STAR-TRACKING IN HIGH RADIATION REGIME: IN-FLIGHT RESULTS FROM THE SMART-1 MISSION

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ABSTRACT

This paper describes how the radiation impact from the passage of the radiation belt was planned mitigated for the Advanced Stellar Compass (ASC) [1], the star-tracker onboard the SMART-1 satellite. Since absolute pointing is essential when using an ion-drive, the ASC was required to operate and deliver high accuracy attitudes throughout the thrust phase of the mission, including the high radiation regions. Unfortunately, the mission phase passages through the radiation belts coincided with two extreme solar storms, such that the planned EOL radiation dose was reached within a few days.

We describe in this paper the mitigation strategy for how to recover the approximately 40 stars in a typical image from the more than 10,000 star-like objects caused by radiation using a feature-based analysis. In particular, the regression aspect versus time and memory resources is detailed. Finally, we present the results from successful in-flight operation on board the SMART-1 satellite mission.

INTRODUCTION TO SMART-1

The SMART-1 satellite is an ESA mini satellite built by the Swedish Space Corporation (SSC). The main mission objective is the demonstration of the usefulness of electrical propulsion (EP) by performing a cost-effective cruise to the moon [2].

The planned trajectory towards the Moon was initiated by an Ariane 5 launch into GTO in September 2003. Using the EP engine a continuous increase of the elliptical orbit was obtained, as illustrated in Figure 1. By carefully planning the orbit and the thrust the satellite was eventually captured by the gravity of the Moon in November 2004.

Figure 1: Artists impression of SMART-1’s trajectory towards the Moon (source ESA)
The orientation of SMART-1 is measured by an Advanced Stellar Compass (ASC) star-tracker, consisting of a double Data Processing Unit (DPU) and two Camera Head Units (CHU). The two DPU and CHU pairs are cross-strapped for internal redundancy.

CCD RADIATION DAMAGES AND STAR-TRACKING

The CCD technology is inherently not sensitive to single event latch-ups, also it is found that CCD chips are highly resistant to gamma and electron irradiation. Only damage from energetic baryon radiation has a strong negative effect on the performance of CCD chips. As energetic heavy particles pass through the CCD, they will have two effects.

Firstly, the particles will generate a trail of ionization along the particle path through the chip. Since CCDs basic function is to accumulate photoelectric charges, they are inherently sensitive to such ionization trails. Since the electrons of the trails rapidly gather in one of the charge wells, pixels, and here add to the photoelectric electrons, such a trail will lead to an excessive charge in one or a few pixels locally around the site of impact. This effect is independent from any other physical parameter, i.e. only dependent on the incoming flux, type and energy of the particles.

Secondly, approximately one out of 2 million passing protons generate a permanent or semi permanent damage to the CCD. This damage is typically a surface defect on a specific pixel, which acts as a donor site, efficiently increasing the dark signal of that pixel, i.e. the pixel becomes brighter wherefore the phenomenon is called hotspots. Since the surface defect that is responsible for the hotspot effect is working as a thermal charge generation site in the lattice, the manifestation is highly (exponentially) dependent on the CCD temperature. This temperature dependency is measured in test to be such, that the CCD can tolerate a total proton dose of 50kRad without measurable degradation, if the CCD is operated at –40°C. At 0°C operating temperature, the acceptable dose from protons decreases to 2kRad.

![Figure 2 - High radiation image from one of the ASC star-trackers on-board SMART-1 acquired at a CCD temperature of 22°C. The image has been inverted for clarity. Left: The full image; right: A zoom in a part of the image. The hotspots are visible as small bright (dark) dots, and the stars as more extended rounded objects.](image)

Common to the two types of hotspots is the particular inconvenience when encountered in point object based low-light applications, such as star-tracking. The
hotspots that effectively produce luminous image dots appear very similar to the image projection of stars. The introduction of a large number of such non-stellar objects will consequently challenge the following pattern recognition. The intensity-inverted image in Figure 2 is acquired from one of the two ASC star-trackers on-board SMART-1 after receiving 1.2kRad to the CCD from protons. The hotspots can be recognized on the image both as small luminous dots and as an increased background noise level.

