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ORIGINAL PAPER

Autonomous star sensor ASTRO APS: flight experience on Alphasat

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Abstract Jena-Optronik GmbH, located in Jena/Germany, has profound experience in designing and manufacturing star trackers since the early 80s. Today the company has a worldwide leading position in supplying geo-stationary and Earth observation satellites with robust and reliable star tracker systems. In the first decade of the new century Jena-Optronik received a development contract (17317/2003/F/WE) from the European Space Agency to establish the technologically challenging elements for which advanced star tracker technologies as CMOS Active Pixel Sensors were being introduced or were considered strategic. This activity was performed in the frame of the Alphabus large platform pre-development lead by ESA and the industrial Joint Project Team consisting of Astrium (now Airbus Defence and Space), Thales Alenia Space and CNES (Centre national d'études spatiales). The new autonomous star tracker, ASTRO APS (Active Pixel Sensor), extends the Jena-Optronik Astro-series CCD-based star tracker products taken the full benefit of the CMOS APS technology. ASTRO APS is a fully autonomous compact star tracker carrying either the space-qualified radiation hard STAR1000 or the HAS2 APS detectors. The star tracker is one of four Technology Demonstration Payloads (TDP6) carried by Alphasat as hosted payload in the frame of a successful Private Public Partnership between ESA and Inmarsat who owns and operates the satellite as part of its geo-stationary communication satellites fleet. TDP6 supports also directly TDP1, a Laser Communication Terminal, for fine pointing tasks. Alphasat was flawlessly brought in orbit at the end of July 2013 by a European Ariane 5 launcher. Only a few hours after launch the star tracker received its switch ON command and acquired nominally within 6 s the inertial 3-axes attitude. In the following days of the early in-orbit operations of Alphasat the TDP6 unit tracked reliably all the spacecraft maneuvers including the 0.1 and 0.2°/s spin stabilization for Sun pointing, all of the apogee engine thrusts, Moon field of view transits and recovered to stable tracking after several Earth and Sun blindings before the spacecraft entered a preliminary Earth pointing in a nominal geo-stationary attitude. The Jena-Optronik TDP6 operation center received daily the star tracker status and attitude data. The huge amount of acquired raw data has been evaluated to characterize the ASTRO APS (STAR1000) star tracker in-orbit performance. The paper will present in detail these data processing activities and will show the extraordinary good results. Due to the diverse transfer orbit satellite operations the key performance star tracker data like attitude random noise, single star noise, star brightness measurement, baffle Sun exclusion angle, temperature control, etc., could be derived and have been compared to the ground based laboratory and field measurements. The ultimate performance parameters achieved and verified as well as the lessons learned from the comparison to the ground test data are summarized in the conclusion of the paper.

Keywords Star tracker · Active pixel sensor · Attitude tracking · Noise suppression · In-orbit data

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1 Introduction

Jena-Optronik GmbH (JOP) located in the city of Jena/Germany is a worldwide leading star sensor manufacturer with heritage in star tracker design back to the early 80s when introducing the first 3-head autonomous star sensor Astro 1. This autonomous star sensor system was designed and manufactured from 1984 to 1987 and launched in November 1989 on Module D to the Soviet MIR space station. Since that corner milestone Jena-Optronik has broadened its star tracker ASTRO-series family with ASTRO 10, ASTRO 15 and ASTRO APS. Today ASTRO 15 is the most sold star tracker worldwide and is operating on several geo-telecom as well as Earth observation satellites.

The autonomous star sensor ASTRO APS has been qualified in 2008/09 [3] for a wide range of space application environments and is already scheduled for a variety of Earth observation and geo-stationary telecommunication programs. The ASTRO APS star sensor is characterized by the application of the CMOS active pixel detector technology and the hardware/software implementation of new and advanced measures in self-autonomy and functionality. Three different qualification test programs satisfying the special requirements of low Earth- and geo-stationary orbits have been performed. The ASTRO APS design is able to accommodate either of the two state of the art space-qualified CMOS APS detectors (STAR1000 and HAS2 from ON Semiconductor/Belgium) on demand. Therefore, stable long-term operation in extreme radiation environments (STAR1000) as well as high dynamic and attitude accuracy (HAS2) requirements can be covered. With the conclusion of the qualification activities the ASTRO APS star sensor was ready for space flight and available as off-the-shelf product replacing step-by-step the CCD-based star tracker systems.

The development contract (17317/2003/F/WE) let by the European Space Agency to Jena-Optronik was performed in the frame of the Alphabus large platform pre-development headed by ESA and the industrial Joint Project Team consisting of Astrium (now Airbus Defence and Space), Thales Alenia Space (TAS) and CNES (Centre national d'études spatiales). Therefore, it was consistent that at the end of this contract a flight demonstration on Alphasat shall be performed. The Jena-Optronik star tracker ASTRO APS is one of four Technology Demonstration Payloads (TDPs) carried by Alphasat as hosted payload in the frame of a successful Private Public Partnership between ESA and Inmarsat who owns and operates the satellite as part of its geo-stationary communication satellites fleet. The star tracker as the TDP6 supports also directly TDP1, a Laser Communication Terminal, for fine pointing tasks. Alphasat was flawlessly brought in orbit end of July 2013 by a European Ariane 5 launcher. Since the launch Jena-Optronik receives daily telemetry data from the ASTRO APS star tracker on Alphasat. These data come down through the Inmarsat control center and are finally stored for evaluation and analysis at the Jena-Optronik TDP6 control center. In between ESA, Inmarsat and Jena-Optronik there have been defined in advance of the launch the rules and regulations how to exchange data and how to control the star tracker especially when commanding dedicated test sequences to characterize the star tracker in all of its capabilities and properties. Today these procedures are well established. Jena-Optronik can define special command and test sequences which are handed over to the Inmarsat control center approximately one week in advance to be executed on pre-defined time frames. This paper shows some of the most exciting in-orbit test results acquired with the ASTRO APS star tracker on Alphasat.

