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Analysis of an energetic electron injection at GEO using FalconSEED: A low SWaP-C, cubesat-compatible instrument for space environments

Anthony J. Rogers, Carlos A. Maldonado
Los Alamos National Laboratory
LANL MS-D436, PO Box 1663, Los Alamos, NM; 505-667-8027
arogers@lanl.gov

John D. Williams, Matthew G. Mcharg, Robert A. Vincent, Richard Balthazor
United States Air Force Academy
Colorado Springs, CO

ABSTRACT

We present a detailed analysis of an energetic electron injection (10s - 100s keV) observed at geostationary Earth orbit (GEO) on March 5, 2022 in order to highlight the capabilities of the Falcon Solid-state Energetic Electron Detector (SEED). The high time- and energy-resolution of SEED are used to quantify the dispersion of the injection front and to explore the morphology of the energy distribution throughout the injection encounter. Observations of the same event from nearby platforms are included for context. The SEED is a CubeSat compatible, single element particle telescope, designed to measure 14 to 145keV electrons in GEO. The flight payload has a volume of 10 cm × 10 cm × 20 cm, in a 4.3-kg, 3.4-W package. The SEED was manifested on the Department of Defense (DoD) Space Test Program Satellite—6 (STPSat-6) which was launched in December of 2021 to GEO at 112 W longitude. During the first year of mission operations, the SEED has demonstrated the ability, evidenced in this paper, of a low-resource particle detector comprised of predominantly commercial-off-the-shelf components to provide relevant science observations of the space plasma environment.

Introduction

The "Build to Performance" paradigm of particle instrument design[1] has led to a pervasive assumption that meaningful scientific observations require ever more complicated instrument designs; that meaningful measurements can only be made with instruments which are more capable (and typically more expensive) than those which came before. With the introduction of cubesats and constellation missions such as HelioSwarm,[2,3] this paradigm is being challenged in favor of multiple simultaneous observations from individually smaller, more constrained platforms which provide context for each other and, together, produce a multi-scale description of the targeted phenomena.

This new paradigm has increased the demand for instrument designs combining low size, weight, and power consumption (SWaP) while retaining sufficient instrument performance to ensure mission success. As a result, and combined with recent advances in sensor, electronics, and other spacecraft technologies, there has been a rapid increase in the number of miniaturized charged particle detectors suitable for space platforms. These include retarding potential analyzers,[4] electrostatic plasma analyzers,[5–10] and charged particle telescopes.[11–15]

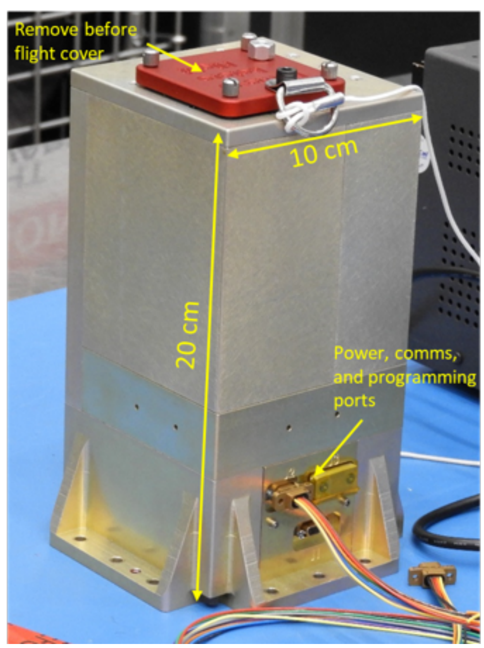

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Figure 1: SEED Flight Instrument[16]

In addition to leveraging recent advances to reduce on-board resource requirements of instruments, manufacturing advances have made commercial-off-the-shelf (COTS) components a conceivable cost-saving alternative to costly custom-designed electronics packages commonly seen on state-of-the-art platforms. Tailored radiation-hardened electronics designs are intended to reduce and mitigate the effects of the natural radiation environment but at significant cost and are susceptible to the low-availability of special-run rad-hard components. Incorporating COTS components in radiation-tolerant designs as part of an overall engineering solution can reduce costs and procurement difficulties associated with specialty rad-hard components. While the risk of Single-Event Upsets (SEUs) and other deleterious radiation effects is increased under this strategy, the expanded use due to drastically reduced SWaP and cost (SWaP-C) can lead to the maintenance of overall science return.

