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Linking Single Event In-Orbit Data to Space Weather

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***Abstract*—Correctable single event upsets observed in a SRAM memory on-board of Sentinel 2A and 2B are studied, with the aim of identifying a correlation between space weather activity and the orbital time and position of occurrence of SEU. Sentinel 2A and 2B are two identical ESA satellites flying at an average altitude of 786 km. The SRAM memory under study is part of the memory system supervisor.**

Event rate, sampled at one orbital period, is heavily superimposed by normal variance due to intrinsic Poisson distribution of SEE. A moving average filter extracts features attributed to the solar cycle, the South Atlantic Anomaly (SSA) seasonal behaviour and device degradation. Further data is needed to study the response to geomagnetic storms, since available ones are relative to a prolonged 'solar lull' period.

Position data is filtered similarly, which is expected to show the movement of the SAA as seen by single events. The two satellites' filtered event positions show common features, but also peculiar, currently unexplained, short-term differences.

I. Introduction

The ESA satellites Sentinel-2A and 2B are dedicated to Earth Observation and in particular they provide multi-spectral imagery from an orbit with an average altitude of 786 km and an inclination of 98°. Their orbital period is 6026 seconds. The satellites are flying half an orbital period apart, which results in a phase delay in ground track of 5 days. [1]

The single event upset counter under study refers to a SRAM memory in the mass memory supervisor. It is used in the preparation of housekeeping data for downlink and resides on a deep-space facing sidewall [1]. 4157 correctable single bit upsets have been recorded for Sentinel 2A in 789 days of operation, while 2776 correctable single bit upsets have been recorded for Sentinel 2B in 524 days. The analyzed data were recorded between 2016 and 2018, a time of minimal solar activity belonging to end of the 24^{th} solar cycle.

To provide further understanding on single event rates in orbit, in this paper the counter behaviour is studied in correlation to space weather. In the context of this paper, the term space weather refers to changes in space radiation environment over long time spans, only. There are two reasons for single event rate to change: a change in radiation environment or a change in cross-section. For the radiation environment of Sentinel 2 the most relevant feature is the South-Atlantic Anomaly (SAA). Changes in SSA particle distribution occur due to:

- Seasonality: Cosmic Ray Albedo Neutron Decay (CRAND), the main source for inner belt particles, undergoes a semi-annual variation in its strength. The results in a semi-annual variation of particle fluxes in the SAA. [2]
- Geomagnetic storms: Strong geomagnetic storms can sweep particles from the inner radiation belt, up to an practically complete clearing [3]. Weaker geomagnetic storms can result in the deposition of solar particles in the inner belt [4]. Also, during geomagnetic storms, the SAA's spatial extent and peak particle fluxes are reduced [5].
- Solar cycle: Particle fluxes in the SAA vary with the solar cycle, because it modulates the influx or galactic cosmic rays and therefore CRAND. There is a particle energy dependent phase delay, with the solar cycle peak preceding the SAA peak [6].

Next to that, cross-section changes in the device are possible due to:

- Temperature: when the satellite goes into eclipse once each orbital period, there will be a variation in component temperature of the same period. Higher temperatures result in lower cross-section onset and thus higher event rate [7].
- SRAMs have shown an increase in cross-section due to total ionizing dose [8] and aging [9], but this effect is unlikely play a role with the S2 satellites.

In what way above mentioned effects can be seen in in-orbit data is subject of this research. In parallel, it shall be tested in what way the peak SEE rate positions of the two satellites develop. Supposedly, short-term changes in peak SEE position are caused by space weather [5], but long-term changes are caused by geomagnetic activity resulting, in a drift of the SAA and thus a drift of peak SEE rate position [10].

II. Methodology

Events are extracted from housekeeping data and filtered using a geographic window to only keep those within the SAA. Then, events are binned in a single event rate signal for each satellite at a sampling of one orbital period. For event position data, a latitude and a longitude signal is produced for each satellite.

