OPERATIONAL EXPERIENCE WITH AUTONOMOUS STAR TRACKERS ON ESA INTERPLANETARY SPACECRAFT

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1. Abstract

Mars Express (MEX), Rosetta and Venus Express (VEX) are ESA interplanetary spacecrafts (S/C) launched in June 2003, March 2004 and November 2005, respectively. Mars Express was injected into Mars orbit end of 2003 with routine operations starting in spring 2004. Rosetta is since launch on its way to rendezvous comet Churyumov-Gerasimenko in 2014. It has completed several test and commissioning activities and is performing several planetary swingbys (Earth in spring 2005, Mars in spring 2007, Earth in autumn 2007 and again two years later). Venus Express has also started routine operations since the completion of the Venus orbit insertion manoeuvre sequence beginning of May 2006. All three S/C are three axes stabilized with a similar attitude and orbit control system (AOCS). The attitude is estimated on board using star and rate sensors and controlled using four reaction wheels. A bipropellant reaction control system with 10N thrusters serves for wheel off loadings and attitude control in safe mode. Mars Express and Venus Express have an additional 400N engine for the planetary orbit insertion. Nominal Earth communication is accomplished through a high gain antenna. All three S/C are equipped with a redundant set of autonomous star trackers (STR) which are based on almost the same hardware. The STR software is especially adapted for the respective mission. This paper addresses several topics related to the experience gained with the STR operations on board the three S/C so far.

2. STR Hardware and Software Overview

The optical system is most sensitive in the optical range of wavelengths from 500 nm to 850 nm with a field of view (FoV) of 16.47 degree (diameter) and a focal length of 46 mm. The charge-coupled device (CCD) has an array size of 1024x1024 pixels and a capacity of 70,000 el in a pixel. The signal rate of a G0 star with visual magnitude 0 is about 3.7 Mel/s. The STR software operates essentially (i.e. apart from test and standby modes and software initialisation) in acquisition mode or in tracking mode. In acquisition mode the STR is designed to perform an autonomous attitude determination without any a priori knowledge based on an image of the full CCD. After successful completion of the acquisition, the STR switches autonomously into tracking mode. In this mode, CCD windows around up to 9 predicted star positions are readout and processed. The resulting star position measurements are provided in periodic telemetry (TM) with a frequency of 2 Hz to the AOCS for subsequent processing together with rate sensor data in the attitude estimation filter.

3. STR initial attitude acquisition

The STR's perform attitude acquisition whenever the inertial reference is lost. This happens regularly for the planet orbiting S/C after a blinding of the STR by the central body (Mars or Venus) and occasionally under special circumstances like unit reconfigurations (commanded or autonomous), tracking losses during wheel offloadings, solar flares etc.. Autonomous acquisitions are either commanded from ground, e.g. in case of redundant unit switch on, or triggered autonomously on board.

For MEX and VEX, already the STR itself triggers an acquisition immediately after an anomalous tracking loss in order to resume tracking without delay. Only if this attempt fails, the STR is falling back to standby mode. For reasons described later, the Rosetta STR falls immediately back to standby. Without STR tracking data, the AOCS software is then propagating the attitude estimation only from rate sensor data and triggering periodically an acquisition of the STR by telecommand. Only after several unsuccessful attempts, the AOCS switches to the redundant STR unit, and if this also fails, performs a transition to safe mode, where the S/C is controlled to point with a fixed S/C axis to the Sun and to rotate slowly around the Sun line.

The overall delay until the S/C enters safe mode after STR tracking loss was originally set to only a few hours. But it turned out, that in case of anomalies like solar flares, it is preferred to keep a controlled attitude for Earth communication even with degraded accuracy rather than to loose the communication link until the solar flare is finished. The delay was therefore increased, such that e.g. Rosetta could maintain an Earth pointing attitude even for several days without STR data during a phase where only weekly passes were scheduled.