2 Star tracker operations on Alphasat

The ASTRO APS star tracker was launched at the 25th of July 2013 on Alphasat to its technology demonstration mission into a geo-stationary orbit. The usual procedure is that the spacecraft is released from the launcher into a geo-transfer orbit on which the satellite climbs up by several apogee boosts into its final geo-synchronous orbit height and later on to its final position. The geo-transfer orbit is characterized by a lot of different environmental conditions which are of high interest for the star tracker in-orbit verification and characterization, e.g., with respect to the spacecraft dynamic, stray light and deploying activities. When reaching its final geo-synchronous orbit position the spacecraft will be moved by the last major attitude control maneuver into the Earth pointing attitude which is then for the next 15 years the operational attitude of the geo-satellite. Now the star tracker is faced to the geo-synchronous Earth rate of 15 arcsec/s or just 360°/day and shall provide without interruption its 10 Hz attitude data to the attitude and orbit control system. In that nominal attitude tracking configuration the reported attitude axes data are characterized by the superposition of the classical star tracker noise budgets (temporal noise, high spatial frequency noise, low spatial frequency noise) and the measured satellite dynamic (control residuals, vibrations, wheel activities, etc.,). In the following sub-paragraphs we will present the ASTRO APS star tracker performance acquired during the environments of the transfer orbit and the nominal Earth pointing operation.

2.1 Geo-transfer orbit

Alphasat was launched on the 25th of July 2013 at UTC 19:54:00. The geo-transfer orbit was entered with the release of the Alphasat spacecraft from the launcher which happened on time in the late hours of the same day. The ASTRO APS star tracker was one of the first equipments which has been powered at this early mission time.

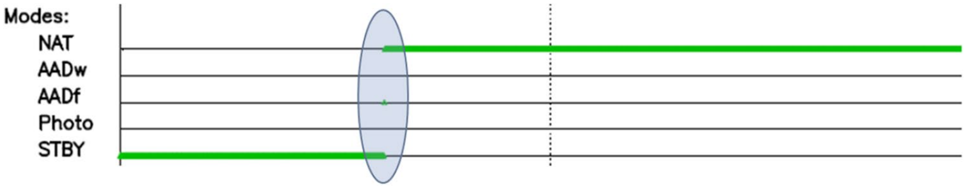


Fig. 1 Initial star tracker “lost in space” autonomous attitude acquisition after launch (*STBY* standby mode, *NAT* nominal attitude tracking mode)

2.1.1 Initial star tracker switch on

The exact star tracker switch ON time was 26th of July 2013, 03:29:35 UTC, just 7 h and 35 min after the launch time. Figure 1 shows the star tracker operating mode state telemetry data after the unit was powered. Approximately 4 s after getting primary power the star tracker responds in the Standby Mode.

In the few seconds before reaching the Standby Mode, the star tracker performs the software image boot process, the memory check and the health status check as well as the operational interface (MIL-1553) initialization. At that time the telemetry data rate was 2 s (0.5 Hz) getting the Status Data Block (SDB) and the Attitude Data Block (ADB). The star tracker itself operates in general during the whole mission life with an update rate of 10 Hz. That means at 0.5 Hz we get each 20th telemetry data package. The SDB showed nominal status, health and housekeeping data. The star tracker operated after power ON with −26 °C interface temperature at its lower operational temperature limit of −30 °C. At 03:50:01 UTC the star tracker SDB reported the valid command receipt of the autonomous attitude determination command (AAD). The star tracker enters into the full frame acquisition mode starting with a full field of view search for star-like objects. The STAR1000 digital video data pre-processing is done at this stage fully in a hardwired data pre-processor. Here the local background is determined to be able to detect the star-like objects also on increased background levels, e.g., caused by Sun stray light. All other objects which do not fulfill the data signature of potential stars (SEU’s, extended objects, streaks, etc.,) are automatically rejected by the pre-processor. When reporting a sufficient number of trackable objects the unit switches into the window mode, checks the single star quality parameters and performs the pixel centroiding. Based on this first set of single star angular coordinates the unit initiates the “lost in space” star pattern identification. The whole on board star catalogue is matched to the presently acquired star pattern without any supporting information. The first star pattern identification solution gets a preliminary status and will be finally declared valid when a sufficient number of pre-set stars confirm the initial solution. All of those briefly mentioned processing tasks have been solved within the time frame of receiving two 0.5 Hz telemetry packages. In Fig. 1 we see that the unit responds 2 s after leaving the Standby Mode in the AADf Mode (autonomous attitude determination during full frame read out) and another 2 s later already in the nominal attitude tracking mode (NAT) at 03:50:05 UTC. That means within 4 s, the ASTRO APS-STAR1000 star tracker entered successfully the nominal attitude tracking. This represents the expected attitude acquisition time duration when being successful just in the first attempt of the star pattern identification.

2.1.2 Spacecraft maneuver tracking

In the geo-transfer orbit the spacecraft was as usual spin-axis stabilized with 0.1°/s angular rate around the body z-axis. The star tracker is aligned to the spacecraft body frame so that its x-axis corresponds to the s/c body z-axis. In addition the star tracker is tilted out of the s/c body frame such that its bore sight will be pointed approximately 55° North out of the equatorial plane when in the final geostationary Earth pointing configuration.

That means the 0.1°/s spacecraft angular spinning rate can be directly seen on the star trackers x-axis. Figure 2 below shows the right ascension versus declination map (RA/DE map) with the star trackers measured line of sight axis track.

The RA/DE data have been just derived from the delivered attitude quaternion data. At begin of the shown RA/DE track we see the spacecraft in the nominal 0.1°/s spin-axis stabilization performing a 360° rotation in one hour. At approximately RA 158° an apogee engine maneuver was initiated. The star tracker just draws its projected artificially shaped line of sight track into the RA/DE map while keeping the 10 Hz attitude tracking at the positive and negative accelerations and the maneuver angular rates reaching in the peak value up to 0.5°/s. The star tracker software managed that rapidly changing dynamics fully autonomously within the NAT mode and without any external support.

