Space Weather

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Key Points:
• The Falcon Solid-state Electron Detector (SEED) is an energetic electron detector that is set to measure electrons in geosynchronous orbit.
• FalconSEED is a low-cost electron detector made from commercially off-the-shelf (COTS) parts.
• The instrument was calibrated in advance of delivery and will measure a spectrum of electron energies from 14 to 145 keV.

Abstract: The Falcon Solid-state Energetic Electron Detector (FalconSEED) is an energetic charged particle sensor that has been developed and tested at the United States Air Force Academy in an effort to monitor electron flux across the energy range of 14 to 145 keV in geosynchronous orbit. This sensor has been developed to complement ongoing efforts by the Air Force Research Laboratory to advance a comprehensive space environment sensor suite, Compact Environmental Anomaly Sensor (CEASE3), for anomaly resolution. In addition, FalconSEED is intended to demonstrate the ability to operate a radiation sensor based on predominantly commercial off-the-shelf components in the geosynchronous environment. This paper describes the design, development, and calibration of FalconSEED. The electron energy spectrum of interest for the FalconSEED sensor is 14 to 145 keV, and it is intended to supplement data acquired from the CEASE3 instrument for anomaly resolution. The calibrations at the Space Atmospheric Research Center at the United States Air Force Academy and Kirtland Air Force Base were used to first establish the conversion between histogram bin number and deposited energy in the sensor, and second have been used to determine the geometric factor as a function of energy. The FalconSEED will be integrated as a science payload on the Space Test Program Satellite-6 which also includes the first flight of the CEASE3 instrument and is scheduled to launch in 2021.

1. Introduction

The geosynchronous orbit (GEO) environment is of particular concern to spacecraft designers and operators due to the dynamic nature of the charged particle environment which can be impacted by diurnal variations, latitude, and geomagnetic activity. Variations in the solar wind properties can cause injections of energetic magnetized plasma leading to the sometimes sudden buildup of high-energy particle populations trapped in the radiation belts. When impinging on spacecraft, this charged particle flux consisting of high-energy ion flux and relativistic electrons can cause hazardous levels of internal and external spacecraft charging, solar panel degradation, and single-event upsets. All three effects can happen simultaneously making the deconstruction of the local space environment conditions and anomalous satellite behavior difficult. Extensive statistical analyses have been conducted in an attempt to correlate satellite anomalies with the plasma fluxes at geosynchronous orbit and electrons between the energies of ~40 eV and ~45 keV (Choi et al., 2011; Thomsen et al., 2007; Thomsen et al., 2013). The studies conducted by Thomsen et al. utilized the Los Alamos National Laboratory geosynchronous Magnetospheric Plasma Analyzers to obtain measurements over the last 1.5 solar cycles. The focus of the study was on the ion and electron populations with energies in the range from ~1 eV to ~45 keV. This energy range encompasses the cold plasma of the extended plasma sphere and the hot plasma of the plasma sheet and is believed to cover the electron populations that are responsible for satellite surface charging (Garrett et al., 1980; Gussenhoven et al., 1985; Katz et al., 1986). The statistical studies of this electron flux in geosynchronous orbit within this energy range are associated with the Kp index and a higher probability of surface charging. Choi et al. conducted a similar statistical investigation of 95 GEO satellite anomalies as a function of Kp index using data from the Satellite News Digest and the Los Alamos National Laboratory plasma spectrometers. The study showed that there is a good correlation between low-energy (<100 keV) electron flux and Kp. Additionally, there is a relationship between geomagnetic activity (as measured by the Kp index) and anomaly occurrences of the GEO.
satellites. Data show that low-energy electrons have similar behaviors with spacecraft anomalies and imply that the spacecraft charging might dominantly contribute to the GEO spacecraft anomalies reported in Satellite News Digest (Choi et al., 2011).

The research involving the correlation of spacecraft anomalies to the specific contributing local environments is incredibly difficult due to the simple fact that a satellite cannot be taken apart and examined in depth after the event. However, the primary populations responsible for these effects can be monitored and correlations between anomalies and the current environment can be made. In particular, in 2001, it was suggested that more than half of documented environmental anomalies (161/298) were a result of electrons charging spacecraft to hazardous levels (Fennel et al., 2001). Also, recent methods have been proposed to better correlate on-orbit anomalies with historical space environment data (O’Brien, 2009). In all cases though, measurements must exist that can be used to determine the space environment in the vicinity of the vehicle during an anomaly.

