 km early November 2003. Therefore the errors in the direction vectors are absolutely negligible at these distances.

3. DETERMINATION OF EARTH DIRECTION IN S/C FRAME

3.1 Slew design

The slews around a set of transversal axes x and y of the HGA nominal bore-sight (= z axis) need to be large enough to make the true bore-sight cover the position of the true Earth direction in both dimensions (see Fig. 1). The guidance function of the normal mode of Mars-Express allows to compute the four attitude quaternion components through a seventh order expansion of Chebyshev polynomials over a freely selectable time period. The guidance command contains the associated coefficients, start and end time. This guidance implementation brings the guidance error essentially to zero for an arbitrary (smooth) attitude profile.
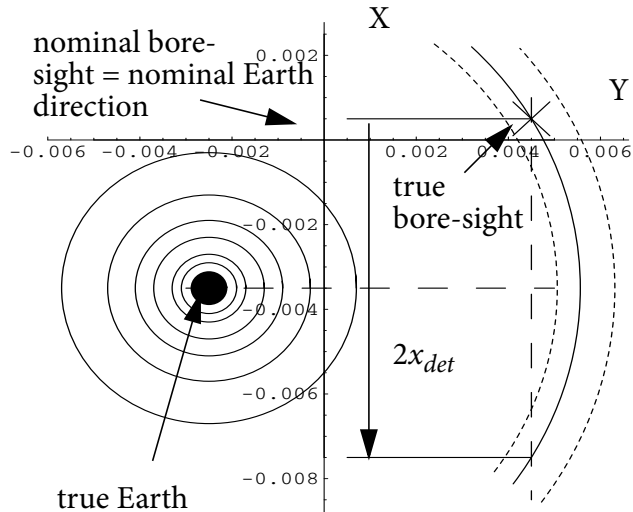

Fig.1. Moving HGA frame in front of fixed Earth, circles are bore-sight directions resulting in the same signal strength recorded at the ground station

The HGA electrical bore-sight had been calibrated during early cruise (on June 13th 2003) using a raster scan stretching over 5.5 hours. The ESA ground station in New Norcia recorded the strength of the unmodulated antenna signal in S- and X-band simultaneously. Lines with 15 equidistant hold points centred around the nominal bore-sight covered 5 deg in x and y direction each. In addition a grid covering an x-y-square of 2 x 2 deg centred at the nominal bore-sight was traversed using 64 hold points with non-zero x and y coordinates. At each hold point the s/c maintained its attitude for 2

minutes by which the errors due to the signal's white noise and to the control error were held to a minimum. Hence a resolution of 0.25 deg granularity was achieved. The time correlated signal strength at the points was fitted to a radiaton pattern with rotational symmetry.
As a result the direction of the true bore-sight in HGA frame was determined with:

$$\left(-0.00205937,\ 0.000215615,\ 0.999998\right)^{T}$$

The calibration error, of course, is the lower limit for the accuracy of the on ground determination of the Earth direction and hence of the attitude. Since the bore-sight was calibrated with the on board estimation process the calibration error is identical to the estimation error plus the signal error. While the stochastic estimation error is negligible a STR misalignment needs to be accounted for.

The link budget had allowed to waive an update of the on board value for the bore-sight direction. However, the separation between nominal and calibrated bore-sight needs to be added to a slew amplitude that was valid for the case of an updated alignment. A slew amplitude of magnitude 1 deg in both directions is considered sufficient for both axes leaving margins for the worst case residual gyro bias magnitude and direction (see Fig. 1).
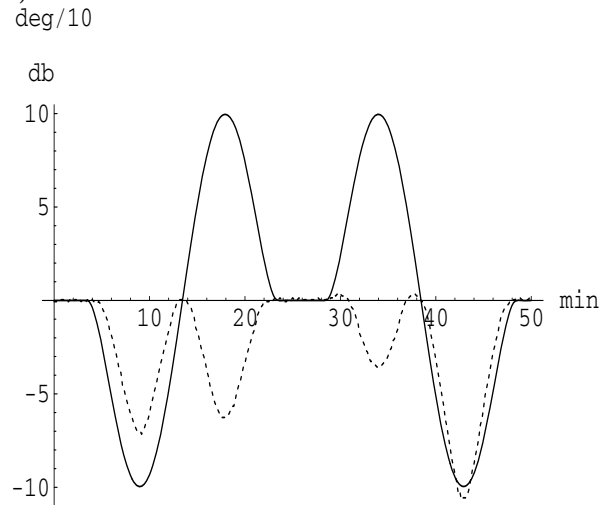

