Calibration and Initial Results of Space Radiation Dosimetry Using the iMESA-R

C. A. Maldonado1, R. Cress2, P. Gresham2, J. L. Armstrong2, G. Wilson3,4, D. Reisenfeld1, B. Larsen1, R. L. Balthazor4, J. Harley2, and M. G. McHarg2

Abstract

The integrated Miniaturized Electrostatic Analyzer-Reflight (iMESA-R) is a space weather instrument designed to measure plasma density, temperature, and spacecraft charging, along with total ionizing dose and dose rate. A constellation consisting of five nearly identical instruments has been designed and developed to act as science payloads hosted on-board Department of Defense satellites operating in low Earth orbit. To validate the dosimetry component of the iMESA-R, a radiation test study was performed to calibrate the dosimeter and ascertain the attenuation due to the instrument aluminum housing. An 80 curie Cobalt-60 radioisotope source emitting beta, X-ray, and gamma ray radiation decay products was used to calibrate the dosimeter response as a function of distance and instrument shielding. We present results of the calibration study along with initial on-orbit data presented from the first operational iMESA-R hosted on-board Space Test Program Satellite 5 in a polar Earth orbit. The initial on-orbit data demonstrate the ability to map the radiation environment, particularly the South Atlantic Anomaly and the auroral regions using total ionizing dose rate due to electrons of $E > 1.5$ MeV and protons of $E > 25$ MeV.

1. Introduction

A magnetic irregularity known as the South Atlantic Anomaly (SAA) allows energetic particles trapped in the Earth's geomagnetic field to reach lower altitudes resulting in a region of high radiation. The geographic location of the SAA is due to the Earth's magnetic dipole and rotation axis being offset by approximately 11º, resulting in a magnetically weak region above the South Atlantic Ocean which allows the inner Van Allen radiation belt, composed predominantly of high-energy protons, to come closer to the Earth's surface than at similar latitudes. In addition to the SAA, the magnetic field lines converging at the magnetic poles allow for high-energy particles, namely, precipitating electrons, to penetrate to LEO altitudes in the auroral regions. While the effects of the space radiation environment are generally not as great of a concern to spacecraft operating in low Earth orbit (LEO) when compared to geosynchronous orbit (GEO), the SAA and auroral zones present increased radiation hazards to satellites and spacecraft.

Systematic effects due to the increased flux of protons and electrons are commonly observed by satellites and the International Space Station as they periodically pass through these regions of space. These adverse radiation effects include single-event upsets (Crabtree et al., 1993; Falguere et al., 2002), anomalous background counts in science payloads (Anderson et al., 2018; Schaefer et al., 2016), increased radiation effects for astronauts (Cucinotta et al., 2001), along with premature aging of computer, detector, and other spacecraft components. In an effort to mitigate these hazards, systematic and engineering controls have been implemented while transiting the SAA such that payloads susceptible to these events will disregard data collected or power down (Heirtzler, 1999), additional shielding has been incorporated to the International Space Station, and extravehicular activities for astronauts are avoided (Johnson et al., 2005). Measurements of the ionizing radiation environment in LEO are therefore critical to mitigating the risks for satellite systems and crewed missions. The radiation fields encountered in LEO are highly complex, and currently, most space mission analysis and design are done with assistance from modeled estimates of dose (Ginet et al., 2007). Accurate mapping of the SAA is somewhat problematic due to the dynamic nature of the region which expands and contracts as a function of short-term geomagnetic storms and the solar cycle. During
geomagnetic storms, energetic protons and electrons are injected from the magnetosphere into the ionosphere via the magnetic field lines. This concentration of energetic particles presents a formidable radiation hazard to orbiting satellites and spacecraft operating in LEO (Herlitzer et al., 2002). Features of the SAA are also changing as a function of variation in the secular geomagnetic field; more specifically, the center of the anomaly is drifting westward between 0.1 and 1.0 degree/year and northward at approximately 0.1 degree/year (Grigoryan et al., 2008). In addition to geographic location, the shape of the anomaly is changing over time as well, having expanded over the last three decades (Pu et al., 2005).