–Falcon SEED

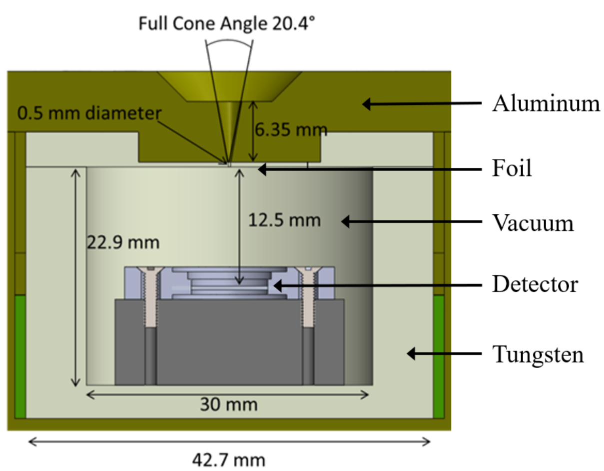

Figure 2: SEED Cross-Section[16]

As a demonstration of this philosophy, the Falcon Solid-state Energetic Electron Detector (SEED) is designed to fulfill a minimum one-year mission lifetime in geosynchronous orbit (GEO) providing relevant observations of the space plasma environment while extensively utilizing COTS components. The SEED was developed at the United States Air Force Academy to monitor electron flux across the energy range of 14 to 145keV at sub-minute resolution across the range of the instrument. The flight configuration is a 2U (i.e. 10cm x 10cm x 20cm), 4.3kg, 3.4W package, as shown in Fig. 1. The sensor itself utilizes a single 301 um-thick silicon solid-state detector, charge-integrating amplifier, and COTS digital pulse processor to measure incident counts of deposited energy to determine incident electron flux in each of 1024 energy bins.

The SEED utilized an integrated counting scheme in energy space and records an integral sum across all energy channels every 15 seconds. Differential energy counts and flux are calculated during ground processing. The actual data rate reported by SEED is typically lower than this 5760 spectra/day maximum due to upset events and extreme caution used in determining if spectra should be retained. If anomalous counts are detected for any energy channel within a given spectra, the entire spectra for that time step is discarded. Additionally, the SEED electronics package is reset every 1200 seconds in an attempt to mitigate these upsets. Each reset causes the SEED instrument to be effectively offline for ≈60 seconds. Actual science data product cadence is therefore variable from $15s$ to $> 75s$ with a mean value of $74s$.

Fig. 2 shows a cross-section of the sensor assembly. A conical aluminum collimator with a full cone angle of 20.4° and additional tungsten shielding effectively limits the instrument field of view to that of the collimator. The pinhole aperture opening of 0.5mm was chosen to prevent saturation of the detector due to the expected electron flux in the mission orbit. An aluminum-coated silicon-nitride X-ray window prevents photons with energy less than 45keV from impacting the detector while being largely transparent to electrons with energy greater than 6keV.

–STPSat-6 Vehicle

The Department of Defense Space Test Program (STP) platform STPSat-6 was launched in December of 2021 to a geosynchronous orbit above 112° W longitude.[17] The platform itself is a refurbished surplus spacecraft bus. It supports a number of experimental payloads such as the Los Alamos National Laboratory (LANL) Space and Atmospheric Burst Reporting System (SABRS) package, the NASA Laser Communication Relay Demonstration (LCRD), and Falcon SEED on the payload pallet.