Fig. 2. +y/+x angular excursions & drop of time correlated signal strength (dashed line)

Fig. 2 shows the time evolution of the guidance profile and the time correlated drop in signal strength recorded at the ground station. The data sampling interval is 10 sec. The first two peaks correspond to the slew around the x-axis (compare Fig. 1). Here the bore-sight moved to the left by 1 deg towards the -y axis, came back and moved 1 deg to the right towards the +y axis and finally came back to the starting position. This slew serves for

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the determination of y_{det}, the angle between the true bore-sight and the Earth direction projected on the y/z plane of a frame centred at the true bore-sight. The second pair of peaks corresponds to the slew around the y-axis. This second slew moved the bore-sight up and down along the x-axis, first towards +x and then towards -x. This slew serves for the determination of x_{det}, the angle between the true bore-sight and the Earth direction projected on the x/z plane of the frame centred at the true bore-sight.

3.2 Control and estimation error

Fig. 3 and 4 show the signal strength vs. angular excursions of the slews. The discernability of the paths forth and back is due to the signal and control error. The control error could be isolated and ruled out by basing the angular excursion on the estimated (reported in telemetry) instead of the commanded attitude. The standard deviation of the control performance during slow slews is known to be about 6 mdeg (Note that in normal mode the control is performed with reaction wheels).

The estimation error needs to be considered as well: The s/c slew axis is identical to the guidance slew axis (control error ignored) only in the estimated s/c frame - not in the true s/c frame. Since we have to assume that the residual gyro bias is non-zero the attitude drift applies exactly to the estimated vs. the true s/c frame. As a result the true slew axes are not exactly transversal w.r.t. the nominal bore-sight. In addition the slew axes for the way forth and back are not identical. Though, for the following two reasons this effect is negligible:

1. The error originating from the fact that the nominal bore-sight does not exactly traverse on great circles is of second order.
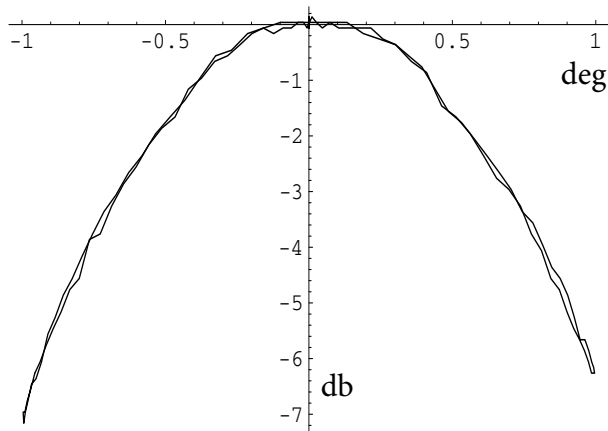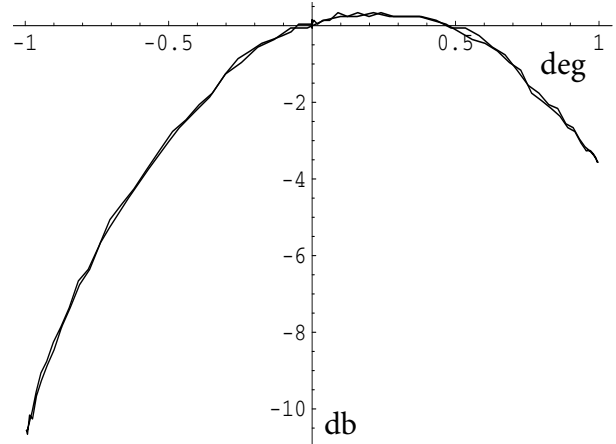
Fig. 4. Signal strength vs. angular x excursion

2. The slew duration is too small for making a significant change in the true slew axis for the way forth and back.

The first reason is the very reason why the slew design can be afforded to be made w.r.t. the nominal instead of the calibrated bore-sight.

