CeREs: The Compact Radiation belt Explorer

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ABSTRACT

The Compact Radiation belt Explorer, CeREs, a 3U CubeSat, is expected to be launched July 2018. The primary science goal of CeREs will be to study the physics of the acceleration and loss of radiation belt electrons, in particular electron microbursts, an important process that contributes to loss of electrons. A secondary science objective of CeREs is to characterize solar energetic particles (SEP), specifically electrons and protons, accessing the near Earth environment via the open field lines over the poles. Solar electron observations will advance our understanding of electron acceleration mechanisms in solar flares and their transport in interplanetary and solar regions. The CeREs CubeSat will be in a low earth, high inclination orbit with a year-long prime-science phase. CeREs measurements complement and extend the science goals of the Van Allen Probes, a NASA flagship mission in a near-equatorial orbit. The MERiT instrument aboard CeREs will detect electrons (protons) at energy levels from ~5(100) keV to ~10(100) MeV using a stack of 8 silicon solid-state detectors (SSDs) and four avalanche photo diodes (APDs), which are provided by Southwest Research Institute (SwRI), the co-I institute. The front-end electronics use an innovative Energy-4 ASIC developed at Goddard Space Flight Center. The onboard CHREC Space Processor card is multi-institutional effort funded by the NSF Center for High-Performance Reconfigurable Computing (CHREC). This paper will describe the CeREs spacecraft and its mission in detail and highlight advancements made in the development of the MERIT instrument and supporting hardware.

INTRODUCTION

CeREs, the Compact Radiation bElt Explorer, will study energetic electron dynamics in the Earth’s radiation belts, solar electron transport and energization, and space weather aspects of solar proton access to geospace. The science payload comprises a novel sensor, MERiT\textsuperscript{1}, a Miniaturized Electron and pRoton Telescope. CeREs is a 3U CubeSat expected to be launched in July 2018 into a circular high-inclination (85°) Low-Earth Orbit (LEO) at 500 km altitude. MERiT is designed to measure suprathermal to relativistic electrons from ~5 keV up to 10 MeV, and energetic protons between ~100 keV–100 MeV. The spacecraft bus and the payload were developed, tested, and integrated at NASA Goddard Space Flight Center (GSFC) with contributions from the Co-Is at Southwest Research Institute (SwRI). The project also involved graduate students from the Catholic University of America and University of Texas, San Antonio.

CeREs is the first fully NASA-SMD (science mission directorate) funded CubeSat and contributes to NASA’s Heliophysics program by: (a) advancing the understanding of the radiation belt electron energization and loss processes by making high-cadence, high-resolution measurements of the energy spectra of electrons over a broad energy range, and (b) will flight-validate an innovative, compact, low-mass, low-power instrument that has many future applications. Through the extensive involvement of graduate students, CeREs will provide valuable training for the next generation of experimental space physicists. CeREs measurements of radiation belt electrons at LEO will extend and complement NASA’s flagship mission, the Van Allen Probes. A photo of the CeREs spacecraft being readied for delivery to the launch provider is shown in Figure 1. The figure also shows the Tyvak rail pod deployer that will deploy the CeREs spacecraft.

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Figure 1: CeREs Spacecraft (left) with the Tyvak Rail Pod deployer (right)
SCIENCE OVERVIEW AND GOALS

As mentioned above, scientific questions addressed by CeREs encompass electron energization and loss in the Earth’s radiation belts and solar electron acceleration and transport, with the former being the primary science goal of the mission. In addition, CeREs measurements of energetic protons over the polar-regions provide information about how these hazardous particles access geospace during geomagnetically disturbed times, an important aspect of space weather. We provide a brief overview of the science and focused goals of CeREs mission below.

Radiation Belt Electron Dynamics

The electron populations in the Earth’s outer Van Allen belts are highly dynamic due to energization and loss processes that occur over time scales ranging from minutes to years. It is currently understood that electron energization results from local in-situ wave particle interactions, radial transport, or a combination of both\textsuperscript{3,4}. It is essential to understand the contribution of both electron loss and energization in order to ascertain the net flux levels in the radiation belts\textsuperscript{5}.

![Figure 2: HILT observations of microbursts\textsuperscript{12} of electrons > 1 MeV](image)

While there are several processes\textsuperscript{6} that deplete electrons in the outer belt, loss due to microbursts has recently gained prominence since they may potentially empty the belts on time scales of days\textsuperscript{7}. Microbursts are short-lived (<1 s) bursts of electrons scattered into the loss cone by interactions with plasma waves in the magnetosphere\textsuperscript{8,9}. Figure 2 shows electron microbursts observed over a radiation belt pass by the HILT\textsuperscript{10}, sensor onboard the SAMPEX\textsuperscript{11} spacecraft. Microbursts are seen as “spikes” over the smooth bell-shaped radiation belt electrons.