In orbit around Mars and Venus, continuous tracking of the STR is not required. Instead, the attitude estimation filter can be based only on gyro data during phases where the STR is blinded by the planet. Originally it was foreseen that special tables of blinding start and end times are prepared on ground and uploaded to the S/C such that the STR unit is commanded by the AOCS to standby shortly before the start of a blinding and to acquisition shortly after its end. This however turned out to be error prone, as these tables were AOCS mode dependent, and inefficient, as the necessary accuracy in the prediction of the blinding times based on the latest orbit reconstruction did not allow for command preparation long in advance. It was therefore decided to use the autonomous re-acquisition mechanism of the AOCS to command the STR back to tracking after the end of a blinding. Entry into blinding is however not an instantaneous event, but the star position measurements of the STR are degrading with the gradual increase of straylight in the FoV over an extended time span until the stars can not be detected any more because of the straylight noise or because they are occulted by the planet. In order to avoid a disturbance on the attitude estimation filter caused by degraded star position measurements shortly before blindings, the STR software parameters that are used to validate star position measurements were re-tuned accordingly.

The attitude acquisition is based on an algorithm to match the patterns of objects detected on the CCD with a catalogue of patterns generated from the Hipparcos catalogue. For MEX and VEX, the patterns consist of triads which are built from nearest neighbours. The catalogue of triads is generated taking into account the sensitivity of the sensor including conversion from visual to instrumental magnitude. The acquisition attempts, with a STR not blinded, are usually successful. Failed acquisitions, other than caused by blindings, could be determined in most of the cases to be due to dynamic conditions (wheel offloading), deficiencies of the catalogue (’holes’ in the sky, i.e. regions without triads) or environmental conditions (solar flare). There remain however a few number of failed attempts which could not finally be clarified. The most probable explanations are stars of a triad which are not detected, or objects detected on the CCD, like faint stars, not identified single event upsets (SEU’s) or hot pixels, that destroy a triad of nearest neighbours. There has been no case so far where an attitude has been determined wrongly.

For Rosetta, the pattern matching algorithm has been improved to cope with an adverse environment around the comet, where dust particles appear as stars in the field of view (false stars) and would destroy the triads. The patterns consist in this case of five neighbours around a central star, but they are not required to be nearest neighbours. In addition, not all five neighbour stars of the pattern are required to be detected for successful identification, but a configurable minimum number. The acquisition process is designed to work even in the presence of up to 1000 false stars in the field of view. Its drawback is the increase of computing time required for the pattern matching algorithm to complete. Whereas 5s is the maximum cycle duration for the MEX and VEX STR’s, up to 800s are allocated for the first acquisition cycle on the Rosetta STR. As the S/C can rotate significantly during this period, the eventually determined attitude might be considerably off from the one when the STR image was taken. Therefore a sequence of 4 acquisition cycles is performed, where the attitude from the previous cycle is used to limit the number of possible patterns from the catalogue that have to be compared with the measured patterns. The subsequent cycle durations can then be shortened to 120s, 50s and 10s, after which the transition to tracking mode can be finally achieved. Still, the maximum S/C rate allowed to ensure successful acquisition is +/-0.01deg/s. These limits were verified by a dedicated test with repeated acquisitions during slews with varying rate. Due to the long cycle durations the Rosetta STR software includes the capability to perform a direct transition from standby to tracking mode, without initial acquisition. In case of a sudden tracking loss (e.g. from SEU or wheel offloading) the AOCS immediately commands the STR directly into tracking mode by providing an attitude that was propagated only by gyros (the MEX and VEX STR’s would always require a full attitude acquisition). This capability allows to avoid the full ca. 16 minutes lasting period required for a complete acquisition from lost in space.

Because of the identified deficiencies in the acquisition process, theoretical field of view analyses are performed before critical operations (e.g. planetary insertion, hibernation phases). An example for a Rosetta near Sun hibernation period in 2005 is shown in figure 1. It shows the angular separation of the STR boresights from regions with reduced acquisition capability due to missing suitable star patterns from the catalogue required for pattern matching. The two curves for STR-B correspond to two separate S/C pointing options, Near Sun Hibernation mode (NSHM) and Safe Hold Mode (SHM). The safe mode is analysed to ensure that the S/C can recover from an anomaly. As the STR-A boresight stays always far away from the critical region in NSHM, only a curve for the SHM pointing mode is visible in the plot for STR-A.

