ZERO-COST MISSION RETURN IMPROVEMENT FROM AUGMENTING STAR TRACKERS WITH PARTICLE SENSOR CAPABILITIES

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1 ABSTRACT

Star trackers have become the industry standard for recovering accurate orientation for spacecraft. The embedded image sensors, CCD or APS, are inherently sensitive to ionizing radiation. An incoming charged energetic particle that passes through the sensor shielding and reaches the image sensor will penetrating the die along its ionizing track, liberate electrons into the individual pixel charge wells. The results are sporadic transient bright pixels, or *fireflies*, and operation in heavy radiation environments challenges the isolation of stars in the star tracker source images. Naturally, these effects are generally undesirable and are negatively affecting attitude performances. The typical remedy is a combination of adding shielding around the image sensor and software identification/isolation of breakthrough radiation imprint.

However, the image *fireflies* from penetrating radiation may be regarded relevant data of the space environment rather than a nuisance for operation. By counting *fireflies* in each source image, the star tracker measures the observed particle flux at high sample rate, effectively augmenting the attitude sensor with particle flux sensor capabilities – at no additional cost. The particle sensory products may be used for a multitude of purposes, e.g. particle environment mapping and on-board zero latency warning to other sensitive instruments. Trajectory or global radiation maps may be compiled on-board as "*Information Made in Space"* augmenting the local or global space weather science and situation awareness products. Finally, enabling the functionality on several platforms will improve differentiation between spatial and secular radiation variations.

We explain the technology behind and discuss its calibration and operation. We present example products from the highly successful application to the NASA JUNO Jupiter probe trackers and the ESA Swarm constellation trackers. Finally, we review the perspectives for improving mission return and the huge potential of this zero-cost mission augmentation.

2 MEASUREMENT PRINCIPLE

All image sensors, CCD or APS type, operate by focusing light onto a grid of pixels. The incoming photons are liberating electrons in the sensor die within a certain exposure period. After read out, amplification and quantization, they form an image accumulated over the period of exposure. For star tracker operation used for spacecraft attitude determination a high light sensitivity is required. This is achieved using long integration periods and high video signal amplification.

When an image sensor is operated in a charged particle environment, energetic particles may penetrate the sensor shielding and liberate several electrons in the image sensor along its ionizing track. The liberated electrons may be generated in or drift to one of the sensors charge wells, and will be read out together with the remaining photo-converted electrons forming the image. The result is sporadically scattered bright pixels in the formed image – located at the individual pixels hit by the charged particles. For Star Trackers, operating at low light conditions, the number of ionization generated electrons may be comparable to that of the photo generated electrons, generating a white pixel or local group of pixels persisting for one frame-time only. This image effects are typically referred to as *fireflies*. For star tracker sensors the effect is aggravated by the relative long exposure times and high amplification. Figure 1 shows a small region of a typical star tracker image operated in a heavy radiation region.