The MERiT instrument (see below) will characterize microbursts with much higher time resolution than prior measurements, as well as provide spectral information in multiple differential channels to better understand microburst properties. In order to distinguish between energization due to radial transport vs. in-situ energization, it is necessary to examine the radial profiles of phase space density (PSD). PSD radial profiles differ for internal, i.e., wave-particle energization, as opposed to those due to radial transport\textsuperscript{13,14}. A recent study using PSD radial profiles has shown that it is possible to identify both processes even though they may occur during a single enhancement event. This is illustrated in Figure 3, which shows both monotonically increasing and peaked radial profiles of PSD for electrons of different energies during an energization event driven by simultaneous high-speed solar wind stream (HSS) and coronal mass ejection (CME)\textsuperscript{15}. Calculation of PSD requires knowledge of both the model-dependent global magnetospheric field and accurate measurements of particle spectra. MERiT measurements with differential energy coverage will reduce uncertainties arising from less precise spectral measurements.

![Figure 3: Van Allen Probes observations of radial profiles of PSD\textsuperscript{16} during an event driven simultaneously by HSS and CME](image)

Solar electron energization and transport

As CeREs traverses the polar-regions, it encounters open field lines, i.e., magnetic field lines that connect to the Sun. Charged particles emanating from various solar sources such as flares, CME shock accelerated interplanetary regions, reconnection regions higher in the corona, etc. are all observable from low earth orbit over the polar caps. Open questions remain concerning regions of solar electron acceleration at lower energies\textsuperscript{16} (~tens of keV). This is due to lack of high quality measurements at these energies, which will be well covered by MERiT measurements. Figure 4 shows solar electron spectra measured by ACE and SAMPEX, which highlight the lack of measurement below 30 keV, and where MERiT will fill the gaps.
Solar proton access to geospace

The geomagnetic field prevents low rigidity (momentum per unit charge) charged particles from reaching low latitudes. The minimum value of rigidity required to reach a point on the Earth is termed geomagnetic cutoff rigidity. This cutoff rigidity, which depends upon the geomagnetic field and direction of arrival, varies during geomagnetic storms when the field is distorted. Proton cutoff variability as measured by sensors onboard SAMPEX during a geomagnetic storm is shown in Figure 5 for 19.0-26.0 (blue), and 22.0-60.0 MeV (red) protons.

Figure 5: Solar proton access to geospace during a geomagnetic storm. The figure shows 19-26 MeV (blue) and 22-60 MeV (red) protons measured by the PET sensor onboard SAMPEX.

The figure also shows the Dst index, a measure of the distortion of the geomagnetic field. It is evident the cutoff location follows the variation in the geomagnetic field, with protons reaching lower latitude as the strength of the geomagnetic field disturbance increases. This is important from a space weather perspective as at times these energetic particles can reach space station orbits.

MISSION REQUIREMENTS AND IMPLEMENTATION

As mentioned before CeREs has 3U form factor, with the payload and the bus occupying almost 1.5U each. Power is supplied by dual deployable solar panels provided by Clyde Space, Glasgow, Scotland and the bus, XB1, provided by Blue Canyon technologies, Boulder, CO. In order to achieve CeREs science, the spacecraft bus was required to:

- Store 854 Mbits of science and 100+ Mbits housekeeping data per day.
- Support UHF-band downlink data rate of 2.2 Mbps, and uplink date rate of 9.6 kbps.
- Provide > 9.2 W orbit-average power
- Launch Mass < 4.58 kg
- Orbital debris compliant with NPR 8715.6
- Point MERiT to local zenith to better than 20°
- Collect >40 kbps of data when >60 latitude
- Provide 148 Full cone clear FOV for MERIT

A cut-away view of the spacecraft with the main functional components is shown in Figure 6.

Figure 6: CeREs cut-away view illustrating the main components and their functionality.
The 3U structure is made of aluminium with Teflon rails for the TyVak Rail-Pod deployer. The spacecraft has a passive thermal design with a battery heater for safe hold. A high level block diagram of CeREs is shown in Figure 7.

Figure 7: CeREs high-level block diagram.