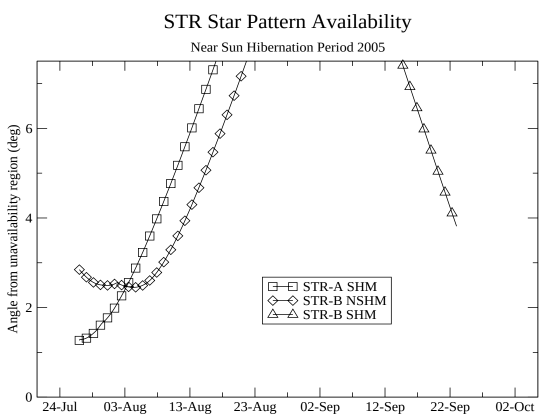

Figure 1: Star Tracker FoV Analysis

Occasionally (e.g. before the MEX planetary insertion) also test acquisitions were performed and additionally slots for slews allocated in the planning schedule which could have been used to change the boresight direction of the STR to a more favourable star field that would ensure acquisition, in the case of tracking loss.

4. STR star tracking

The tracking algorithm is the same for the STR’s on all three missions. The positions of stars in the field of view of a cycle are predicted from the attitude and rate estimate of the previous cycles. Among these candidate stars, up to 9 are selected for tracking, based on their magnitude and their distance from the boresight. Around the predicted positions, CCD windows are commanded and read-out in the next cycle. The CCD output is processed to derive for each star its raw position as the barycentric mean and its magnitude as the sum over all significant pixels. The raw positions are corrected for distortion, and the attitude and rate estimate updated and provided in periodic telemetry.

Tracking is lost whenever the number of stars that can be reliably detected drops below 2. The number of tracked stars is therefore closely monitored. In most of the cases there are more than 9 catalogue stars visible in the field of view and 9 stars are tracked by the STR. For less than 9 stars, the reduction is due to a reduced number of catalogue stars in the FoV or some stars are not detected. Already early in the mission, cases where stars are not detected have been observed. The cases were analysed and plausible causes identified. For example, when a single catalogue star was generated out of 2 or more Hipparcos stars which were supposed to create overlapping signals on the CCD, the individual stars were actually measured separately and could therefore not be correlated with the catalogue entry. Or sometimes the conversion from visual magnitude to instrumental magnitude was suspected to prevent the STR from detecting the star. In special cases, even dedicated slews were performed to bring a specific star at a certain position on the CCD of the STR and to generate CCD dumps around this position to analyse in detail the raw signal data (see also example below).

To evaluate the tracking performance in more detail, TM of the STR is regularly processed and the tracking probability for each individual star is computed. Over the years, a considerable portion of the catalogue is now covered and the statistical data allow to predict to some extent the actual number of stars that can be tracked for a given field of view. This allows to distinguish normal behaviour from degraded performance (e.g. from a solar flare). In the following, as an example, results for the nominal STR on MEX are presented and discussed in more detail.

Since launch in June 2003, in total 2999 stars have been tracked and/or predicted to be tracked. This is more than 90% of the 3227 stars in the catalogue. Considering that several stars (ca. 150) can never be selected for tracking (they are only used for acquisition), the coverage even increases to more than 95%. Of these 2999 stars, 1026 (34.21%) were always tracked successfully and 2382 (79.42%) were tracked with a probability greater or equal than 95%. Among the remaining 20%, 3.53% (106 stars) were tracked with a probability of less than 20% and even 97 (3.23%) with a probability of less than 1% which means that there is a considerable number of stars which are almost never tracked. The distribution of stars depending on the tracking probability can be seen in more detail in the histogram of figure 2.

One reason for failed star detection is the uncertainty in the prediction of the star instrumental magnitude. A polynomial of order 2 in the B-V colour index was used in the creation of the on-board star catalogue. The error in the actually measured instrumental magnitude is in the average about 0.1m. However deviations up to 0.6m occur.