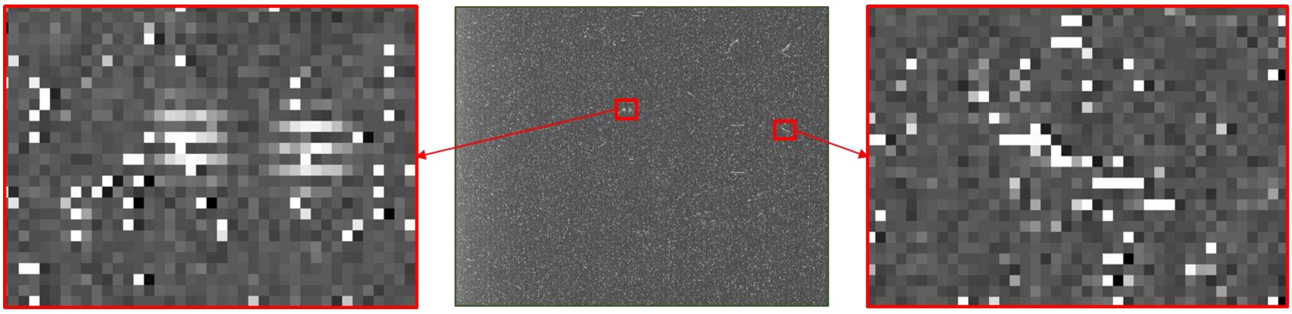

Figure 1: Image acquired from one of the JUNO ASC star trackers during heavy electron radiation. Left and right shows zoom of regions. In the left zoom region, a star is seen within a large number of fireflies. The right zoom region shows an ionization trail generated by an energetic particle penetrating close to parallel to the focal plane.

The effect being a challenge to nominal star tracker operation in heavy radiation regimes is typically remedied by introducing heavy mass shielding around the image sensor, effectively absorbing the lower energy part of the particle population, thus decreasing the count number. While the mass shielding reduces the *firefly* count to a level that can ensure accurate attitude determination it will not bring the count to 0. This originally unwanted highly penetrating radiation may be exploited in a number of ways to provide valuable in-sight into the surrounding particle environment.

- By counting the number of *fireflies* in a star tracker image and compensating for the shield thickness a rough estimate of the external particle flux during the image exposure is found.
- By performing the count during each star tracker attitude cycle, a time series of the external radiation along the spacecraft trajectory may be established.
- By combining several spacecraft orbits global maps of the ionizing radiation may be compiled
- By combining maps over time, secular effects can be identified
- Combining coherent measurements from several spacecraft provides insight into the detailed evolution of isolated radiation events.
- Finally, combining measurements from spacecraft with different mass shielding (i.e. particle cut-off energy) provides the means to derive spectral distribution.
- Typically the shield length varies between the lens direction and all other, resulting in a particle telescope function

We suggest adding this basic functionality to all possible star tracker systems and making the count rates available to the scientific community.

3 CALIBRATION

Calibration of the radiation transport model is key to obtaining a high fidelity of the radiation count rates, especially if data from different spacecraft with different radiation mass shielding configuration and/or environment are used in combination. We used the following hierarchical calibration:

- Basic sensor sensitivity
- Radiation transport model

3.1 Basic sensor Calibration

The sensor sensitivity was established by recording the count rate response while the sensor was exposed to radiation with a known energy and flux. In our calibration electrons with mean energy of 1 MeV (max up to > 2 MeV) from a Strontium 90 decay source were used. While the particle energy was kept constant, the flux was varied by changing the distance between the image sensor and the radiation source. The output of this calibration is a simple constant identifying the number of counts obtained from each penetrating particle.

Equivalent calibration of detection efficiency with 30 and 100 MeV protons was performed at PIF of the PSI.

3.2 Radiation Transport Model

The radiation transport model was obtained from an inverse Monte Carlo simulation (ray tracing) of a CAD model of the image sensor with all structural elements included. Tens of thousands rays were simulated eventually providing both a shield depth distribution curve and an average shield depth. Figure 2 shows a shield depth distribution of an example system.