On the other hand the same consideration needs to be taken into account what concerns the drift along the (longitudinal) bore-sight axis. The rotation about this axis that accumulated since the gyro bias estimation was frozen causes a rotation in the relation between the x/y coordinate system of Fig.1 and the true transversal HGA axes. This is a first order effect. In the unrealistic case that the component of the residual gyro bias along the HGA bore-sight had magnitude $90 deg/\Delta t$ the coordinates for the true Earth direction in the HGA frame would depend on the determined coordinates as follows[1] (ignoring the alignment error):

$$\left(-y_{det},\; x_{det},\; \sqrt{1 - x_{det}^2 - y_{det}^2}\right)^T$$

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1. The formula is not exact: It only better illustrates the effect from the rotation around z. The computation of a direction from given angles x and y is:

$$\begin{bmatrix} \dfrac{Tan(x)}{\sqrt{1 + Tan^2(x) + Tan^2(y)}} \\ \dfrac{Tan(y)}{\sqrt{1 + Tan^2(x) + Tan^2(y)}} \\ \sqrt{1 - \dfrac{Tan^2(x) + Tan^2(y)}{1 + Tan^2(x) + Tan^2(y)}} \end{bmatrix}$$

Fig. 3. Signal strength vs. angular y excursion

Hence the transformation between the determined and the true coordinates is known only after the determination of the drift along the HGA bore-sight (being the reason for the (Yes) in Tab. 1).

3.3 Evaluation

From Fig. 1 it is obvious that the data in Fig. 3 and 4 have to be fitted to a vertical symmetry axis. Only these data which have a counterpart on the mirror branch with the same signal strength can be used. A special shape of the left (or right) branch is not assumed. The results are:

$$y_{det} = 0.0172 \pm 0.0009 \, deg$$

$$x_{det} = 0.2152 \pm 0.0011 \, deg$$

For the determination of the y coordinate 96 data points were usable, for the x coordinate 54.
To obtain the transversal attitude drift these values (and errors) need to be added to those for the calibrated bore-sight (see Sec. 3.1 and Fig. 1).

3.4 Result

The de-pointing of the nominal bore-sight was 0.10 deg within 23 hours. The magnitude of the true gyro bias around transversal HGA axes was therefore close to 0.06 deg/h which is the value that was frozen when the solar flare hit Mars-Express.

3.5 Options for ground interaction

The above values are sufficient to cancel the off-pointing of the HGA bore-sight from the Earth direction by commanding slews (hereby using the estimated s/c frame as reference) to the desired attitude. However, to cancel the estimation error a gyro bias update resulting from Equ. 1 needs to be commanded to the inertial measurement package (after having applied a multiple of the negative residual bias to make the s/c drift back). This bias update requires values per gyro axis. As discussed above the values for x_{det} and y_{det} are only applicable for the estimated s/c frame, not for the true s/c frame. The gyro axes of course are only specified w.r.t. the (true) s/c frame. It is this latter frame in which the Earth direction needs to be known to perform an attitude determination that is required by Equ. 1.

4. DETERMINATION OF ROTATIONAL DEGREE OF FREEDOM

32 hours after the loss of the tracked stars Mars-Express re-acquired inertial attitude succeeding with the AA&CAD STR mode. The determination of the rotation angle of the s/c around the HGA bore-sight was there-fore obsolete. What follows has been planned and not been operationally executed.

4.1 Sun acquisition sensors (SAS)

The SAS consists of four solar cells located on four sides of a tetrahedron. There are two redundant sets of SAS on Mars- and Venus-Express, four on Rosetta. For Mars-Express the zenith axis z of the SAS which is nominally lit by the Sun is tilted by 14.5 deg out of the plane in which the Sun is nominally located.