To address this need for on-orbit environment data for anomaly attribution, the Air Force Research Laboratory developed the Compact Environmental Anomaly Sensor Risk Reduction (CEASE RR) and its follow on, CEASE3 (Lindstrom et al., 2018). Of particular interest for this work is that the CEASE3 sensor in its current design possesses an energy coverage gap between 50 and 100 keV between its electrostatic analyzer and its lowest-energy particle telescope. This gap was permitted in its design because electrons between 50 and 100 keV are typically much less numerous than lower energy plasma electrons. In addition, these electrons have a CSDA range between 21 and 70 μm in aluminum so are not of great concern for deep dielectric charging. However, there have been indications with recent space environmental anomalies that this region can be important. In particular, electron population measurements during the Galaxy 15 anomaly suggest that the electron temperature reached 85 keV (Ferguson et al., 2011)). Because of these concerns, the Falcon Solid-state Energetic Electron Detector (FalconSEED) instrument was designed to specifically address the gap region with good overlap between both the CEASE3 ESA sensor and the CEASE3 particle telescopes. The instrument itself is intended to be flown alongside the first CEASE3 instrument on the Space Test Program Satellite-6 so that its data can be combined with space environment data from CEASE3. These data can be used in several ways. The first method is to compare how well interpolation between the lowest CEASE3 particle telescope channel at approximately 100 keV and its upper ESA channel at 50 keV match a continuous measured spectrum provided by FalconSEED. This should provide significant insight into how much information is being lost by having this gap present in CEASE3. Second, any observed anomalies throughout the mission will provide opportunities to use the gap-filled data in their investigation. Finally, the combined data can be used to further environmental models such as AE9 (Ginet et al., 2013).

In addition to filling an energy measurement gap for the CEASE mission, the SEED instrument will demonstrate the ability of commercial off the shelf components to fulfill a one-year mission lifetime in GEO to reduce cost while still producing a product that can survive the harsh environment of space. In particular, FalconSEED expands upon previous successful efforts that have used similar detectors in low earth orbits for X-ray spectrometers (Mason et al., 2016). By moving beyond LEO, FalconSEED will demonstrate that relatively low cost, commercial off the shelf-based undergraduate space instruments can contribute to an expanded understanding of the space environment in less well sampled orbital regimes.

2. Instrument Design

An effort to reduce the size, mass, and power requirements of modern spacecraft has led to an increased interest in small satellite programs by
government agencies, private industry, and academic institutions. A subject of particular interest to spacecraft designers is the implementation of these small satellites into formation-flying constellations capable of replacing existing larger multifunctional satellites. Advances in sensor and other spacecraft technologies, coupled with the spatial data acquisition unique to small satellite constellations, make it possible for low-cost, small-satellite missions to obtain key distributed measurements of the space environment (i.e., space weather). The spatial, spectral, and temporal measurement capabilities of the constellations have the potential for real-time observations of the dynamic space weather environment to aid in the advancement of geospace and atmospheric research. The FalconSEED instrument is designed with this in mind and is to be compatible with cubesatellite platforms in terms of size, weight, and power. The final flight payload is shown in Figure 1 with a volume of 10 cm × 10 cm × 20 cm, in a 4.3-kg, 3.4-W package.