The apogee maneuver was finished at about 0.0° RA and +70° DE when the star trackers line of sight track shows the continuation of the 0.1°/s spin-axis stabilization.

2.1.3 Moon in the field of view

Only when we are in the geo-transfer orbit we have potentially the unique possibility to see other objects like the

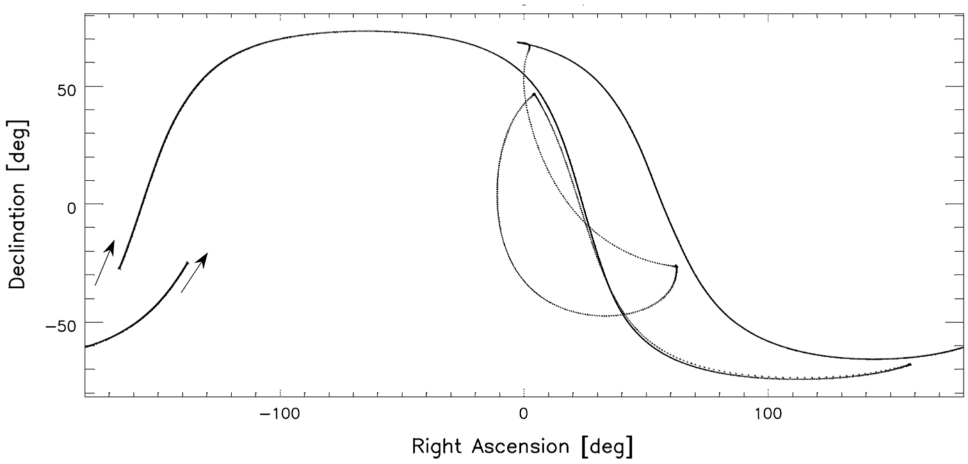


Fig. 2 Star tracker line of sight track in the RA/DE plane during attitude tracking of an apogee engine maneuver. The maneuver starts from 0.1°/s s/c z-axis spinning and ends up again in this spin stabilization

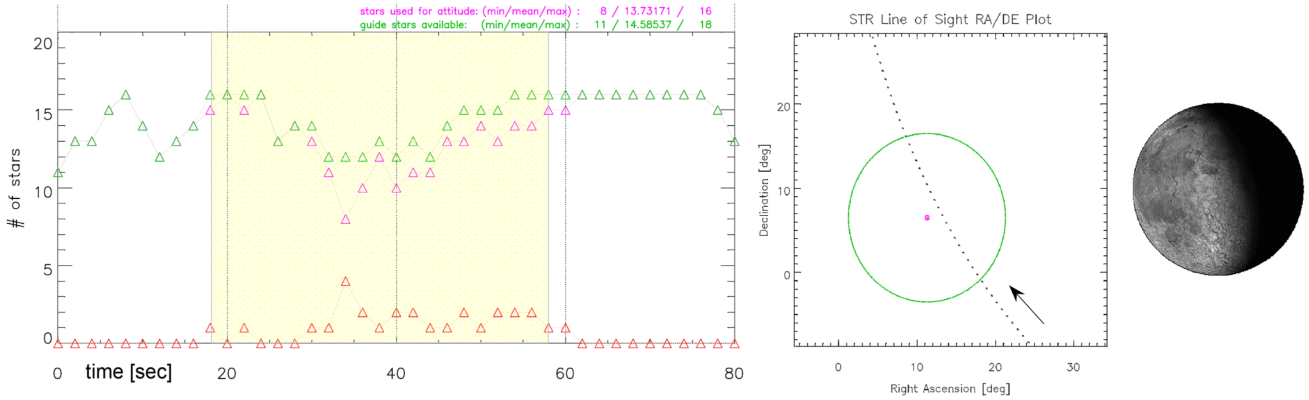


Fig. 3 Star tracker field of view Moon passage with 0.5°/s; *Left* available stars and stars used for attitude tracking during the Moon passage which is highlighted; *Mid* star tracker line of sight track, Moon with encircled star tracker field of view size; *Right* present Moon phase during the field of view passage

Moon, the Sun or the Earth which is excluded for the later geo-synchronous operation in s/c Earth pointing mode. For sure it was not in our hands to point the star tracker into those objects of special interest, instead of that we had to check the ephemerides in relation to the star tracker viewing direction. During the whole geo-transfer orbit operations we could reconstruct 29 star tracker field of view Moon passages. Figure 3 shows the 0.5 Hz step-by-step star statistics telemetry data during the Moon passage.

In middle plot of Fig. 3 we see the RA/DE map with star trackers line of sight track direction when moving through the Moon. For better illustration we have drawn the encircled star tracker field of view (20° circular) around the present Moon coordinates. The apparent s/c slew rate was 0.5°/s. That is why we see 20 measurement instances taken with 2 s rate during the Moon passage. The Moon phase at the day of the experiment as shown on the right-hand side above was at half full Moon status. But more interesting is to look at the measured star statistics when having the Moon in the field of view. The green symbol represents the number of available on board catalog stars and the magenta symbols show the number of stars used for attitude processing (the red symbol is just the difference). Therefore, we start with 100 % star tracking success, all stars available are tracked and used attitude processing. When the Moon enters the field of view (beginning at 19 s) we see that we lose 1–4 stars for attitude processing. That could be expected, because the Moon introduces some stray light and is itself an extended object with a diameter of 0.5°. So it depends on the present guide star distribution in the field of view which stars might be temporarily covered by the Moon stray- and direct light. During that Moon passage the absolute minimum number of valid attitude stars was still 8. Immediately after the Moon passage we come back to the 100 % star tracking success (available stars equals used stars). In all of the 29 Moon field of view passages the ASTRO APS-STAR1000 star tracker never lost the nominal attitude tracking.