The output of the SAS measurement unit are electrical currents originating from the Sun illumination of the solar cells. If the Sun is in the zenith of the SAS frame all currents are (theoretically) equal.
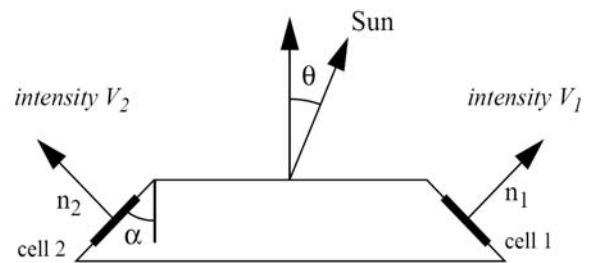

Fig. 5. SAS tetrahedron profile and measurement quantities

Let x and y be the axes of the horizontal projection of the tetrahedron. If the Sun direction fulfils

$$-\alpha \le \theta \le \alpha \qquad (3)$$

the normalized difference

$$V_n = (V_1 - V_2)/(V_1 + V_2) \qquad (4)$$

(see Fig. 5) between the currents from opposite cells serve as a measure for the angle θ between the projection of the Sun direction on the x/z (resp. y/z) plane and the z axis. This measure is antisymmetric in θ and independent from the distance to the Sun. Furthermore it is independent from the out-of-plane angle of the Sun in Fig. 5. Assuming a solar power reception that is proportional to the projection of the solar flux vector on the normal unit vector of a cell (Lambert's law) the linear coefficient in a Taylor expansion of $\theta(V_n)$ around

$V_n = 0$ is $\tan\alpha$. The quality of the linear Taylor expansion degrades at the range borders. A correction to Lambert's law that corresponds to an attenuation due to optics phenomena is specified by the manufacturer and applies to the proportionality factor. For all three s/c the pyramid angle α has 22 deg magnitude.

4.2 Ground operations

By contrast to the determination of the Earth direction the Sun direction in SAS frame can be determined without any slew just by reading out the values for the four cell currents from telemetry. However, the Sun at least needs to illuminate all four cells.

The values for θ_x and θ_y in the nominal attitude were 34.0 deg and -14.6 deg respectively. Respecting Equ. 3 only θ_y could have been determined without slews. Since only one rotational degree of freedom needs to be fixed the knowledge of this angle is sufficient. The closer the Sun is to the zenith the more accurate is the linear Taylor expansion and hence the determined Sun direction. The smallness of the values for x_{det} and y_{det} confirm the quasi-coincidence of estimated and true bore-sight: A slew around the HGA bore-sight towards smaller θ_y would improve the determination.

Errors that cannot be minimized by ground operations are rooted in the following circumstances:

1. The alignment of the SAS frame w.r.t. the s/c frame has not been systematically calibrated in-flight.
2. The manufacturer specifies a dispersion of the cell performance that translates into 0.84 deg for the 3σ confidence level of θ.

4.3 Evaluation

The remaining rotational degree of freedom is fixed by the rotation around the true Earth direction that is needed to make θ_y take on its measured value. Let this angle be α. As we have seen in Sec. 3.2 the true Earth direction in s/c frame couples with the magnitude of α. Consequently, the rotation axis of α depends on the magnitude of α. This means that the rotation axis and the rotation magnitude need to be solved for self-consistently:

The values for x_{det} and y_{det} restrict the true Earth direction in HGA frame to the manifold of directions that can be generated by a pure rotation around the z axis. To every single element of this manifold corresponds a definite rotation angle α that is needed to transfer the nominal value of θ_y to its measured value. Only for one element of the manifold this angle is equal to the angle of its generating rotation from x_{det} and y_{det}. This is the self-consistent axis of the true Earth direction with a self-consistent magnitude of α. As a by-product from this computation the true attitude is obtained and Equ. 1 can be used to solve for the residual gyro bias.

The rotational degree of freedom is the less error prone the more sensitive the Sun direction is with it. The separation angle between the Sun and the Earth direction seen from the s/c was app. 38 deg for Mars-Express. An error in the estimation of θ_y is amplified by $1/Sin(38deg)$ in the determination of the rotation angle α.

5. CAUTION MEASURES FOR VENUS-EXPRESS

There are several lessons learned from the experience with Mars-Express:

1. A STR outage for several days is within the realms of possibility.
2. The calibration of the HGA bore-sight is the key for the demonstrated procedure.
3. A systematic calibration of the SAS is an asset for a rigorous on ground attitude determination.

In view of the critical Venus orbit insertion manoeuvre (April 2006) ESOC went for the prerequisites of the ad-hoc operations and analyses performed for Mars-Express.