Then, the signals are processed based in the manner of classic time series decomposition, assuming an additive model. So to remove noise from the signal, a right-sided moving average filter is applied. The window size of the filter is 20 days with event rate, and 90 days with event positions. Both filter windows have been obtained experimentally. [11]

III. Results

Figure 1 shows the filtered single event rate signals and linear approximations.

Figure 2 shows the movement of the peak SEE rate position and contrasts these qualitatively to single event rate and space weather proxies. Latitude and longitude signals are also given individually, to allow for qualitative comparisons.

Residuals of event rate and position signals are auto-correlated with a delay of 7 orbital periods, which corresponds to 11.7 hours.

Given the moving average window size, the effects of eclipses, and therefore differing temperatures, have been filtered out. An possible annual temperature variation of unknown extent, due to Earth's orbit about Sun, would remain.

IV. Discussion

Findings of single event rate analysis are:

- The linear trends are 0.0163 events per orbital period and year for Sentinel 2A and 0.0165 events per orbital period and year for Sentinel 2B. Because of the phase delay between solar cycle and SAA, the trend will continue for the future, before it reverses once the subsequent solar cycle begins.
- The filtered event rate does not vary homogeneously for the two satellites. The reasons for this are unclear and the observation is generally unexpected, because the satellites are identical and visit the same positions.
- Event rate minima are found to sometimes coincide with minima of the SAA in June and December, and event rate maxima sometimes coincide with SAA maxima shortly after VEX and AEX [2]. However, the amplitudes and occurrence of this phenomenon vary between Sentinel 2A and 2B, so it cannot clearly be confirmed.
- The strongest geomagnetic storm (by minimum DST) of the time considered occurred in September 2017. Seemingly, Sentinel 2A event rate reacts strongly to it, because its event rate starts to decrease at just that time. However, single event rate of Sentinel 2B was already in decline already and shows no further reaction to that storm. Next to that, the strength of the geomagnetic storm indicates that its influence on the inner belt should be weak.

Satellite	Longitude Drift	Latitude Drift
Sentinel 2A	-1.25°/y	-0.12°/y
Sentinel 2B	-2.08°/y	1.10°/y

TABLE I
SAA Drift Rates

The inspection of single event positions reveals:

- The annual drifts, determined by linear regression, are depicted in Table I. There is a large difference in latitude drift between the satellites, that is explained by Sentinel 2B having a strong northward position deviation in the beginning of 2018.
- The satellites share some features in how the tracks evolve, e.g. from approx. May 2017 to approx. September 2017, both satellites' event positions change in a circular fashion, moving counter-clockwise. Also, the event positions change only little in both satellite's between April 2018 and July 2018.
- There is an effect that causes only the event position of one satellite to drift away strongly for a short period of time.
  Sentinel 2B undergoes a far northwards loop between December 2017 and March 2018. During that time, Sentinel 2A's event position remains confined to the approximate center of event position history.
  Sentinel 2A moves northward, starting August 2018. At the same time, Sentinel 2B continues to move about its initial August 2018 position.
  Next to that, Sentinel 2A gets stuck in a eastwards position from mid September 2017 to end October 2017, while Sentinel 2B continues on a trajectory towards the event position center (purple). This deviation of Sentinel 2A happens just after completing the circular movement it undergoes together with Sentinel 2B.
  These observations do not coincide with spikes in Disturbance Storm Time Index (DST), so they cannot be attributed to geomagnetic storms. The differences must vanish within 5 days, because this is the ground track phase delay of the satellites.

The correlation of residuals is attributed to the orbit of the satellites: they make full passes of the SAA twice a day, once in sunlight and once in eclipse. This corresponds to a period of 12 hours, which can explain the correlation pattern on 11.7 hours time scale.

V. Conclusion

Using a moving-average filter, a non-random component has been discovered in single event rate and position with an SRAM aboard Sentinel 2A and 2B. The main conclusions are:

- There is a trend in single event rate on Sentinel 2 SRAMs, attributed to the solar cycle. It complies well between the two satellites.
- The single event signals of Sentinel 2A and 2B do not strictly follow the semi-annual cycle in SAA activity.