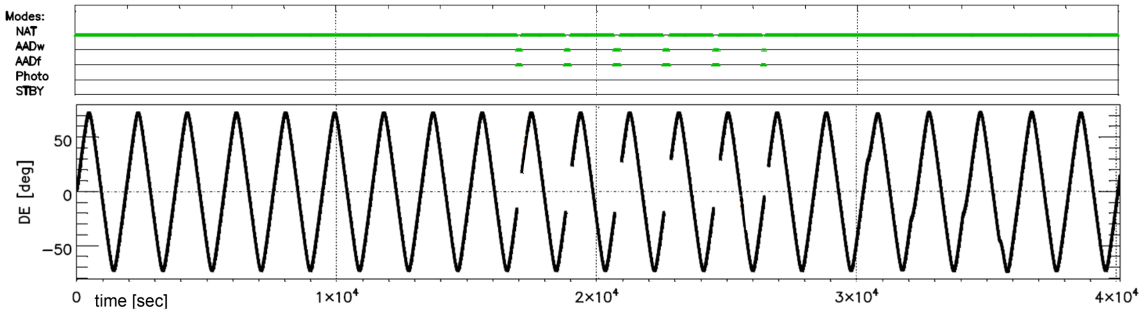


Fig. 4 *Top* Star tracker operational mode switches (*top*); *Bottom* declination measurement with 6 Earth blinding gaps at a spacecraft rotational rate of 0.2°/s

Remark: The actual ASTRO APS star trackers in production (either STAR1000 or HAS2) all have a full sphere guide star coverage of at least 16 guide stars in any viewing direction. The TDP6 ASTRO APS on Alphasat carries a full sphere 9-star coverage catalogue which is enhanced to guarantee 16 guide stars for its targeted geo-track between +50 and +60° in declination.

2.1.4 Earth blinding

As mentioned above, to see objects like the Earth is only possible during the geo-transfer orbit operations of the spacecraft. We could figure out several Earth blindings to which the star tracker was faced. The geo-transfer orbit is characterized by its highly elliptic shape so that the Earth aspect angle under which the star tracker is affected by the Earth disc or horizon is a function of the distance to the Earth. That can vary between several hundred kilometers up to 40.000 km. In addition the illumination conditions might range between full day light and night time. Figure 4 shows 40,000 s plot of the derived declination from the star tracker attitude quaternion. The spacecraft is spinning with 0.2°/s. In the middle of this plot we some attitude data gaps which are caused by Earth viewings within the tracker field of view. We can see 6 successive Earth blindings, one for each full 360° spacecraft rotation. At the upper part of the figure we see the corresponding mode switching which the star tracker performed by itself fully autonomously. This has been treated by Jena-Optronik as very valuable in-orbit data, just to study the star tracker mode transits under stray light conditions. This is not adequately possible at ground or laboratory conditions. Each Earth field of view transit was reported by the star tracker with just and only 1 mode switch (NAT− > AAD and AAD− > NAT) without any toggling in between the mode states at the stray light boundaries. The "loss of track" counter in the telemetry increased exactly by the number of 6 during this sequence.

2.1.5 Sun blinding

Due to very fortunate circumstances during the geo-transfer orbit, the star tracker was subjected to a direct Sun viewing into the focal plane. Figure 5 shows the 2 s step-by-step telemetry data when running into the Sun-blinded situation.

On right-hand sight we see the RA/DE map with the star trackers line of sight track (black) moving towards the 26° Sun distance line (red). The ASTRO APS stray light baffle is specified to keep full performance operation up to 26° Sun half cone angle. The plot shows that the nominal Sun exclusion angle line (26°) was passed for further 1.4° closer to the Sun. The star tracker lost attitude tracking at 24.6° Sun distance angle beat the requirement by 1.4°. On the left-top plot we see the reported background level. At 26° the background level is still close to the zero line which confirms the excellent background light compensation by the software algorithms. At the data point when we lose attitude tracking (red symbol) we had as last NAT background value 2,500 ADC counts (ADC-analog to digital converter). That means the star tracker operated successfully with more than the half ADC dynamic background light for valid attitude tracking. The left-bottom figure shows the number of guide star available (green symbol) and the number of stars used for attitude tracking (magenta). Due to the continuously increasing amount of background stray light it could be expected that the number of used high quality tracking stars decreases accordingly. That confirms the excellent operation of the single track star quality assessments made in situ during each star tracker processing cycle. Only stars with sufficient single star quality parameters are forwarded to the attitude processing. The last reported data instance before losing attitude tracking due to upcoming Sun blinding shows more than half ADC range dynamic background light and still 6 high quality attitude stars from at all 12 available stars. What an amazing result!