The FalconSEED instrument is designed to characterize the energetic electron flux from 14 to 145 keV in the local space environment. The data will be used for anomaly attribution due to energetic electron flux impinging upon orbiting satellites (Brautigam, 2002). The sensor uses a single 301-μm-thick silicon solid-state detector and digital pulse processor to measure detected counts as a function of deposited energy to determine the incident electron flux. As an electron travels through and interacts with the semiconductive material of the detector, electron–hole pairs are produced which in turn generate a

![Figure 1](image1.png)

**Figure 1.** Measured energy spectra without exposure to radiation sources or photons for a 2-min collection period.

![Figure 2](image2.png)

(a) Cesium-137

(b) Barium-133

(c) Cobalt-57

**Figure 4.** Energy spectrum measurements taken using the Cs-137, Ba-133, and Co-57 radioisotope sources.
current pulse (Gold et al., 1998). A charge integrating amplifier (Amptek A250) is then used to convert the charge pulse to a voltage tail pulse. A digital pulse processor (DP-5) is then used to first digitally shape it into a trapezoidal shape; the height of this shaped pulse is proportional to the free charge liberated by the energy deposited in the detector. The pulse processor then determines the pulse height and increments the specific histogram bin corresponding to the peak height in one of the 1,024 specific histogram energy bins. This forms the energy spectrum histogram data that the FalconSEED instrument collects.

A cross section of the instrument illustrating the critical components and physical dimensions is shown in Figure 2. The open area between the space environment and the silicon detector is an aluminum conical collimator with a full cone angle of 20.4°, ending in a pinhole aperture of 0.5 mm in diameter. The aperture diameter was selected to prevent saturation of the instrument signal due to the expected electron flux in the mission orbit. The detector is shielded on all sides other than the aperture with tungsten to reduce background count rates. The tungsten housing is surrounded by an aluminum shell of which the conical entrance is created. Placed just within the sensor housing, an Amptek “C-series” X-ray window composed of silicon nitride with an aluminum coating, nominally 400 nm thick, is used to prevent photons from impacting the detector. The foil allows electrons with energy of greater than 6 keV to pass through while simultaneously preventing protons below 45 keV from passing through to the solid-state detector.

3. Calibration Results
The FalconSEED instrument was calibrated using radioisotope sources along with a well-characterized energetic electron source. In order to characterize the detector response, the instrument was bombarded with 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.

3.1. Background Noise Calibration
The first goal of calibration was to identify instrument signal. This was accomplished by taking energy spectra while the instrument was not exposed to either energetic particle sources or photons. The data in Figure 3 show energy spectra taken over a 2-min exposure time, the same exposure time as the calibration data. In terms of background radiation, there are less than 10 counts per histogram bin number outside of the noise peak.

3.2. Benchtop X-ray Calibration
The initial calibration of the FalconSEED instrument was conducted using 5 μg samples of the cesium (Cs-137), barium (Ba-133), and cobalt (Co-57) radioisotope sources whose emissions are well characterized (Be et al., 2016; National Nuclear Data Center, 2019). The first test was conducted using Cs-137 with the exposure to the source lasting 24 min. The measured spectra produced a resolved peak at histogram bin number 216, corresponding to the expected energy from X-ray emission at 32.06 keV and is shown in Figure 4a. The second test was conducted using Ba-133 and the spectra are shown in Figure 4b. The collection lasted for 112 min producing distinguishable peaks at histogram bin numbers 209 and 485 which correspond to X-ray and gamma emissions at 30.85 and 80.99 keV, respectively. The third test was conducted using Co-57, lasting for 112 min, which produced a resolved spike at histogram bin number 926 as a result of...
gamma emissions at 122.1 keV and is shown in Figure 4c. The 136-keV photopeak is visible as a shelf on the right side of the 122.1-keV peak; however, the 14.4-keV Co-57 gamma ray photopeak and 6.4-keV X-ray peak are not resolvable from the electronic noise. The peak to the left at approximately histogram bin number 500 is due to X-ray escape (Patt & Iwanczyk, 1998).

### 3.3. Energetic Electron Flux Calibration

To further characterize the detector response the instrument was bombarded with electrons of known energies ranging from 10 to 53 keV. This additional calibration of the flight instrument was conducted at the Spacecraft Charging and Instrument Calibration Laboratory located at Kirtland AFB. The calibration effort was conducted in the Mumbo test facility which consists of a 1.2 m × 1.8-m cylindrical test chamber equipped with high-uniformity electron and ion sources. 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 13-cm full width half maximum beam with $0.1 \pm 0.1$-fA/cm$^2$ flux density and energy ranging from 10 to 50 keV (Hoffmann et al., 2012). The current produced by the electron source at each energy setting was monitored using a 4-inch-diameter faraday cup and is shown in Figure 5.