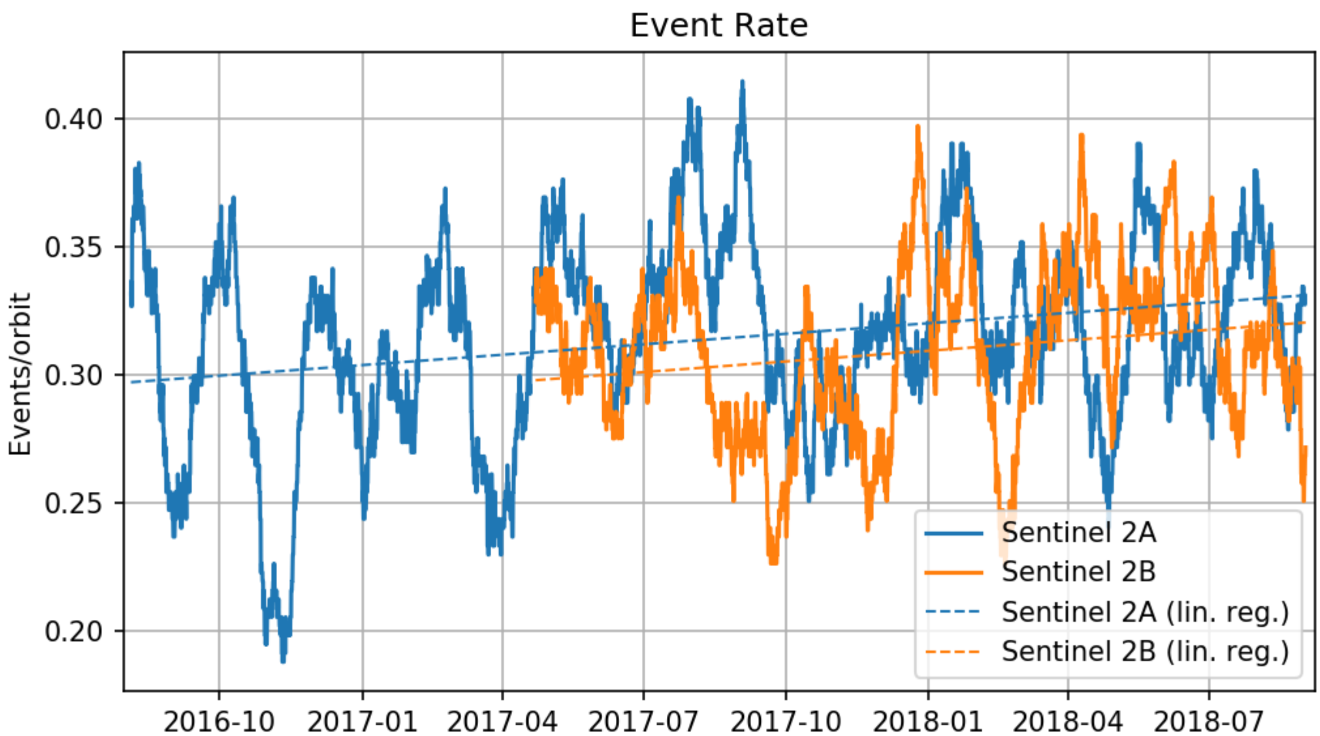

Fig. 1. Sentinel 2 Filtered Single Event Rate

Also, reactions to geomagnetic storms are ambiguous. Further data, especially such recorded during times of more severe solar activity, can help to gain clarity. Also, a comparison to measurements from particle counter payloads for proper attribution of the observed fluctuations.

- The peak event rate positions show similar movement down to intra-year level, which might be an effect of the SAA. However, differences between the satellites indicate that the peak SEE position is distorted by currently unknown effects. An analysis of the affected memory addresses can clarify if these differences were caused by localized heat generation (hot spots) within one of the memories.

This paper has looked into the interpretation of single event counter data, both temporal and spatial, in light of space radiation environment changes. Ideas for continuation and verification are given.

The potential of this line of research lies in making available a new source of space weather monitors, even on missions where there is no dedicated sensor. In particular, future satellite constellations are expected to improve data quality by making available large quantities of spatially distributed sensors.