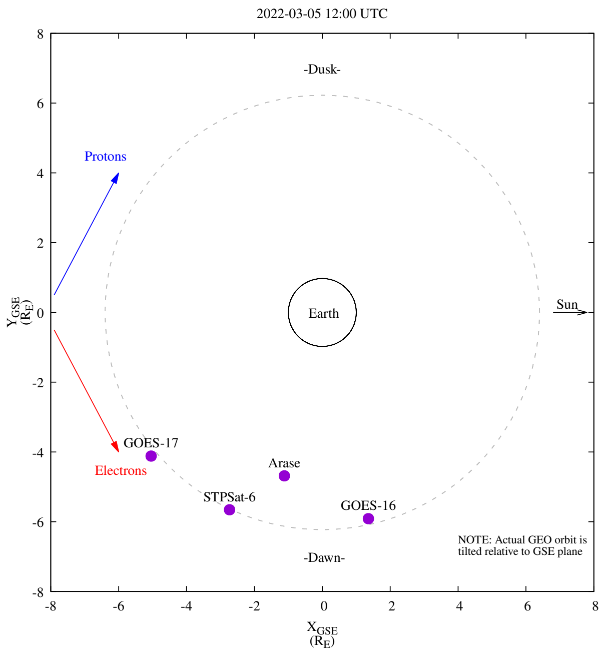

Figure 3: Relative Location of STPSat-6

–SEED Calibration

The FalconSEED instrument was calibrated prior to launch using several radioisotope sources along with a well-characterized energetic electron source, described in detail by Cress, et al. (2020). To characterize the detector response, the instrument was exposed to x-rays, gamma rays, and electrons of known energies. The recorded energy spectra were then used to correlate the histogram bin number against the incident energy. The initial calibration of the Falcon SEED instrument was conducted using Cesium (Cs-137), Barium (Ba-133), and Cobalt (Co-57) radioisotope sources, using the x-ray and gamma peaks. The detector was then calibrated using electrons of energy 10 to 35keV at the Spacecraft Charging and Instrument Calibration Laboratory located at Kirtland AFB. The electron source used to characterize the instrument response uses a photocathode for electron generation and accelerates the particles between parallel grids. The source can produce a 13cm full width half maximum beam with 0.1 ± 0.1fA cm 2 flux density and energy ranging from 10 to 50keV.[18] Additional efforts to perform on-orbit cross calibration with the LANL SABRS Plasma Spectrometer (ZPS-Hi) co-located on-board STPSat-6 and the nearby GOES-16 and -17 platforms is the focus of current research efforts.[16]

Event Overview and Context

Several hours of periodically southward Interplanetary Magnetic Field (IMF) (B_z[19,22] < 0 in Fig. 4(*upper*), red line) preceded the event discussed here. This led to a series of mild- to moderate substorms throughout the same period (see Fig. 4(*lower*) SMU/SML,[20,21] blue/magenta lines). A period of sustained southward IMF beginning around 2022-03-05T0900 UTC is correlated with the sudden storm commencement signature in the ring current (Fig. 4(*lower*), black line). A minor geomagnetic storm followed (minimum SYM-H of $-58nT$), as well as significant enhancements of the westward electrojet (SML $< -1250nT$).

The related enhancement of substorm activity produced several energetic particle injections from the magnetotail which were observed by multiple platforms in geosynchronous orbit such as Geostationary Operational Environmental Satellites (GOES) -16 and -17, which orbit 2hrs in Magnetic Local Time (MLT) eastward and westward of STPSat-6 respectively during this event (see Fig. 3). The orbital arrangement of these platforms as well as the fortuitous timing of the onset of the most significant substorm activity 1100 UTC provides an opportunity to showcase the science capabilities of FalconSEED.

Observations

Three significant electron injections were observed by SEED during 12 hours of 2023-03-05, denoted by vertical lines on Fig. 5. The first, appearing at 0630 UTC (blue line) when STPSat-6 was near-midnight, extends only to 25keV and is short in duration as observed at SEED. Additional context provided by GOES-17[23] (see Fig. 6, green line) shows this to be the high-energy electron extent of a Type 2 injection as described by Mauk and Meng[24] (their Fig. 8), where the initial injection onset was near 0100 UTC as observed in ion data while STPSat-6 was near the dusk flank. The electrons, having circumnavigated the inner magnetosphere, finally arrive at STPSat-6 and SEED much later.

The second injection, at 1100 UTC (white line, Fig. 5) when STPSat-6 was nearing the dawn flank (see Fig. 3), is identified as a Type 1 injection, indicated by the rapid fall-off of higher-energy fluxes and persistence of lower-energy electrons. This suggests that the injection boundary was Earthward of STPSat-6 and that SEED was observing an active acceleration region. High-energy proton data (not pictured) from various platforms shows drift echoes