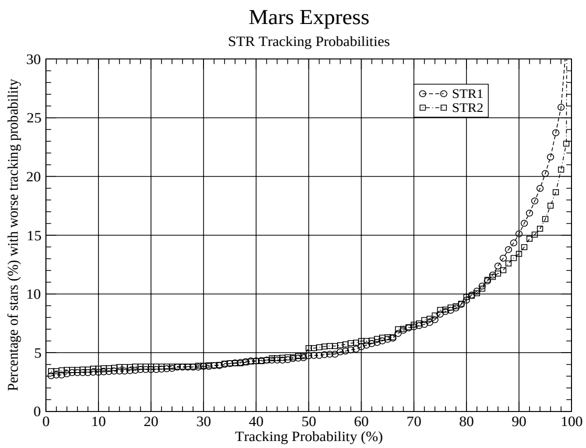

Figure 2: Single star tracking performance

Hipparcos star 52009 is an example of an apparent mismatch between magnitude prediction and actual measurement. Its visual magnitude is 4.89, but its B-V colour index is very high, namely 2.8. The STR on-board catalogue contains this star with an instrumental magnitude of 1.75, based on the polynomial conversion law. But it is doubtful whether, for such high colour indexes, the conversion from visual to instrumental magnitude is still applicable. It turns out that this star is never tracked by the STR units. Instead, exactly during the period where this star should have been tracked by the STR, SEU's are regularly flagged in the STR telemetry. This is consistent with a much fainter star magnitude and the STR algorithm for SEU detection, as described in the following. Two conditions are necessary when an object is flagged as an SEU by the STR:

- The signal of an object is concentrated only in one pixel and has a minimum CCD output voltage level of 0.01 V above the mean background.
- Around the centre pixel of the object, there are not at least 3 neighbour pixels which have a signal higher than a fraction of 8% of the signal in the centre pixel.

For Hipparcos star 52009, the expected signal (based on the catalogue instrumental magnitude of 1.75) at 0.1s integration time is 0.332 V and the detection threshold above the mean background level is set for this star to 0.013 V. As the star is actually measured much fainter, only one pixel exceeds the threshold and is therefore flagged as SEU. The fact that an SEU is not always flagged but only with some lower frequency is explained by the fact, that the star is moving across the CCD such that sometimes the signal is concentrated mostly in one pixel resulting in an SEU, and sometimes distributed over several pixels resulting in no detection, and thus no SEU.

Star tracking can also fail if the entry in the on-board star catalogue represents a conglomeration of nearby stars. According to the design, they are supposed to be detected by the STR as a single signal with the centre at the photometric barycentre of the combined stars. For example, the Hipparcos stars 74778 and 74750 have an angular separation of 67 mdeg, which corresponds to ca. 4 STR pixel. Their instrumental magnitudes are 5.2 and 5.9. They were combined into a single on-board star catalogue entry with a direction in between the two star positions with a ratio of ca. 1:2 (according to the ratio of their signal) closer to 74778. The catalogue magnitude of 4.7 represents the combined signal of both stars. This catalogue star is however never tracked by the STR's. For analysis purposes, a CCD dump of a window around its direction was taken. It is shown in figure 3. The signal is given in digital units of ca. 17 el and was collected over an integration time of 0.1s. The positions are given in pixels (1 pixel = 16 mdeg) relative to the corner of the window. The dump revealed that the signals of both individual stars are in fact not detected by the STR as a combined signal. Instead they are detected separately and thus both don't match the catalogue entry.