5.1 STR updates

The STR manufacturer presented an improved tuning of the thresholds for the detection of stars. This tuning has been confirmed in practice yet by Mars-Express: The STR had become much more robust w.r.t. Sun blinding. In addition the optical properties of a suspicious mounting device in the STR field of view have been modified .

5.2 HGA bore-sight calibration

Due to the fact that Venus is an inner planet Venus-Express has got two HGA: A smaller one is oriented towards the cold face of the s/c and is used during cruise and around inferior conjunctions, the other is mounted in the opposite direction of the cold face and is used around superior conjunctions.

The bore-sight of the HGA used during cruise was calibrated for 3.5 hours seven days after launch. Instead of a raster scan over a grid of hold points a spiral pattern centred aound the nominal bore-sight was used which is shown in Fig. 6. The complete data sample consisting of
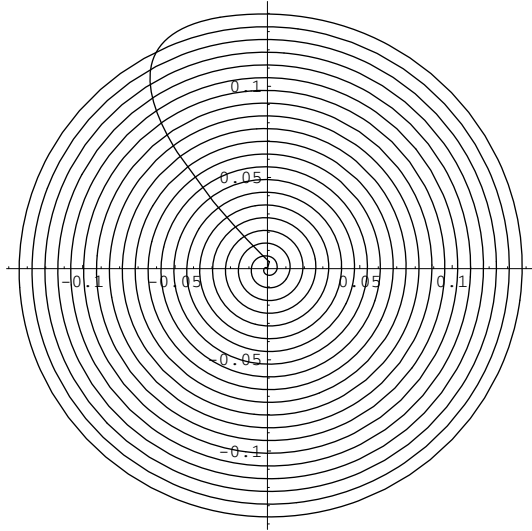
Fig. 6. Path of Earth direction in HGA frame, coordinates are the transversal components

app. 13,000 points has been fitted to a bore-sight direction.

As a result the separation angle between nominal and calibrated bore-sight was 0.44 deg. Again here, an alignment update was not necessary on link budget grounds and has not been executed.

5.3 SAS alignment calibration

The zenith axis of SAS XZ is located in the s/c x/z plane which the Sun traverses during the cruise to Venus (see Fig. 7). It was in-flight calibrated on February 27th 2006. This was done through an elongation by +/- 5 deg of the Sun along the s/c y axis. Since the Sun moves in the s/c x/z plane and the time of a STR outage cannot be anticipated the calibration was performed for nine solar aspect angles of the s/c x axis equally spaced by 5 deg in the range 54 deg to 94 deg.
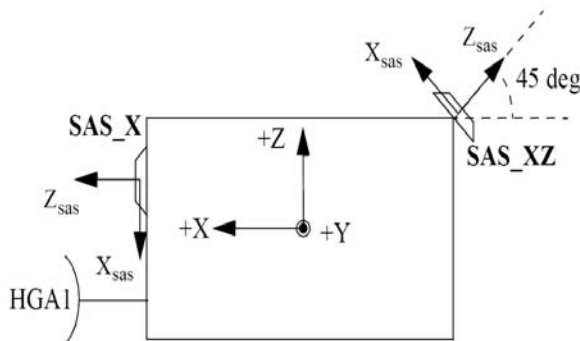

Fig. 7. Locations of SAS on Venus-Express

The antisymmetric property of $\theta(V_n)$ had been dropped. Instead, a general linear dependency was postulated to which the acquired telemetry data were fitted.

For each of the solar aspect angles a set consisting of a constant and a linear coefficient was obtained. Thus the alignment error and the manufacture dispersion are absorbed by the nine sets.

Again θ_y serves to fix the third rotational degree of freedom. Because of the calibration of the critical regime around $V_n = 0$ the accuracy of the on ground attitude determination had been considerably increased compared to Mars-Express.

Fortunately the space weather was fairly calm during cruise and the STR of Venus-Express went smoothly through it. As a matter of fact the separation angle between Sun and Earth was optimum with nearly 90 deg before Venus orbit insertion.