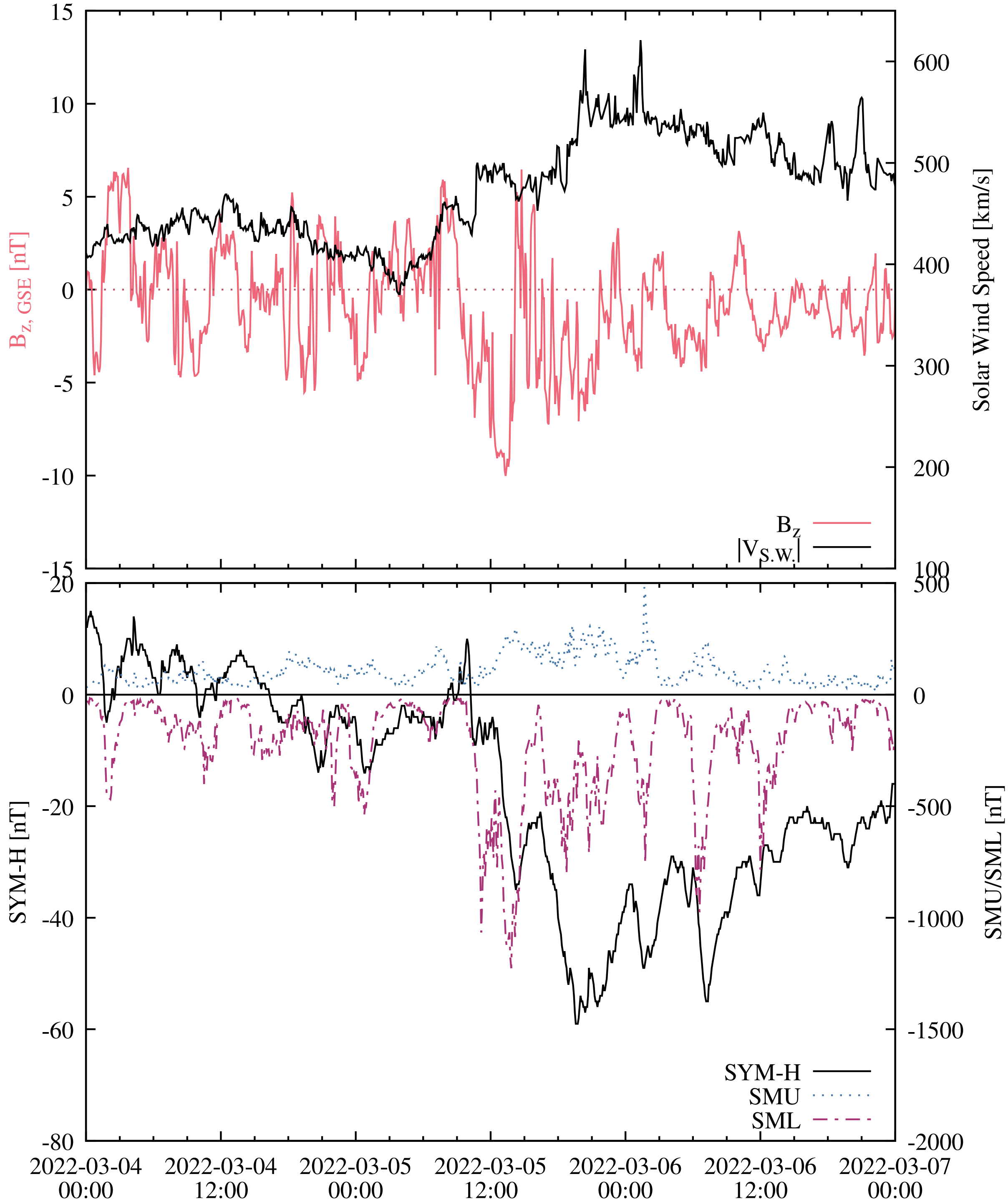

Figure 4: Overview of Key Solar Wind[19] and Geomagnetic Indices[20, 21]