The calibration tests were conducted with a collection time of 2 min with the instrument placed 1 m downstream of the electron source. Three separate runs were conducted at each energy with the average of the runs shown in Figure 6. The spectra taken for the 10- and 12-keV electron energy settings cannot be clearly distinguished from the noise peak. This is partially due to energy loss to the foil; however, the calibration of known incident energy and recorded histogram bin number will account for this energy loss. For this reason, the lowest resolvable limit of the instrument is identified to be 14 keV. The maximum of the peak was identified by fitting a Gaussian distribution to the raw counts and determining the fitted maximum. The fit was not used to obtain values such as flux or temperature but merely the histogram bin number at the location of the maximum which is then related to the known electron energy flux applied during calibration. A large background signal is seen between the noise peak and the main signal peak for higher-energy electrons; this background did not contribute to the Gaussian fit of the main peak. The signal generated in lower channels from high-energy electrons will have to be accounted for when analyzing a spectrum on orbit.

The FalconSEED instrument response to energetic electrons has been thoroughly characterized as a function of known energy from direct detection of electrons and detection of Compton electrons created by X-rays and gamma rays. The data have been used to produce a linear plot of energy per histogram bin number, as shown in Figure 7. After calibration combining all our test data the linear fit of energy per bin is

$$y = 0.1465x - 3.837$$

where $y$ is the energy in keV and $x$ is the related histogram bin number with an $r$-squared value of 0.9961. The lower energy data points obtained using the electron source are in close agreement and follow a linear fit; however, the higher-energy data points obtained using the radioisotope sources deviate slightly. This is possibly due to energy loss as the electrons pass through the thin foil separating the aperture and the detector.

The instrument response in terms of the field of view for the instrument was also measured in the Mumbo chamber at streaming electron energies ranging from 15 to 30 keV as shown in Figure 8. The aluminum collimator of the sensor head has a full cone angle of

![Figure 7. Data and linear fit for energy as a function of histogram bin number.](image)

![Figure 8. Measured energy spectra as a function of electron energy and angle of incidence.](image)
Figure 9. Response of FalconSEED calculated from the angular data shown in Figure 9.

Equations (2) and (3) use the subscript B to signify the beam area A and known counts C. Subscript i refers to the measured counts C. The effective area A of the detector. The low response of the detector is expected based on the small aperture size of FalconSEED. The rise in response as a function of energy suggests a possible dead layer in the solid state detector. Once on-orbit, the instrument will collect data for 2-min time intervals, summing the total counts per histogram bin number, store the data packets to a memory buffer, and then transmit to the ground station once per day. Further analysis comparing measured counts to other instruments on the satellite will be needed to convert from raw counts to science data such as energy and flux.

4. Conclusions

The FalconSEED instrument has been calibrated using a combination of radioisotopes and an electron beam source, which collectively produce X-ray, gamma ray, and electron energies ranging from 10 to 122.1 keV. The three radioisotope sources, Cs-137, Ba-133, and Co-57, were used at the Space Atmospheric Research Center to test X-ray and gamma ray energies of 30.85, 80.95, and 122.1 keV, respectively. The flight unit was calibrated at Kirtland AFB using an electron beam source with streaming electron energies ranging from 10 to 53 keV. The noise due to internal electronics results in signal saturation for energies below 14 keV effectively making these energy bins unusable for science data. A linear fit of the calibration data from 14 to 122.1 keV indicates that the maximum energy able to be measured by the detector will be 145 keV corresponding to a histogram bin number of 1024. The flight payload has been delivered for integration to STP-Sat 6 with an estimated launch date in late 2020.

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References

Be, M., Chisté, V., Dulleu, C., Browne, E., Baglin, C., Chechev, V., et al. (2016). Table of radionuclides. Monograph BIPM-5. 8.

Brautigam, D. (2002). CRRES in review: Space weather and its effects on technology. Journal of Atmospheric and Solar-Terrestrial Physics, 64.