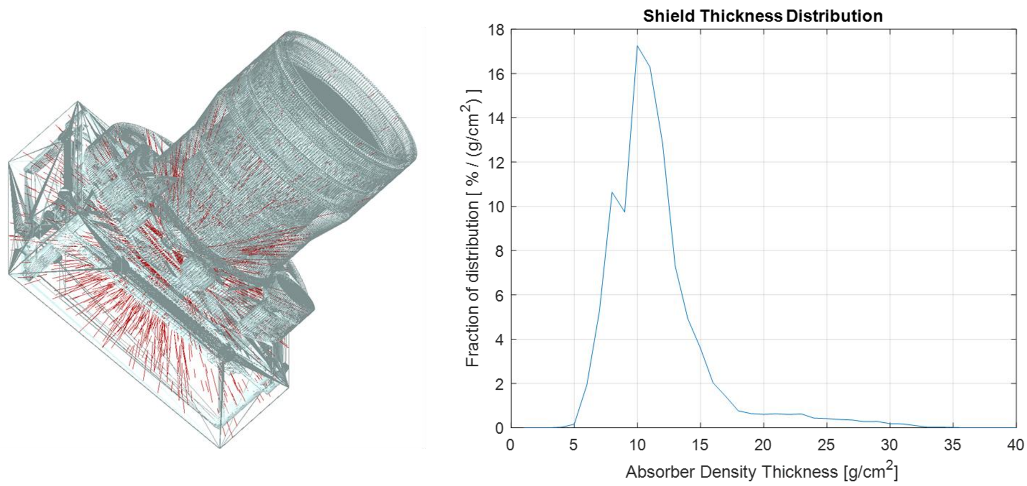

Figure 2: Left: Output from inverted Monte Carlo ray tracing simulation. The shield depth is calculated along the rays (red lines in figure). Right: Distribution of shield depths along the simulated rays.

4 EXAMPLES FROM FLIGHT

We have implemented the *firefly* count rate feature on a number of star trackers on a few selected spacecraft missions in order to demonstrate the concept. Those missions span a wide range of orbital/radiation environment classes:

4.1 ESA Swarm Mission

The ESA Swarm mission is a three spacecraft mission with two spacecraft orbiting in tight constellation in a lower altitude (~450km) and one spacecraft orbiting in a higher altitude (~550km) – all in polar circular orbits. Each spacecraft is equipped with three star trackers all setup for reporting *firefly* count rates. This configuration allows both spatial distributions using the two lower orbiting spacecraft. However, since the three star trackers on each spacecraft point in different direction and since the mass shielding is not uniform, this directional sensitivity is utilized to identify the particle incident direction (West/East ward). Figure 3 shows the West/East gradient as observed by the starboard and port star trackers on-board Swarm-B [1].

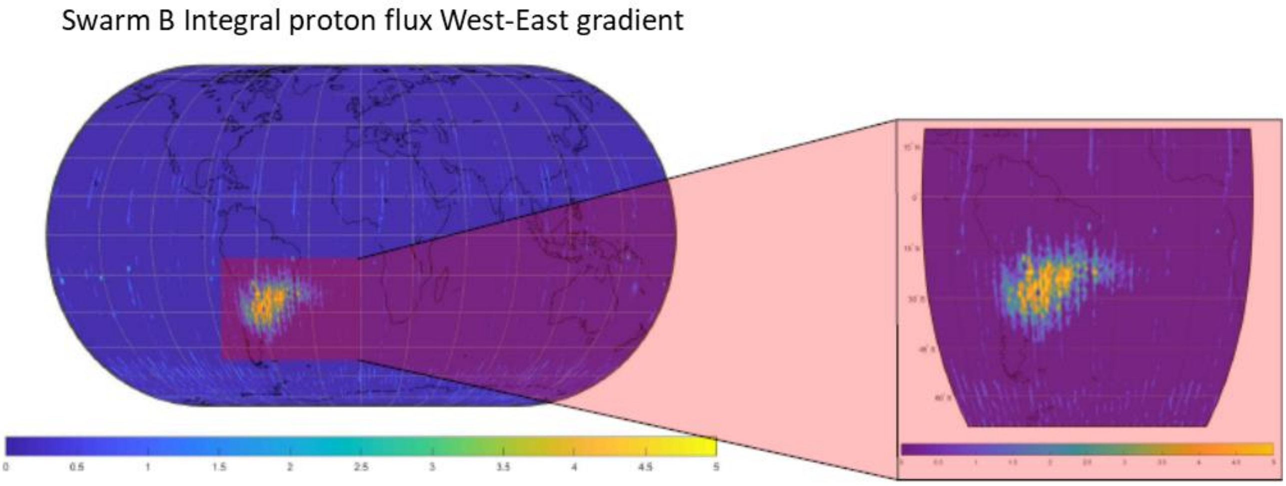

Figure 3: Differential firefly count between starboard and port star trackers on-board Swarm B showing a West to East gradient