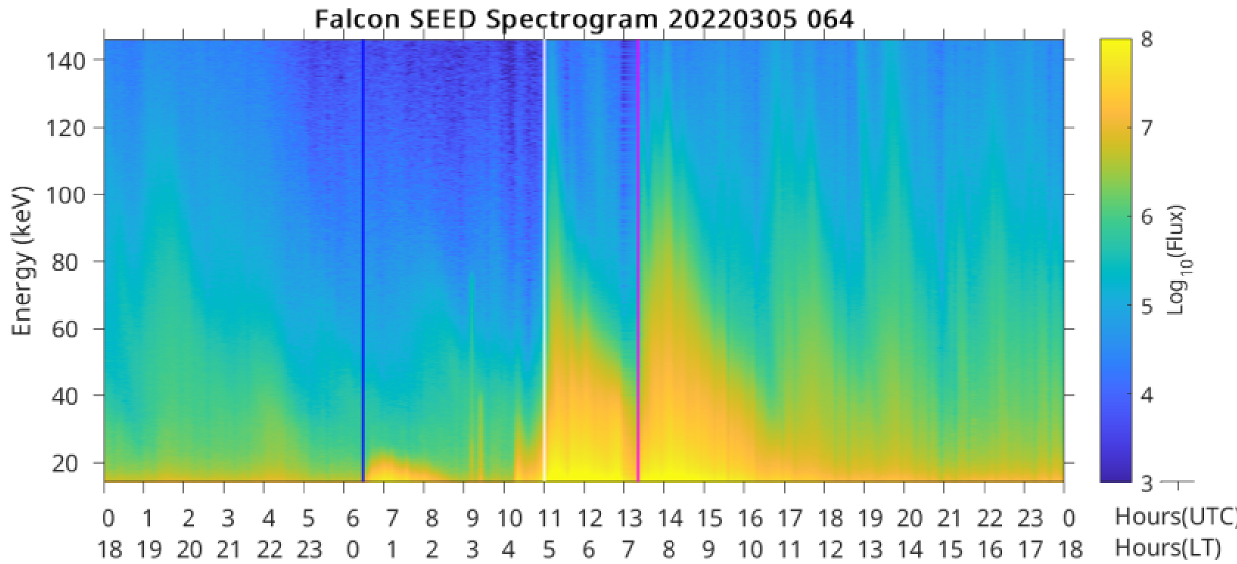

Figure 5: Incident Electron Flux ($electrons/cm^2 \cdot sr \cdot keV \cdot s$)

of the ion component of this injection as it propagates several times around the inner magnetosphere via gradient drift.

A third prominent injection at 1320 UTC (magenta line), when STPSat-6 was on the dayside of the dawn flank, is identified as a Type 7 injection, differentiated by a Type 1 by a subdued and delayed ion response (see Fig. 6*c*) similar to the delayed electron response described in a Type 2 injection above. This injection coincides with the strongest enhancement in the westward electrojet (SML, Fig. 4(*lower*), magenta) and the steepest variation of ring current (SYM-H, Fig. 4(*lower*), black). Not surprisingly, multiple geosynchronous platforms such as GOES-16 and -17 observe significant and persistent increases in overall flux in the outer radiation belt beginning at this injection and the one previous.

Several weaker flux enhancements are also visible in the SEED spectra. The majority of these are moderately-to-highly energy dispersed, meaning that enhancements appear at higher energies before lower energies. These are interpreted as drift echoes of previous injections as the particles gradient drift about the inner magnetosphere. The energy and time resolution of SEED is sufficient to attempt drift tracing to estimate the injection boundary location where the echo originated. This technique as applied to Falcon SEED is the subject of ongoing work.

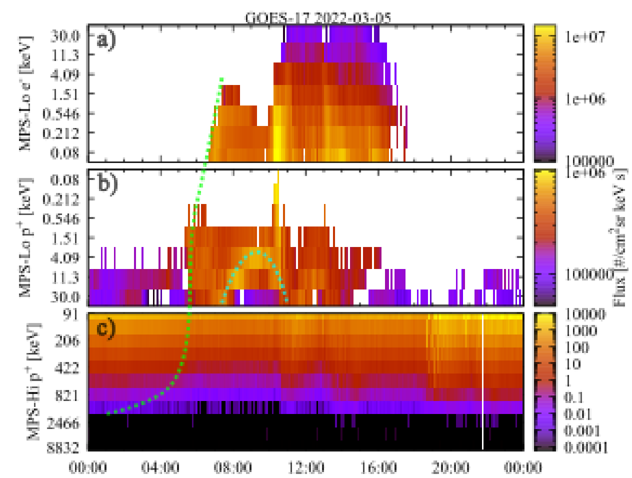

Figure 6: GOES-17 MPS[23] Electron & Ion Data (NOTE: Ion Energy in Decreasing Order)

Small, short-time-duration features are apparent in the SEED spectrogram between 0900–1030 UTC. These have been tentatively identified as possible effects of significant spacecraft charging, with intense charging lines seen in ion data both on STPSat-6 (not pictured) and on GOES-17 (see Fig. 6*b*, blue curve). Collaborations are ongoing with other payloads on board STPSat-6, including the LANL SABRS-3 team, to determine the degree of spacecraft charging present and compare that to estimated values using SEED data. This will be the focus of a future report.

Conclusion

The Falcon SEED is a compact, low-resource solid-state electron detector suitable for monitoring the local space plasma environment. The COTS electronics package utilized by SEED introduces performance challenges when attempting to maximize the cadence of measurements, but ones which are easily mitigated using careful ground processing techniques. Despite the inherent trade-offs of this low SWaP-C design, SEED is capable of making and reporting science-quality observations of the local plasma environment, such as the energetic injection events associated with a minor geomagnetic storm on March 5th, 2022. Combined with additional resources which can sample different energy and species regimes, SEED is demonstrably capable of being a useful component of a comprehensive space environment sensor suite.

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