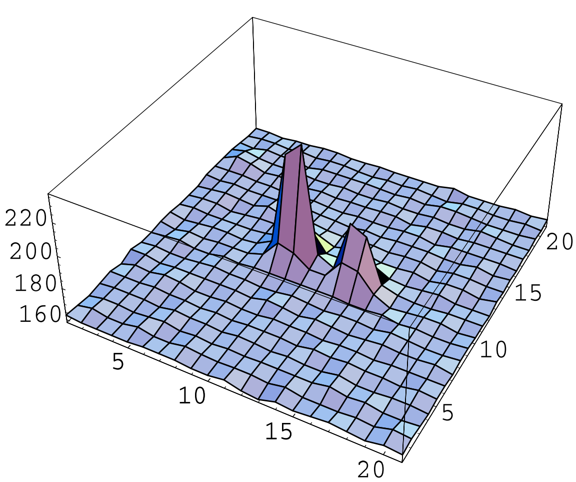

Figure 3: CCD dump of star pair

Apart from loosing track of individual stars, full tracking losses occur only very occasionally (apart from blindings from a planet). In most of the cases this happens during wheel offloadings when, due to thruster pulses, the stars don't appear at their predicted positions. But also solar flares and SEU's in the optical head electronics caused sudden tracking losses.

For the performance of the AOCS attitude estimator, the accuracy of measured star positions is the most important parameter. This accuracy consists of a temporal noise and a random bias error. The temporal noise error in the measured star direction (=noise equivalent angle, NEA), is induced by CCD dark current, readout and photon noise. As an example, for VEX, it was expected to be between 0.2 mdeg and 2.2 mdeg for stars with magnitudes between 2 and 5.4 and for stable pointing (i.e. no apparent star motion on the CCD). The random bias error in the measured star direction is induced mostly by the residual distortion errors (i.e. after correction with an on ground calibrated distortion model of order 5) and the centroiding error. Again for VEX, this contribution was expected to be in the range from 1.0 to 1.9 mdeg.

The actually achieved star direction measurement accuracy was estimated based on the variation in the angular separation of star pairs derived from the measurement in TM. If the star directions were measured perfectly, the derived angular separation would remain constant. Following measurements of star positions during tracking over time (and moving across the CCD), the variation in the derived angular separation provides a measure for the star direction measurement accuracy. The variances of the derived angular separation between the two stars of a pair is the sum of the position variances for the stars within the pair. As the stars appear in several pairs and assuming that the measurement errors of the individual stars are not correlated, a direction measurement error was derived for each tracked star. This was done by a least squares fit of the position variances to variances of star distances. A result, for the VEX STR's, depending on the star instrumental magnitude is shown in figure 4. The solid lines in the figure show the design values for the random bias (squares), the NEA (diamonds) and the total position error (circles), i.e. the root sum square of the random bias and the NEA. The points (triangles, up for STR-A, down for STR-B) are the accuracies as derived from TM.

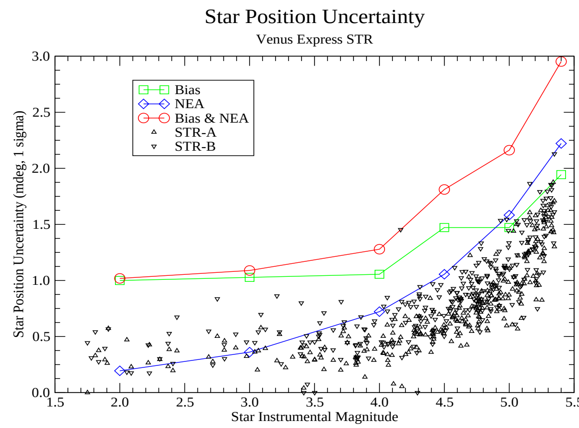

Figure 4: VEX STR-A star position uncertainty

The actual position error for stars below magnitude 4 is dominated by the random bias and is nearly constant below 1 mdeg. Between magnitudes 4 to 5.4 the position error increases up to ca. 2.2 mdeg due the increase in NEA. The results are based on data collected during a VEX STR alignment calibration in the commissioning phase after launch, and are consistent with the design specification.

Another performance parameter is the Sun exclusion angle to avoid loss of tracking caused by straylight, especially for VEX. To verify the actual performance, TM during a slew in January 2006 was processed with the STR units in tracking mode. During the slew, the separation angle of the STR boresight from the Sun decreased down to a minimum of about 45 deg. In tracking mode, the STR TM contains in addition to the position of the detected stars, the mean and standard deviation of the background noise. Although these value refer only to the selected windows around the tracked stars, they provide a good indication of the overall straylight level as the tracked stars are spread over the full CCD. Figure 5 shows the background levels as reported by the STR's during the slew as signal rate as function of the Sun aspect angle. The values are scaled to the Sun distance at Venus (i.e. about 25% higher than the TM values at the time of the test when the S/C was 0.8 AU from the Sun).