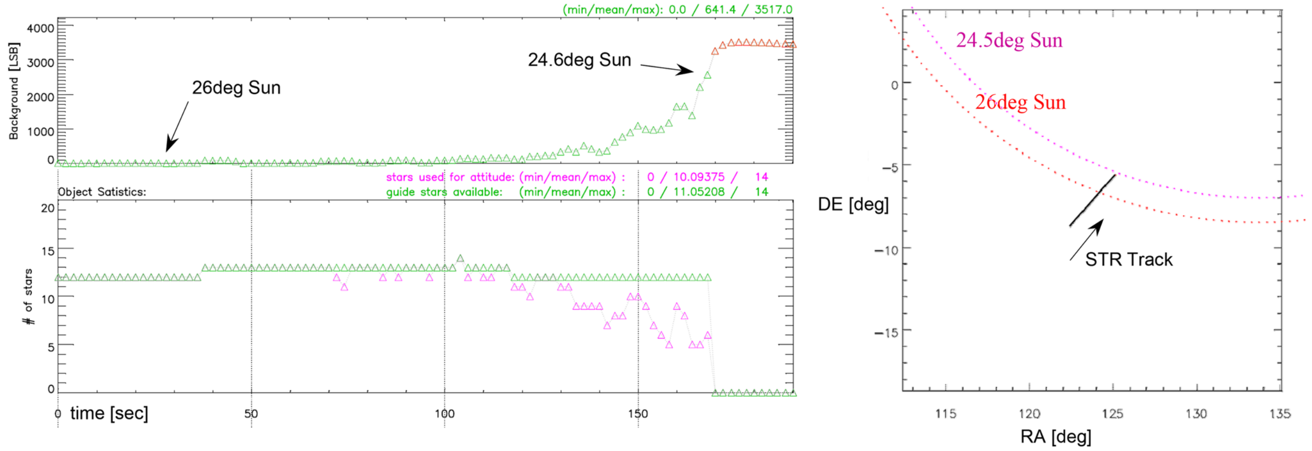


Fig. 5 Star tracker telemetry data immediately before entering the nominal Sun exclusion angle of 26°; *Left-top* Measured focal plane background signal level (Δ *green*) up to loss of attitude tracking (Δ *red*); *Left-bottom* Available guide stars (Δ *green*) versus guide stars used for attitude tracking (Δ *magenta*); *Right* Star tracker line of sight track (*black line*) towards the 26° Sun distance line and the 24.5° Sun distance line

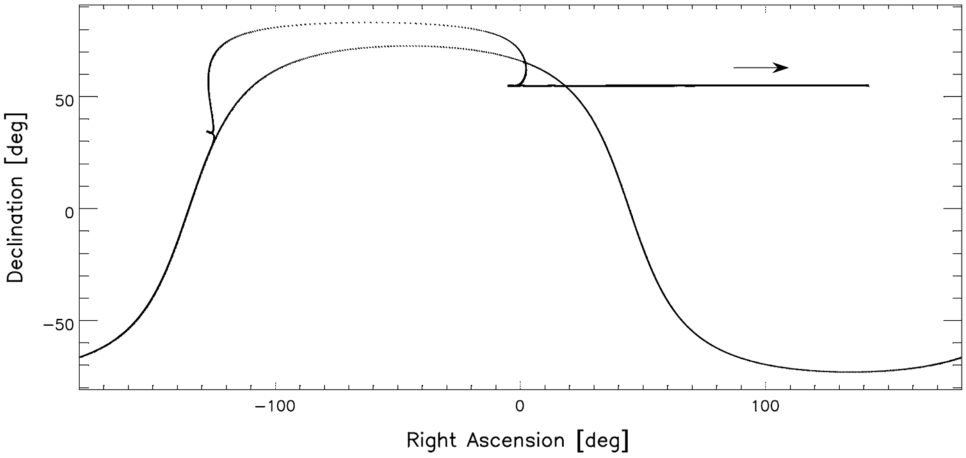


Fig. 6 Star tracker line of sight track in the RA/DE plane during the final maneuver to enter s/c Earth pointing. The maneuver starts from 0.2°/s s/c z-axis spinning and ends up in nominal Earth pointing

Remark: The TDP6 ASTRO APS star tracker is equipped with the STAR1000 CMOS APS detector. This detector carries on-chip a 10bit A/D-converter. Within the star tracker pre-processor the digital video signal data bus is implemented with 12bit data width to support also HAS2. The STAR1000 10bit video signal is shifted to the internal upper 10bit of the 12bit data bus. That's why the background level reported in Fig. 5 *covers a 12bit equivalent range. E.g. the real physical STAR1000 half dynamic ADC range is about 512 ADC counts.*

2.1.6 *Enter s/c earth pointing*

We will finish this section with leaving the geo-transfer orbit operations. This point of time in the in-orbit operations is characterized by the last attitude maneuver which brings the spacecraft into an Earth pointing attitude at approximately 8° East. Figure 6 shows exactly this spacecraft maneuver tracked again by the ASTRO APS star tracker without any interruptions. The corresponding line of sight track is shown below within the RA/DE map. Before initiating this last transfer orbit maneuver the spacecraft was spinning with 0.2°/s. At RA −120° the spacecraft Earth pointing maneuver has been started and ended up at RA −8° as seen on the map below. Beginning from this point in time the star tracker responds with an attitude data signature as typical for the geo-stationary operation. From now we see a fix declination of +55° and a daily right ascension from 0.0 … 360°. In October 2013 the spacecraft reached its final geo-position at 25° East.

2.2 Nominal earth pointing on geo-orbit

When reaching the geo-stationary orbit the TDP6 star tracker downlink telemetry data rate was changed from 0.5