The XB1 bus

The XB1 is a complete solution, providing bus functionality for GN&C, EPS, Thermal, C&DH, RF Comm, and SSR. A precision star tracker and two Sun pointers (coarse and fine) provide attitude control with pointing accuracy that exceed mission requirements. XB1 also provides for real time commands as well as command macros. The XB1 is powered on and able to receive RF communications during all points of the mission. Should an upset occur, radiation or otherwise, all spacecraft components reset to safe mode. Two modes exist for the GN&C – sun point mode and fine reference point mode. Sun point mode acts as a safe mode while fine reference pointing being used for all other mission modes and is command able from the ground. For CeREs, sun point mode has the spacecraft X-axis toward the sun, which is perpendicular to the solar panels, the Z-axis along the length of 3U, and the Y-axis completing the coordinate system. The space-craft will automatically enter this mode at boot, anytime battery voltage drops below a threshold, or as a result of any fault. Onboard ADCS hardware powered during this mode includes the reaction wheels, star tracker, torque rods, three-axis magnetometer, inertial measurement unit, coarse sun sensors, and the battery.
heater. Fine Reference Point mode is entered when the following requirements are met: (a) valid attitude, obtained by star tracker, propagated by IMU, (b) valid time, obtained by GPS, propagated by onboard oscillator, and, (c) valid orbit / ephemeris – obtained by GPS. The GPS is set up to be activated after initial checkout activities are completed and will run duty cycled to reduce the overall power consumption onboard. The star tracker is always enabled in the XB1 system. Should either the GPS or star tracker fail, the telemetry generated may be uploaded to the spacecraft via a ground command. A high-level block diagram of the XB1 bus is shown in Figure 8.

![XB1 high-level block diagram.](image)

**The Electrical Power Subsystem**

The XB1 electrical power system receives power input from the deployable COTS solar arrays purchased from ClydeSpace and stores charge in an internal lithium ion battery pack made of up three series cells with a capacity of 2.6 Ah and a maximum voltage of 12.6 V. Ten switched power rails provide positive 3.3, 5, 7, and 12V.

**The RF Subsystem**

CeREs uses the Cadet UHF radio, which is internal to the XB1. The XB1 maintains the 3.3V power to the radio to enable the receipt of RF commands and only enables additional power rails when commanded. The command to transmit enables a beacon, single packet of high FIFO data, to be sent at a set rate. In order to downlink stored data from the low FIFO, this beacon must be active. As the Cadet radio is directly connected to the XB1 bus, all communications to the payload flows through both components. Similarly, all data generated by MERiT pass through the XB1 to be stored in the four-gigabyte FIFO queue onboard the Cadet.

**Flight Software**

The flight software (FSW) has a modular structure and comprises several core modules. The Core Flight Executive (CFE) is a set of mission independent reusable core flight software services and operating environment that provides standardized Application Programmer Interfaces (API). The applications can be added or removed at run-time and contains platform and mission configuration parameters. These core components include:
ES (Executive Services), which manage the software system; SB (Software Bus), which provides publish/subscribe software bus messaging interface; TIME (Time Services), which provides spacecraft time; EVS (Event Services), which provides interface for sending, filtering, and logging event messages; and TBL (Table Services), which provides interface to manage table images. FSW also has core flight software services (CFS) and all CFS applications are reused with minor project-specific configuration changes. These services cover all the major aspects such as file uplink downlink, house keeping, commanding, scheduling, etc. Mission specific CFS, i.e., custom applications are provided for instrument component management (APD, SSD, FEE) and science telemetry output.

**SCIENCE PAYLOAD: MERIT**

The Miniaturized Electron Proton Telescope, MERiT, the science payload, combines a solid state particle telescope and APDs to extend the energy range of measured charged particles to much lower values (~ few keV) than is usually possible using SSDs alone. There are 8 electron and 10 proton differential channels for the SSD stack and 16 APD channels. The data from the APDs are of two types: differential channel rates for electrons, protons, and mixed channels ranging in variable cadence; integral proton rate at variable cadence. The data from the SSD stack are of three types: singles rates from each of the eight SSDs, differential channel rates for electrons and protons at variable cadence, and PHAs from all eight SSDs, including differential channel IDs, for a variable number of events. The instrument operates two modes: high time resolution or microburst mode (MB) and low time resolution or SEP mode (see below) and is fully configurable and can be modified on flight.

All the key constants that determine thresholds and differential channels can be uploaded via ground command, as are the instrument mode boundary settings. The nominal boundaries correspond approximately to the radiation belts and polar caps for MB and SEP modes respectively. The entire stack is enclosed in tungsten-aluminium (W-Al) shielding to prevent contamination from side penetrating particles, and a requirement of contiguous hits in the detector stack within 250ns (changeable via ground command) ensures minimal background due to chance coincidences. Onboard processing for MERiT is done by CSP20, a radiation tolerant Zynq FPGA-ARM processor, developed by the CHREC consortium.