6. ROSETTA'S EARTH STROBING MODE

The AOCMS of Rosetta provides a survival mode that recovers from lost in space without use of the STR. This mode is called Earth Strobing Mode (ESM). ESM is entered (if authorized by ground) upon repeated failure of the AA&CAD mode of the STR while the s/c is in safe mode. The control is performed by the thruster reaction control system. Rosetta has got four redundant sets of SAS. Two of them are mounted on the solar arrays - one on each panel. The medium gain antenna (MGA) with a bore-sight along the s/c x-axis (see Fig. 8) is autonomously configured for ground communication. In RAM as well as in ROM the time evolution of the separation angle between the Sun and the Earth direction seen from the s/c is stored.

Before entry to ESM the solar arrays are slowly turned to the current separation angle, the so called Earth strobing angle (see Fig. 8). The guidance of the s/c is autonomous and keeps the Sun perpendicular on the solar array mounted SAS. This causes the s/c body to move in inertial frame rather than the solar arrays. Then the s/c starts to rotate around the Sun line with a revolution period of 6 hours (see Fig. 8). The estimation of the rates is done by the gyros. Based on these rates the AOCMS integrates the phase angle that - together with the SAS measurements - represents the estimated attitude. The thrusters control the s/c w.r.t. to both the guidance rates and its integral, the guidance phase angle.

The MGA bore-sight traverses a cone around the Sun direction on which the Earth direction is located. However, the rotation phase angle for which the Earth is intercepted cannot be known by the AOCMS since it
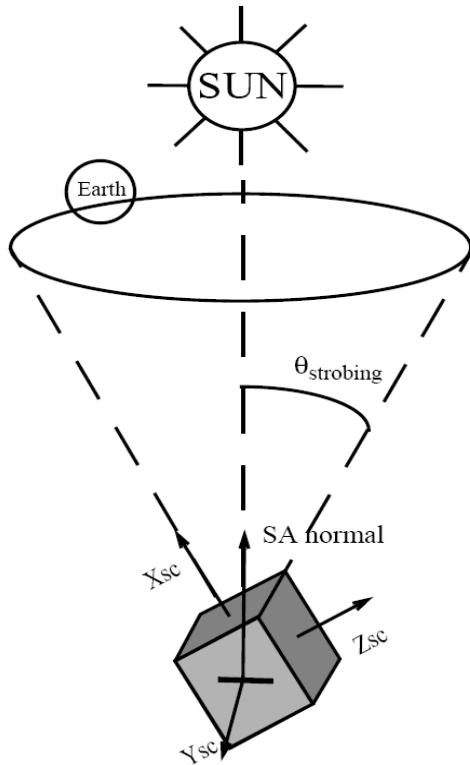
Fig. 8. Earth Strobing Mode

comes from lost in space. Upon detection of the MGA carrier by ground the s/c can be telecommanded. Because the uplink budget is less restrictive than the downlink budget telecommanding is possible not only during the peaks. The ground can increase the rotation period to 2 hours and tighten the control by switching to appropriate control gains. Then the time evolution of the signal strength recorded at the ground station has a 2 hours period with one sharp peak. Once this peak is time correlated the s/c attitude evolution is known by ground. The gyro bias (around the Sun line) can be determined by the deviation of the duration between two signal peaks from 2 hours.

To establish continuous safe communication the rotation can be stopped when the rotation reaches the Earth phase angle. The gyro bias can be updated and a residual bias be corrected by commanding an off-set on the phase angle (and be cancelled by another gyro bias update). A switch to a modulated signal carrying telemetry data enables on ground analysis of the situation on board the s/c.

7. CONCLUSION

Thanks to the knowledge of the orbital position of the s/c a safe communication link with Mars- and Venus-Express via the HGA can be maintained in the case of a

STR outage for an unlimited time. The calibration of h/w alignments and a series of ground interactions are suitable to confirm the stability of the gyro bias. Although the residual gyro bias is small *a priori* as well as *a posteriori* the mathematical treatment does not make assumptions on its magnitude. However, the procedure is not an option if the AOCMS is lost in space.

The Earth Strobing Mode of Rosetta interchanges the roles that the Earth and Sun direction play for the on ground attitude determination: The co-alignment of a definite s/c axis with the Sun direction allows to fix the remaining rotational degree of freedom with help of the signal from the MGA. A crucial prerequisite is the on board knowledge of the time evolution of the angular separation between the Sun and the Earth over the whole mission life time.