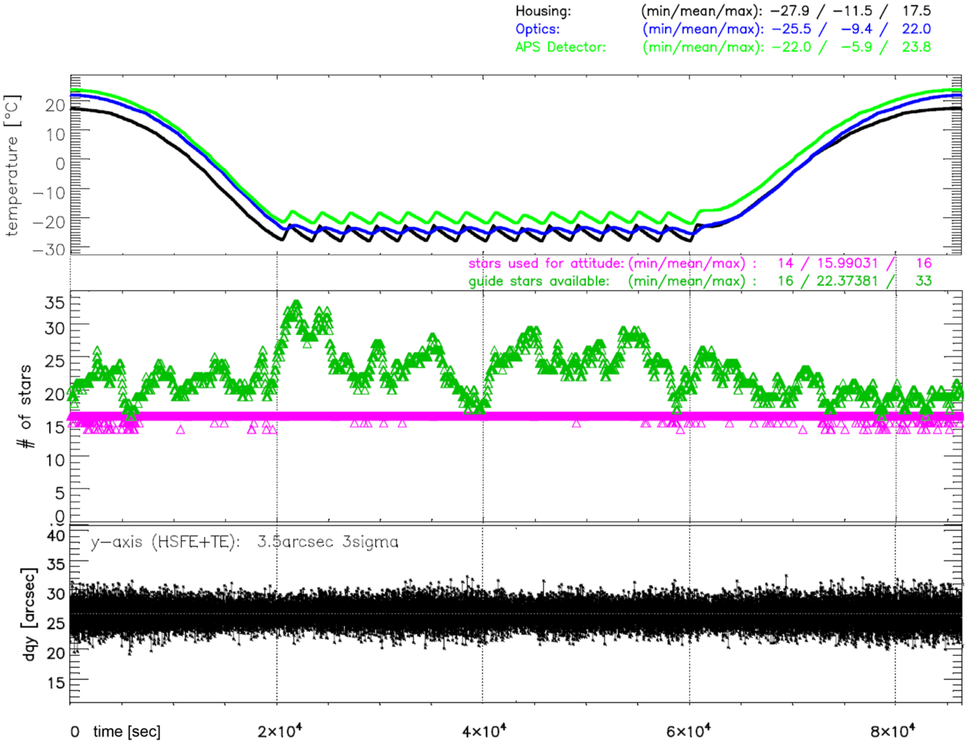


Fig. 7 24 hours geo-operation at spacecraft Earth pointing; *Top* Star tracker temperature swing; *Mid* Star catalogue coverage for the geo-operation with minimum 16 stars available (Δ *green*) and the stars used for attitude tracking (Δ *magenta*); *Bottom* Attitude random error for the star tracker *y*-axis

to 0.33 Hz. The star tracker itself operates with a fix data rate of 10 Hz. In Fig. 7 of the next page we see 0.33 Hz telemetry data (each 3 s) from the Status Data Block (SDB) and the Attitude Data Block (ADB) over a full geo-synchronous day (86,400 s). On the top plot the daily temperature telemetry data of the star tracker are given. The ASTRO APS star tracker carries 3 temperature sensors, one at the interface plate (housing), the second at the STAR1000 CMOS detector and the third at the optics barrel. The daily temperature swing on the star tracker interface is from −27.9 to +17.5 °C, a daily delta of 45.4 K. The APS STAR1000 detector reports a few degree Celsius higher temperatures in relation to the mechanical interface plate. This could be expected due to the STAR1000 power consumption of approximately 250 mW. This experienced delta temperature confirms the on ground measurements and characterizations during the thermal vacuum cycling tests. The thermal electrical cooler has a set point of +30 °C STAR1000 chip temperature and remains, therefore, in the OFF state. The middle plot shows the star statistics again with the number of available guide stars and the number of the used high quality stars for attitude tracking. This plot is a nice confirmation that the on board star catalogue was populated to minimum 16 stars for the targeted geo-track. Over one full day we have 16 stars in minimum available and 33 stars in maximum. In case of more than 16 available stars the attitude tracking software picks up the best suited set of 16 stars for attitude tracking. The order of precedence in guide star selection is always from bright to faint. It depends on the stars population whether the 16th star is a mean magnitude star or more at the limiting magnitude edge. In the last case, the rejection statistics down to 14 attitude stars is a bit higher (see magenta plot). Due to the constant noise floor we see no correlation between attitude stars rejection and the detector operating temperature. The bottom plot shows the *y*-axis attitude random noise which was calculated simply by the delta quaternion of successive telemetry data blocks [2] that are acquired each 3 s. The reported mean value represents, therefore, the *y*-axis angular rate of 25.8 arcsec/3 s = 8.6 arcsec/s which is the expected value at +55° declination and Earth rate [15 arcsec/s × cos(55)]. Building the successive delta quaternion over a time period of 3 s shows the uncorrelated temporal error and partly also residual high spatial frequency error due to the stars movement within the 3 s. This results in a figure of 3.5 arcsec 3sigma *y*-axis attitude random noise over a full day.

Despite of the large daily temperature swing of the STAR1000 detector (−22.0 … 23.8 °C, ΔT 45.8 K) in that mission phase we see no correlation to the attitude axes random noise, as seen above by the *y*-axis noise. This confirms nicely the error budget model of the star tracker. At the 10 Hz star tracker cycle and corresponding exposure time the dark current becomes visible in the noise figures above +30 °C chip temperature. Therefore, full performance can be kept up to that operating point without having the necessity to power the thermal electrical cooler. Experiments in the laboratory and on night sky showed ASTRO APS star

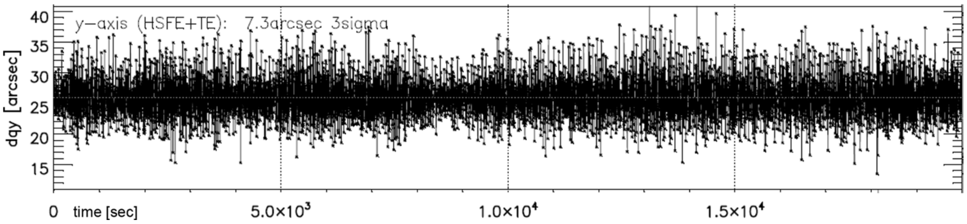


Fig. 8 *Y*-axis noise (TE, HSFE) at disabled FPN correction and DSNU and White Spot rejection. Data acquired at 22nd Dec 2013, Duration: 20,000 s, Orbit segment: RA: 143…226°, DE: 55°

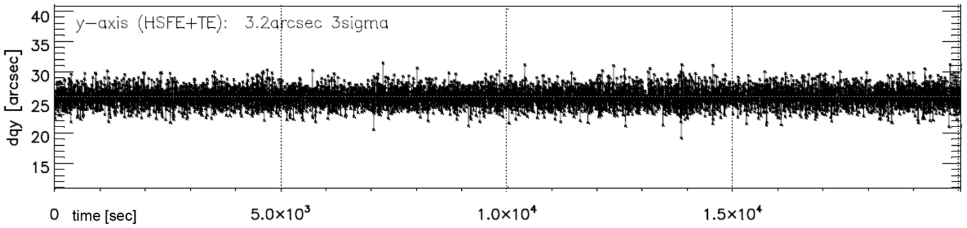


Fig. 9 *Y*-axis noise residuals (TE, HSFE) at enabled FPN correction and DSNU and White Spot rejection. Data acquired at 23rd Dec 2013, Duration: 20,000 s, Orbit segment: RA: 143…226°, DE: 55°

tracker functionality up to +60 °C but truly with reduced performance in the noise budgets.