**Figure 9:** Photos showing MERiT sensor stack (left) and Front End Electronics board (right).

Figure 9 shows the fully-assembled sensor stack surrounded by the shielding and the front end electronics being tested in the laboratory. The resource parameters and the energy ranges of electrons and protons measured by MERiT are listed in Table 1. MERiT has been described in greater detail elsewhere21.

<table>
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<th>Table 1 MERiT Resources and Parameters</th>
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<td>Protons</td>
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<tr>
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<tr>
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SPACECRAFT INTEGRATION AND TESTING

CeREs was integrated at GSFC’s Heliophysics Energetic Particles Laboratory after component-level testing. All components, including the solar panels, science payload, and spacecraft bus were tested for functionality and performance verified. Some components, e.g., SSDs and the APDs, were flight qualified to NASA specs by the vendor. After the spacecraft was fully integrated, random vibration, thermal vacuum, and balance tests were performed, with the spacecraft meeting or exceeding the launch provider’s requirements. Acoustic testing was found to be unnecessary based on the results of the vibration test results. A Rail-Pod shock analysis showed compliance with launch requirements. Venting analysis confirmed that both the payload and XB1 were compliant and capable of surviving launch ascent pressure profile. NASA provides CeREs launch via the ElaNa-CSLI program on the Electron launch vehicle built by Rocket Labs.

Random Vibration test

The random vibration test and low-level signature sweeps tests were conducted for each spacecraft axis, at GEVS-acceptance levels, to demonstrate compliance with the Launch Vehicle requirements. The test sequence for each axis started and ended with a low-level signature sweep, interleaved by random vibration. The results of the test were that all requirements were met with no significant structural changes or failures, and full functionality of the spacecraft was maintained after completion of the test.

Thermal vacuum and Thermal Balance test

Although the launch provider only required a bake out, CeREs underwent a four-cycle thermal vacuum and thermal balance test, including a bake out on the first cycle. Bake out was held at 60°C for 6 hours, per requirement. The extended duration profile was selected based on survival temperatures of key components. The test setup consisted of thermocouples placed on the outside of the spacecraft, heater panel facing the -X face of CeREs, and the shroud set to space temperature. Thermal balance testing proved that the design is valid. No component violated its temperature limits through the testing. Overall the balance temperatures were on average within 3°C of thermal model predictions.

COMMUNICATION, COMMANDING, AND GROUND SUPPORT

The Wallops Flight Facility (WFF) handles the communications, commanding, and data downlink for CeREs. WFF maintains UHF Radar that supports a number of small satellites all using the same Cadet radio and GSE. The natural gain provided by the 18.3m dish enables high data rates (3.0 Mbit) for these missions. WFF is staffed for pass times that occur between 0730 and 2330 Eastern during the week, with commissioning exceptions available, as necessary, with coordination.

CeREs uses the Virtualized Multi-Mission Operations Center (VMMOC) at GSFC. The VMMOC will connect directly to the GSE at WFF and will be the primary point of contact with the spacecraft. ITOS, or integrated test and operations system, will have a specific database for the CeREs mission, leveraging those generated by other supported CubeSat missions. The VMMOC will handle all commanding and downlinking of telemetry from the spacecraft. All telemetry will be captured by the VMMOC, forwarded to the Mission Engineering Data System (MEDS), and submitted to the Telemetry as a Service (TaaS) web portal for use by the Science Operations Center (SOC). TaaS will archive telemetry as received from the VMMOC and provide a web interface for plotting or export selected data. MEDS will process the raw telemetry from the spacecraft utilizing the COSMOS command and telemetry system. MEDS is a virtual machine that exists on multiple NASA computers at GSFC and is managed by the CeREs PI, PM, and Lead Systems Engineer. Since MEDS is a virtual machine, it is fully portable and can be distributed as necessary.

Figure 10: Communication system connecting the MOC to CeREs using the Wallops Flight Facility.

The communications system connecting WFF and CeREs is shown in Figure 10. The downlinked data from the VMMOC is obtained and will be sent to the Science Operations Center (SOC) located at SwRI to process raw telemetry into scientifically usable data.

Commanding

There are two types of stored XB1 commands, absolute and relative time sequences or macros.
The absolute time stored commands use TAI time (in seconds since J2000) at which the command should be executed. Four hundred of these commands may be stored onboard the spacecraft and up to eight may be executed in one 5Hz cycle. When uploaded from the ground, these commands are stored in RAM and will not persist through a reset. Stored commands may be overwritten and a ground command exists to clear all stored commands. CeREs uses absolute time commands to trigger relative time sequences discussed in the next section.