4.2 NASA JUNO Mission

The NASA JUNO mission is a spacecraft in highly eccentric orbit about Jupiter. Since Jupiter has a strong magnetic field it has belts of trapped particles (mainly electrons) similar to the Van Allan belts of the Earth. The 54 day orbit is laid to pass JUNO in an altitude of merely 0.1 Jovian radii – well below the radiation belts. However, as the Jovian bulge changes the apsides of the orbit, JUNO is facing gradually heavier radiation.

JUNO is equipped with four star trackers as part of the *Magnetic Field Investigation* [3], where one has recorded *firefly* count rates for each of the 41 (and counting) perijove passes. This configuration allows the following:

- Generation of a topological map of the Jovian magnetic field
- Identification and description of disturbances in the count rates generated when JUNO crosses the magnetic field lines that passes the orbit of the Jovian satellites. Especially Io and Europa leave trails in their trajectories that generate large disturbances. From studying the disturbance, significant constraints on the trails can be derived. Figure 4 shows how a time series of *firefly* count data is interacting with the Jovian moon Ganymede during a perijove passage.

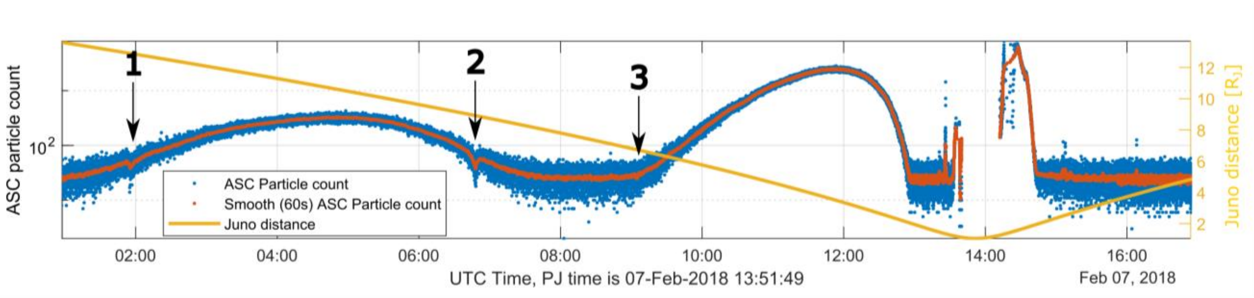

Figure 4: Time series of star tracker firefly count data from JUNO's perijove passage #11. The disturbances in the count data (marked 1, 2 and 3) corresponds with passages of the magnetic field lines that passes the orbit of the Jovian satellite Ganymede [2].

4.3 NASA Magnetospheric Multiscale Mission

The NASA/MMS mission consists of four spacecraft flying in a tight tetrahedral constellation with inter-satellite distance of tens of km from a highly elliptical orbit. Each spacecraft is equipped with four star trackers, where one is setup to report *firefly* count rates. Having coherent count rates from distributed sensors allows spatial characterization of transient events. The mass shielding on these trackers are so heavy, though, that we have not observed transient events sufficiently strong to enable adequate resolution. The radiation within the Earth's Van Allan belts is sufficiently heavy to be detectable with good resolution though. sample passage is shown in