Since September 2013 the ASTRO APS star tracker operates reliably on Alphasat within its performance specification and mostly beyond this.

2.3 Performance of first characterization experiments

Beginning with the time when Inmarsat took over the Alphasat spacecraft for the nominal commercial in-orbit services, the technology demonstration payloads entered also their experimental and characterization phase as agreed in the private public partnership contract between ESA and Inmarsat. Up to that time the TDP6 star tracker was just a powered ON AOCS sensor reporting continuously its nominal status and attitude data to the spacecraft control computer and down to the Inmarsat control center and finally to the Jena-Optronik mission server.

The TDP experimental phase is characterized by the fact that the payloads can be actively controlled and re-configured by the unit system engineers. In fact, the unit operator, as Jena-Optronik GmbH for the TDP6 star tracker, can submit each week one week in advance a well-scheduled command and experiment sequence to be executed via the Inmarsat control center. In the following sub-paragraphs some the ASTRO APS star tracker in-orbit characterization experiments are shown.

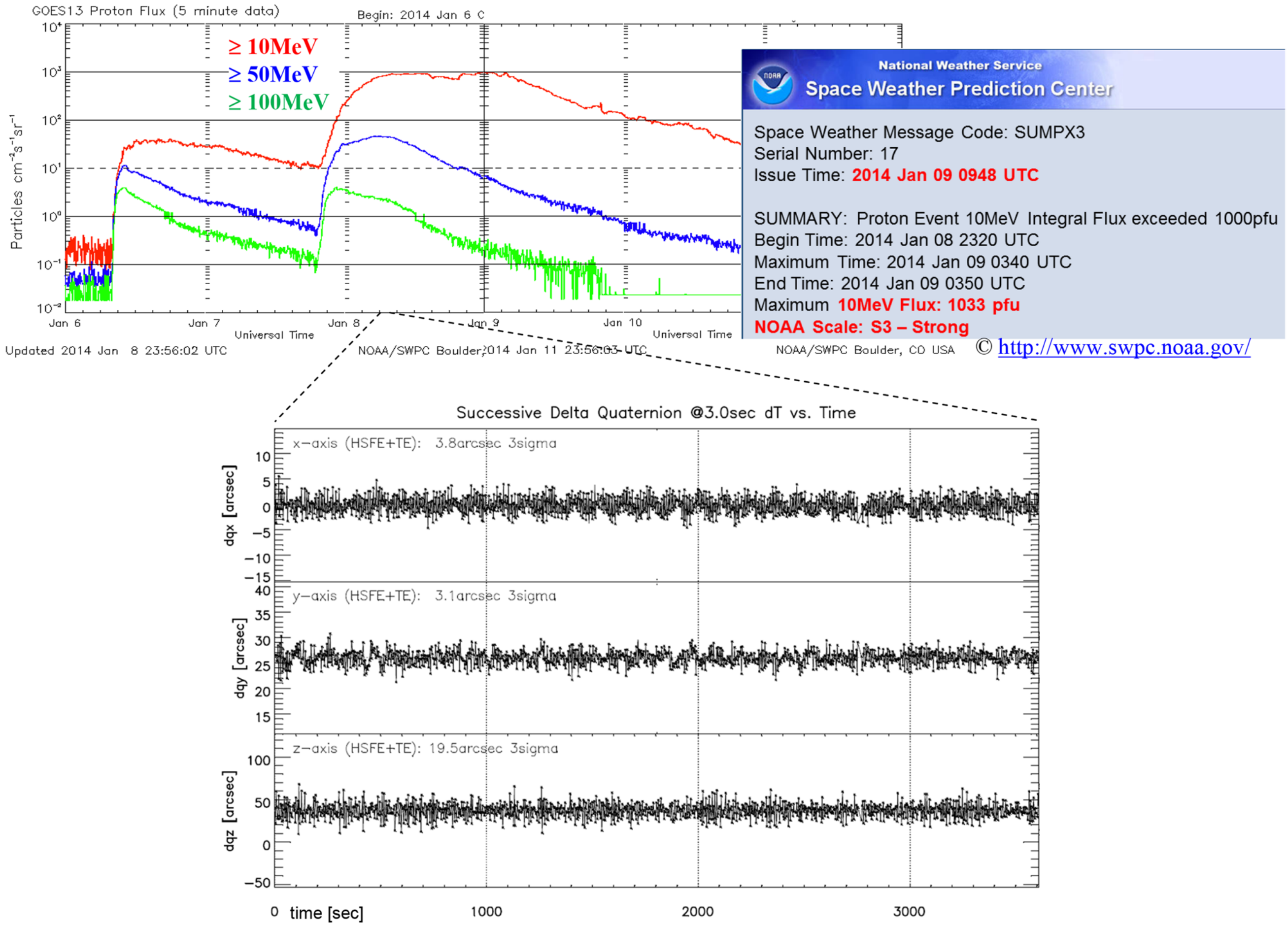
2.4 Evaluation of the smart background noise rejection algorithms

The ASTRO APS star tracker on Alphasat carries some of the new and advanced background noise rejection algorithms developed by Jena-Optronik GmbH, e.g., like the in situ autonomous and self-adaptive DCNU (dark current non-uniformity) and White Spot rejection algorithm [1].

So it was of high interest to show with the ASTRO APS in-orbit configuration the achieved gain in noise suppression. For that purpose the DCNU and White Spot rejection algorithm was disabled and enabled again for the same period of time over two days to compare the same geo-orbit segment regarding the processed star patterns. Figure 8 below shows a 20,000 s period *y*-axes attitude random noise, calculated again from the 3 s successive delta quaternion [2].

The attitude random noise increases to 7.3 arcsec 3sigma with disabled noise reduction measures compared to the already verified performance as shown in Fig. 7 (3.5 arcsec 3sigma). To be fully representative we evaluated the next day the star tracker attitude data again for the same orbit segment but with enabled noise reduction algorithms which is the nominal star tracker operation. Figure 9 shows that result from the 23rd of December 2013.