Choi, H. S. L. J., Lee, J., Cho, K. S., Kwak, Y. S., Cho, J. H., Park, Y. D., et al. (2011). Analysis of GEO spacecraft anomalies: Space weather relationships. Space Weather, 9. S06001. https://doi.org/10.1029/2010SW000597

Cress, R., & Maldonado, C. (2020). FalconSEED calibration dataset. Retrieved from osf.io/sj6ca

Fennell, J., Koons, H., Roeder, J., & Blake, J. (2001). Space charging: Observations and relationship to satellite anomalies. Noordwijk. s.n.

Ferguson, D. C., Denig, W., & Rodriguez, J. V. (2011). Plasma conditions during the Galaxy 15 anomaly and the possibility of ESD from sub-surface charging. Orlando, FL, 49th AIAA Aerospace Sciences Meeting.

Garrett, H. B., Schwank, D. C., Higbie, P. R., & Baker, D. N. (1980). Comparisons between the 30- to 80-keV electron channels on ATS 6 and 1976-059A during conjunction and application spacecraft charging prediction. Journal of Geophysical Research, 85A(3), 1155–1162.

Ginet, G. P., O’Brien, T. P., Huston, S. L., Johnston, W. R., Guild, T. B., Friedel, R., et al. (2013). AE9, AP9 and SPM: New models for specifying the trapped energetic particle and space plasma environment. In N. Fox, & J. L. Burch (Eds.), The Van Allen Probes Mission, (pp. 579–615). Boston, MA: Springer.

Gold, R. E., Krimigis, S. M., Hawkins, S. E. III, Haggerty, D. K., Lohr, D. A., Fiore, E., et al. (1998). Electron, Proton, and Alpha Monitor on the Advanced Composition Explorer spacecraft. Space Science Reviews, 86(1/4), 541–562.

Gussenhoven, M. S., Hardy, D. A., Rich, P., Burke, W. J., & Yeh, H. C. (1985). High-level spacecraft charging in the low-altitude polar auroral environment. Journal of Geophysical Research, 90(A11), 11009.

Hoffmann, R., Ferguson, D., Wheelock, A., & Patton, J. (2012). The Spacecraft Charging and Instrument Calibration Laboratory: A New Frontier in American Spacecraft Charging R&D. Nashville, Tennessee. s.n.

Katz, I., Mandell, M., Jongeward, G., & Gushenheim, M. S. (1986). The importance of accurate secondary electron yields in modeling spacecraft charging. Journal of Geophysical Research, 91(A12), 13739.
Lindstrom, C. D., Aarestad, J., Ballenthin, J. O., Barton, D. A., Coombs, J. M., Ignazio, J., et al. (2018). The compact environmental anomaly sensor risk reduction: A pathfinder for operational energetic charged particle sensors. IEEE Transactions on Nuclear Science, 65(1), 439–447.

Mason, J. P., Woods, T. N., Caspi, A., Chamberlin, P. C., Moore, C., Jones, A., et al. (2016). Miniature X-ray solar spectrometer: A science oriented, university 3U cubesat. Journal of Spacecraft and Rockets, 53(2), 328–339.

National Nuclear Data Center, 2019. NuDat 2.7 database. [online] Available at: https://www.nndc.bnl.gov/nudat2/

O’Brien, T. P. (2009). SAES-GEO: A Spacecraft Anomalies Expert System for Geosynchronous Spacecraft. Space Weather, 7, S09003. https://doi.org/10.1029/2009SW000473

Patt, B. E., & Iwanczyk, J. S. (1998). Improved energy resolution for scintillator based gamma-ray detectors obtained using a CsI (TI)/Si-PIN detector. Review of Scientific Instruments, 68.

Sullivan, J. D. (1971). Geometric factor and directional response of single and multi-element particle telescopes. Nuclear Instruments and Methods, 95(1), 5–11.

Thomsen, M. F., Denton, M. H., Lavraud, B., & Bodeau, M. (2007). Statistics of plasma fluxes at geosynchronous orbit over more than a full solar cycle. Space Weather, 5, S03004. https://doi.org/10.1029/2006SW000257

Thomsen, M. F., Henderson, M. G., & Jordonova, V. K. (2013). Statistical properties of the surface-charging environment at geosynchronous orbit. Space Weather, 11, 237–244. https://doi.org/10.1002/swe.20049