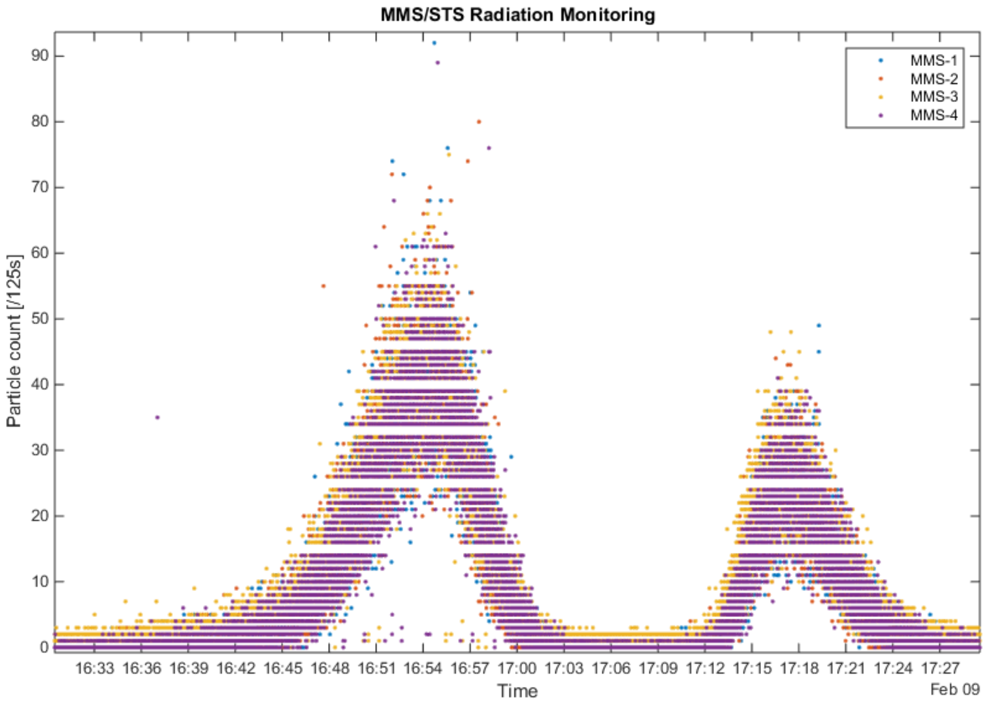

Figure 5: Star tracker firefly count data from a sample passage of the Earth's Van Allan of the four NASA MMS spacecraft [4]. The delay between the four spacecraft is clearly visible.

5 DISCUSSION OF THE POTENTIALS

A number of applications where star trackers have been augmented with *firefly* count capability have been discussed in this paper, but are the sensitivity/resolution adequate to provide decent science? Spacecraft missions dedicated to both map the radiation environment and to provide detailed time series of radiation from e.g. solar events have launched and has operated for decades. What can this relative coarse sensory do to improve our understanding of high energy particle fluxes in space?

The answer is simple – the multitude. Spacecraft have usually at least two star trackers installed for redundancy. This functionality could easily be applied to many more spacecraft – hundreds. With a decent calibration, each spacecraft could contribute with count rates to enable a good spatial distribution at short timescales. The different shield depth curves from the different sensors could be used to obtain spectral sensitivity. This could eventually bring valuable knowledge of the behaviour and lifecycle of short-lived transient events – measured coherently from a tight grid of sensors.

6 SUMMARY

We have developed a simple technique to continuously assess the surrounding radiation environment as a zero-cost bi-product from star trackers.

We have successfully operated a dozen of star trackers using this technique on-board a large variety of spacecraft missions for a handful of years and have obtained valuable results.

We suggest that more star trackers – from all possible vendors – are updated with *firefly* count capability and that count rate data are made public available to the science community

7 REFERENCES

[1] Herceg, M. et al (2018). *The Swarm mission high energy particle flux investigation*. Poster session presented at AGU Fall Meeting 2018, Washington DC, United States.

[2] Herceg, M. et al (in review). *Energetic Electron lensing caused by the Ganymede's Magnetic Field*

[3] Connerney, J. E. P. et al (2017). *The Juno Magnetic Field Investigation*. Space Science Reviews, 213(1-4), 39–138. https://doi.org/10.1007/s11214-017-0334-z

[4] Shulman, S. et al (2018). *Turning mms star sensors into high energy particle detectors*. In Proceedings of 15th International Conference on Space Operations [AIAA 2018-2714] American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2018-2714