With that in-orbit characterization experiment we could successfully show the efficiency of these innovative noise reduction measures which are today standard software procedures in the star tracker flight models. This excellent noise figure of 3.2 arcsec 3sigma achieved with a STAR1000-based star tracker unit can be furthermore improved when using the HAS2 detector which provides higher sensitivity and lower noise. For example, HAS2-based units show <2.3 arcsec 3sigma attitude random noise under the same conditions. We would like to recall here that these introduced noise reduction measures do not limit the star tracker attitude data bandwidth as simple attitude filters would do. The noise contributors like the dark current non-uniformity, the fixed pattern column noise and white spots are corrected and/or compensated directly in their pixel raw data representation.



Space Weather Message Code: SUMPX3
Serial Number: 17
Issue Time: 2014 Jan 09 0948 UTC

SUMMARY: Proton Event 10MeV Integral Flux exceeded 1000pfu
Begin Time: 2014 Jan 08 2320 UTC
Maximum Time: 2014 Jan 09 0340 UTC
End Time: 2014 Jan 09 0350 UTC
Maximum 10MeV Flux: 1033 pfu
NOAA Scale: S3 – Strong

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Fig. 10 *xyz*-axes temporal noise calculated by successive 3 s Δt quaternion at 2014 Jan 8, 06:00:00–07:00:00 UTC when the 50 MeV reach the maximum fluency

2.5 Operation under solar flare environment

In January 2014 an S3-solar flare (“strong” on NOAA scale) was reported by the NOAA GOES space weather monitoring satellite fleet. Exactly at that time when the solar flare came in, the days from the 7th to the 9th of January 2014, a “lost in space” re-acquisition experiment was scheduled to the Inmarsat control center. Therefore, we could in addition study the star tracker performance under a solar flare, when solving the “lost in space condition” during the initial attitude acquisition without any supportive data.

Figure 10 shows in the lower part the 3-axes attitude random noise for 3,600 s (again delta quaternion, ΔT 3 s) when the 50 MeV particle fluency reached its maximum. There are no outlier measurements in the attitude axes noise data streams. Affected single star centroiding fields are recognized by the star tracker processing software and rejected from the final attitude solution.

All of the 25 initial “lost in space” attitude acquisitions have been performed successfully under the solar flare environment which touched the lower S3-level limit at the NOAA scale in its peak fluencies. This result could be expected due to the still rather small proton flux >30 MeV reaching the detector plane with 100…200 events/image compared to the star sensors capability of up to 50.000p $+/\text{cm}^2/\text{s}$ (12,000 events/image) shown on ground test equipment. When passing the high energetic protons dominated Van Allen belt in the early mission phase the star sensor unit was subjected to a much higher proton flux. Unfortunately at this time, experiments like “lost in space” acquisitions could not be performed for the TDP. However, the unit operated in the nominal attitude tracking mode and delivered the status data block (SDB) and the attitude data block (ADB). The post-processing of these data showed no increased attitude axes random noise when passing the high energetic proton belt.

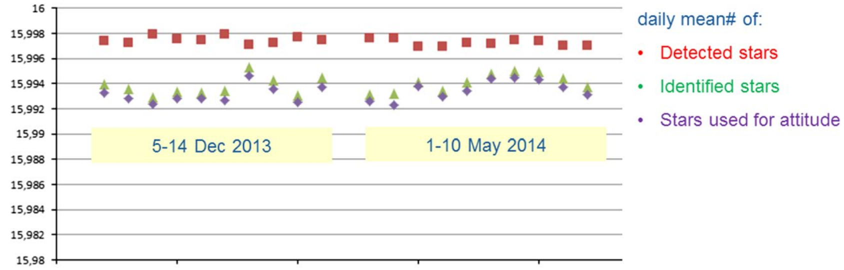

Fig. 11 Star statistics of the daily mean detected, identified and attitude stars over a period of 6 month

3 Conclusion

The ASTRO APS star tracker characterization experiments on Alphasat are still ongoing and planned to go on for the time frame of the first 3 years in orbit. The next scheduled experiments will focus on the single star measurement performance verification like, single star TE and HSFE, magnitude measurement accuracy, spectral class transformation response, etc. In addition, we evaluate in regular periods the star acquisition and tracking statistic to monitor any kind of aging effects. This is a well-suited measure for degradation effect monitoring because the star tracker repeats each geosynchronous day the same star patterns processing.

Figure 11 shows the statistics of mean detected, identified and attitude stars for each 10 days in December 1013 and May 2014. There is no sign of any kind of degradation effect seen in this figure. The values vary in a range of 0.002 stars. This variation is caused by tiny drifts in the spacecraft orbit inclination which changes the star statistics accordingly to a very small amount.

After the intense design and development process from the first idea to the product under in-orbit operation we can present the ASTRO APS star tracker performing within and beyond the specification limits on Alphasat. The Alphasat platform has provided and still provides an excellent environment, especially during the geo-transfer orbit for the ASTRO APS star tracker characterization measurements. The ASTRO APS-STAR1000 star tracker could be successfully verified regarding the attitude measurement performance, the capability to operate with the Moon in the field of view and the Sun exclusion angle.

In the TDP6 experimental phase the efficiency of the introduced noise suppression algorithms could be shown as well as the capability to solve the “lost in space” acquisition under a solar flare environment. The experiments with the TDP6 star tracker are scheduled for the first 3 years in-orbit operation on Alphasat so far. As the next activities we will investigate the single star performance data and the raw photo mode detector data to get feedback for the further developments.

The Jena-Optronik GmbH engineering team is in particular proud that it could show to operate the radiation hard STAR1000 CMOS APS detector in a high-performance geo-telecom star tracker product. That opened the flexibility to equip the radiation demanding mission profiles (e.g., 15 years geo-telecom) with the STAR1000 detector and the agility demanding programs with the HAS2 APS detector.

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