RADIATION - PLANNED AND REALIZED

Since a high dose of radiation was expected from the radiation belt passages, the standard ASC CHUs were fitted with an augmented shielding. Simulation results including this extra shielding demonstrated that the total dose, end of life, was 550Rad from protons to the CCD for the planned mission trajectory. With a planned operational temperature envelope from -25°C to 0°C, the CCD can sustain 2kRad leaving a (reasonable) sufficient margin.

Unexpected events lead to a significantly different radiation environment than expected. The two major effects were:

1) A prolonged cruise phase through the inner radiation belt
2) The massive solar eruptions in late October and early November

The effect from the radiation affected both the ASC and other equipment on-board the S/C. Received radiation doses based on GOES 11 measurements suggest that during the short phase from launch to the end of the Halloween storm up to 150% of the EOL dose was received [3].

As launched, the ASC SW/HW combination was trimmed to deliver full performance at up to 0°C throughout mission life. After launch, it was however soon realized, that the operational temperatures of the CCDs deviated substantially from the expected of that part of the mission. The reason for this effect, is a combination of several effects, but is at the time of writing still not fully understood. The fact is, that the operation temperature of the CCDs during LEOP was more than 10°C for a significant part of the time. At certain operation phases, temperatures higher than 25°C was measured.

MITIGATION STRATEGY

The combined effect of the higher radiation dose and temperature called for an improved rejection mechanism against hotspots. In order to design a software discrimination of hotspot signatures that could be installed in-flight, their image characteristics, or features, were identified from ASC images downloaded from the S/C. In particular, the features that are different from those stemming from true image objects (stars) were of a high interest. One such analysis lead to the following non-prioritized list:

- The luminosity of static hotspots is highly temperature dependent.
- The projection of true stars follows the point-spread function of the lens.
• The image positions of static hotspots are permanent.
• A dynamic hotspot will appear in one image only
• All the hotspots have distinct morphologies

A filter is implemented independently for each of the above-mentioned features. These filters are further detailed in [4]. By keeping the filters independent, their individual parameters and thresholds could be optimized without intervening with the other filters. Furthermore, if several filters were included, relaxations can be put on the individual filter thresholds to avoid false discrimination of true image objects. This is especially important since the rejection must leave the true stellar objects unaltered if full accuracy shall be obtained. Finally, the individual filters based on the above-mentioned characteristics do have different computational requirements. Thus, by carefully selecting the order in which they were executed, the total computational requirements could be minimized.

PERFORMANCE

After upload of the improved hotspot discrimination filters, the star-tracker performance has been thoroughly investigated.

The validity, defined as the percentage of valid updates, can be estimated by performing a rolling binning of the valid flag of the individual attitude package. Using this method, it is observed that the figure is close to 100% when operating in the orbit around the Moon.

The coverage is defined as the ability of the star-tracker to determine the attitude for all possible orientations. It is a strict requirement that the ASC must have complete coverage without a priori knowledge. From in-flight measurements it is observed that after the filter upload, the coverage has decreased to some 95%. The reason for the remaining 5% non-coverage is well understood and can be fixed by tuning a single system parameter. The project has been found, however, that since the two CHUs are operated simultaneously, a valid attitude solution is always present, wherefore the required 8-byte patch has not been uploaded.

The pointing accuracy can be estimated by calculating the inter-boresight angle (IBA) between the two CHU’s for simultaneous attitude measurements. Since the two CHU’s observe different parts of the sky, the attitude determination for the two CHU’s rely on completely different data and are thus independent. The IBA varies less than 36° peak-to-peak over an orbit including platform flexures, corresponding to a 1Φ value of 6” for the two instruments or 4.2” per CHU. This measure includes orbit-level harmonic variations, which are believed to be caused by thermally induced flexures of the spacecraft body.

The ASC performance is further detailed and elaborated in [3]. Based on the above-described performance measures it is found that the ASC star-trackers on-board the SMART-1 satellite are in good shape and sufficient margin towards EOL performance is once again obtained.
REFERENCES


[2] The ESA SMART-1 homepage: www.esa.int/smart-1