CeREs will typically use the absolute time sequences to trigger macros for nominal operations. Macros can be triggered to immediately begin or to start at an absolute time, utilizing a macro execute command encapsulated in an absolute time command uploaded from the ground. Note that macros also have the ability to trigger themselves upon completion, if desired. A macro is a list of commands whose execution is scheduled for a specified time after initiation. Absolute commands may be used to initiate a macro a specific time. A macro may call itself, creating a repeating process. Macros are numbered and their ordering is important due to the way in which they are disabled. For example Macro #51 covers nominal orbit configurations.

MISSION OPERATIONS

Deployment and Commissioning

As the spacecraft exits the deployer, separation switches will be released, allowing the spacecraft to power up and boot the FSW. The XB1 will begin the transition to sun point mode and a deployment macro will activate and run through the deployment sequence for both the antennas and the solar panels, twice. This is timed to ensure at least one of the attempts will be made during insolation (sun exposure). The deployment macro disables the low voltage checks, as a successful deployment is required to run in order to charge the spacecraft in sun point mode and to communicate with the ground. Upon completion of the deployment sequence, the beacon will begin at a rate of once per minute until the rate is modified by the ground station via macro command from 1 minute to 10 seconds for approximately 15 minutes before returning to 1 minute.

Nominal Orbit

A nominal science orbit, defined and controlled via an orbit macro, is broken into nine stages. Each stage is targeted to run over a range of latitudes. The actual run time for each stage is based solely on wait commands that may need to be adjusted on orbit, using predicted TLEs and orbit determination, to account for the actual orbit’s timing. Six of the eight stages are a form of science mode, either MB or SEP, and are based around the polar-regions, while the other two are utilized to publish telemetry to the radio. The different regions of a CeREs orbit and the modes of operations in those regions are shown in Figure 11.

![Figure 11: CeREs nominal orbits showing the different modes and their dwell times](image)

While in a science mode, the spacecraft will be in the fine reference-pointing mode with the primary axis (\(Z\)) pointed to zenith and the secondary axis (solar array, \(-X\)) to the sun. While not in science mode, the pointing of primary and secondary axes will be exchanged to prioritize charging. Once all stages are complete, the macro simply runs again immediately for the next orbit. The orbit macro is designed to start at the equator and will be re-triggered occasionally via absolute time sequence to keep the stages in sync with the orbit. When the CeREs team detects drift, a new absolute time sequence will be loaded via ground command to restart the orbit macro. The nominal values for the transitions into different modes are commandable from the ground, with the nominal values designed to capture mostly microbursts while traversing the radiation belt horns, and, mostly, solar particles over the polar caps.

Contingencies and special events

As the CeREs orbit begins to decay or change due to drag, the macros used to drive science operations will also become invalid. This is due to the fact that they are based upon relative time passing from the start and not actual orbit parameters. To account for this, the science macros will be stopped, updated as necessary, and restarted again. Should an event check be triggered on board the spacecraft, the immediate response will be to downlink data that was generated after the prior pass for further examination. Once mission engineers have verified the health of the spacecraft steps may be taken to resume nominal operations. If the event check is no
longer enabled, individual commands will be used to set the event checks back to the nominal state. A majority of event checks simply place the spacecraft back into sun-point mode. The nominal science setup will also need to be performed in order to resume operations.

Special events, such as a CME impact, or a conjunction with other spacecraft studying allied phenomena could benefit from measurements from the CeREs spacecraft. Additional macros will be created and placed onboard that include a wait and a duration of time the high data rate collection should be run. The nominal orbit macro will be halted in order for this to occur and resumed once special operations are concluded.

SUMMARY

The Compact Radiation belt Explorer, CeREs, is a 3U CubeSat designed to study electron dynamics in the Earth’s radiation belt, with a focus on furthering our understanding of electron microbursts, an important process that depletes electrons. In addition, it will contribute to our understanding of solar electron transport and acceleration as well as monitor solar proton access to geospace, which constitute a space weather hazard. CeREs will be launched in July 2018 and has a prime science mission of one year. Onboard, CeREs carries onboard MERIT, an innovative low mass, low power instrument capable of measuring electrons and protons; the former with very high time resolution over a wide energy range. CeREs data will be available to the research community in accordance with NASA’s open data policy. The CeREs mission team comprises not only senior scientists but also graduate students, post doctoral fellows, and young engineers, thus providing a training ground for the nation’s future scientists and engineers.

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