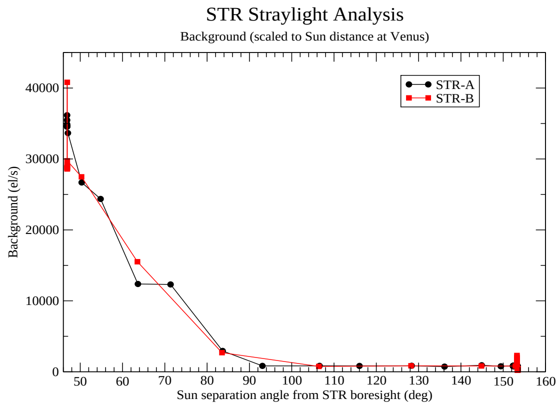

Figure 5: VEX STR Straylight Analysis

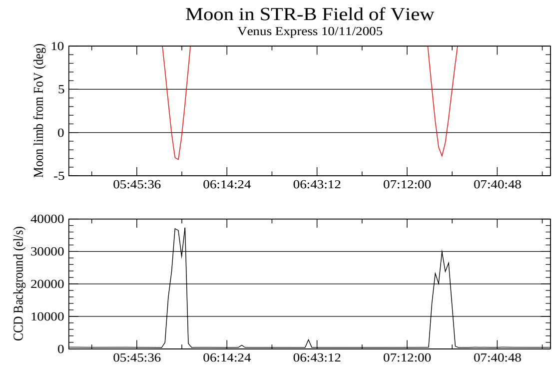

Figure 6: Moon in STR-B Field of View

Down to about 90 deg, there is no straylight effect visible. Below 90 deg, the measured values are consistent with the design values that were taken as basis for the performance prediction. However they confirm the significant increase of straylight at Sun angles close to 45 deg. In operations, tracking can usually be maintained with Sun angles down to 45 deg. However acquisitions at angles close to 45 deg sometimes fail. This is due to the fact that in tracking mode the threshold that is used to detect a star signal above the background can be adjusted to the expected signal strength of the star. For an initial acquisition, where no prediction on expected star positions and magnitudes is available, the threshold has to be lower which leads to increased noise that is identified wrongly as a signal from a star.

During VEX LEOP the STR tracking performance could be evaluated for the case of an extended object in the FoV. In the morning of the 10th of November 2005, a test orbit correction manoeuvre was executed. During the slews to and away from the manoeuvre attitude, the redundant STR unit B was kept on, and the Moon came into its FoV. At this time, the distance of the S/C to the Moon was about 190,000 km, the apparent diameter of the Moon therefore about 1.1 deg. The separation angle of the Moon limb from the edge of the circular STR-B FoV is shown at the top of figure 6. At 05:55:37 UTC, the Moon limb entered the circular FoV, with the Moon fully within the FoV 22 seconds later. It started to exit the FoV at 05:58:39, and left it completely again after another 20 seconds. A similar timing occurred at the slew back from the manoeuvre attitude at around 07:22.

Fully within the FoV, the Moon extended over ca. 3540 pixels. During this period, the STR unit kept tracking. However instead of the maximum of 9, the number of tracked stars dropped during the first Moon entry down to 7 stars, and during the second Moon entry down to 6. The CCD background level, averaged over the windows around the tracked stars is shown at the bottom of figure 6. Corresponding to the times when Moon was in the FoV, the mean background level increased with levels up to ca. 40,000 el/s.

However successful tracking with the Moon close to the STR boresight was not always ensured. Later on the same day, with the S/C following the default Earth pointing attitude, the Moon came again close to the STR-B FoV. More or less at the time of smallest angular separation of about 10.6 deg, but still completely outside the FoV this time, the STR lost tracking for one cycle but immediately resumed after full acquisition.