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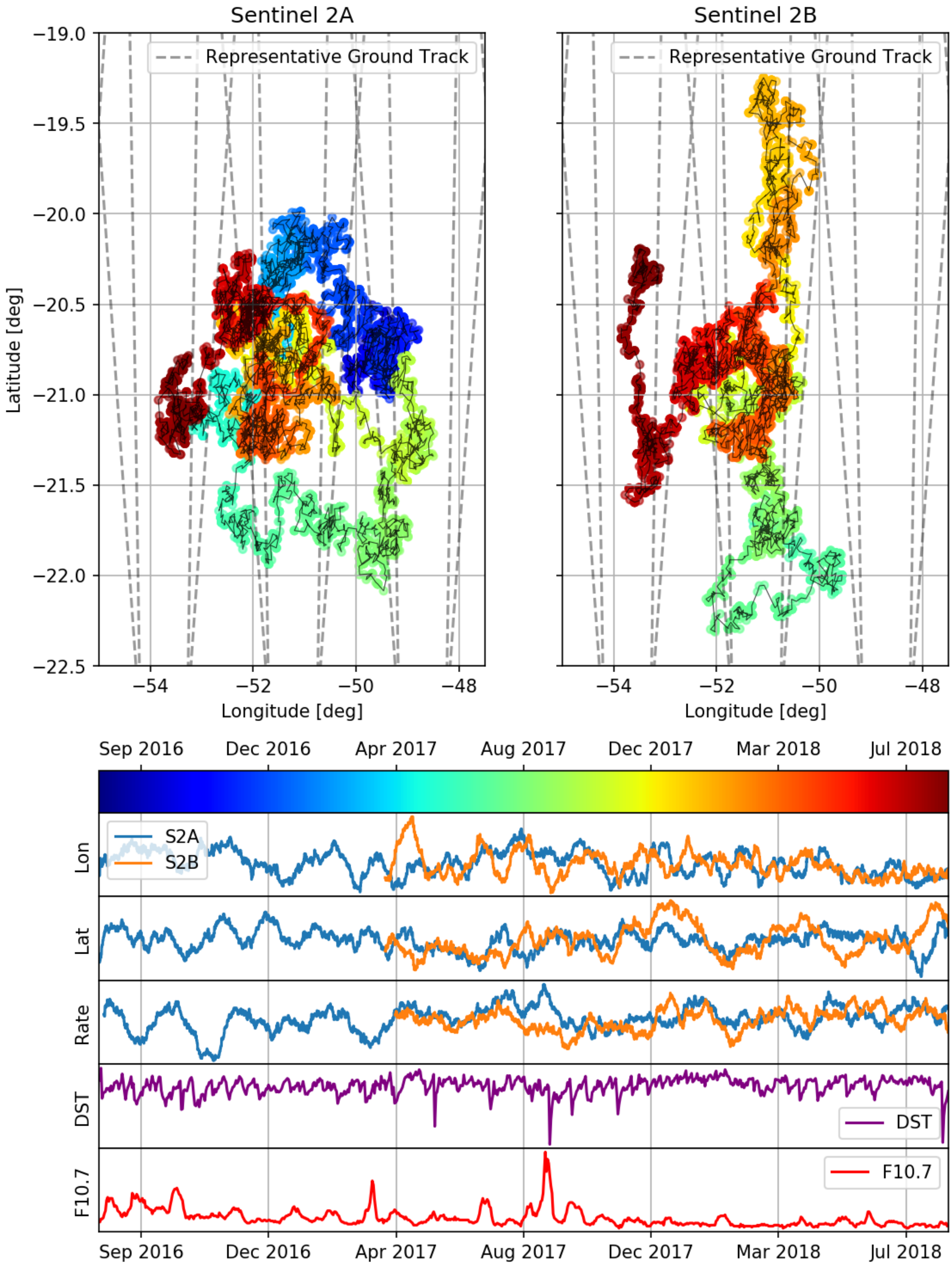

Fig. 2. SAA Movement as seen by Sentinel 2 Single Events