A more recent study using the Along Track Scanning Radiometer series of instruments to monitor the SAA found that the SAA’s strength and extension are anticorrelated with the solar activity expressed by the solar radio flux at a wavelength of 10.7 cm ($F_{10.7}$) (Casadio & Arino, 2011). This is due to heating of the upper atmosphere by ultraviolet and vacuum ultraviolet radiation during periods of increased solar activity which in turn produces higher neutral density in the altitude region above the SAA consequently leading to the increased absorption of trapped particles. During periods of minimal solar activity when the neutral particle density is much lower, trapped energetic charged particles are able to penetrate to lower altitudes at a higher rate thus increasing the charged particle flux and boundaries of the SAA in solar minimum conditions (Dachev et al., 1999; Huston et al., 1996).

This inverse relationship between solar activity and SAA characteristics provides a unique opportunity to study the extension of the region at its greatest dimensions. The current evolution of the Sun between solar cycles 23 and 24 remains highly anomalous compared to previous periods having been abnormally quiet over a relatively long solar minimum (Schwadron et al., 2012). Solar cycle 23 is currently near minimum and appears to be decreasing to a historical low as shown in Figure 1. This presents an ideal opportunity to map the maximum boundary of the SAA and measure the evolution of the change in structure from deep solar minimum to the rise of solar cycle 24. The constellation of iMESA-R instruments, each equipped with a microdosimeter, will act to measure the total ionizing dose (TID) due to the combined flux of electrons, protons, galactic cosmic rays that penetrate to the interior of the satellite, effectively monitoring the health of the instrument while simultaneously mapping regions of increased radiation in LEO.

2. iMESA-R Constellation

The iMESA-R instruments are a series of space weather sensors that have been developed at the U.S. Air Force Academy Space Physics and Atmospheric Research Center in an effort to provide multipoint in situ ionospheric measurements. The instrument has two diagnostic components: a laminated electrostatic plasma analyzer to measure plasma density, temperature, and spacecraft charge in addition to a microdosimeter to measure TID and dose rate. The entire instrument consists of the electrostatic analyzer sensor head, microdosimeter, and two electronics boards, all of which are encased in an aluminum housing depicted in Figure 2.
Figure 2. Note that the field of view for the electrostatic analyzer is shown using dashed lines and is oriented normal to the velocity vector of the host satellite.

The microdosimeter is surrounded by a combination of cables, fittings, bolts, PCBs, and the electrostatic analyzer sensor head, where any straight path from the dosimeter to the space environment will travel through at least one wall of the instrument enclosure. An energetic charged particle passing through the instrument housing must pass through a minimum of 1/8 inch (~3 mm) of aluminum or greater allowing only electrons of $E > 1.5$ MeV and protons of $E > 25$ MeV to penetrate this minimum amount of aluminum (based on the National Institute of Standards and Technology calculated Continuous-Slowing-Down-Approximation ranges from the ESTAR and PSTAR websites) thus setting the lower-energy limit for the TID caused by incident energetic electron and proton flux (National Institute of Standards and Technology, 2019).

The Space Environment Information System was used to provide an estimate of the total dose for the Teledyne microdosimeter by modeling the dose absorbed by a silicon detector as a function of aluminum shielding depth along the Space Test Program Satellite 5 (STPSat-5) mission orbit at solar minimum conditions (Heynderickx et al., 2004). The software utilizes the AE8/AP8 trapped particle model to provide spectra for the trapped electron and proton flux. The model additionally provides the dose due bremsstrahlung radiation caused by precipitating energetic electrons in the polar regions of interest to the iMESA-R onboard STPSat-5. The absorbed radiation for a silicon detector through a 24 hr mission segment is shown in Figure 3 where the total dose of 3.87 Rad at the instrument housing thickness of ~3 mm indicates that the dose is predominantly due to trapped electrons and protons. The dose due to bremsstrahlung radiation is approximately 2 orders of magnitude lower and therefore assumed to be negligible for the microdosimeter housed within the iMESA-R aluminum instrument casing.

A constellation of these instruments has been developed to cover a range of orbits thus allowing for the collected data to act as multipoint boundary conditions which can then be assimilated into environmental models for the purpose of increasing their space weather forecasting (Balthazor et al., 2015; McHarg et al., 2015). The iMESA-R has been integrated and launched as a science payload on-board the Green Propellant Infusion Mission (GPIM), Orbital Test Bed (OTB), Space Test Program Satellite 4 (STPSat-4), STPSat-5, and the Space Test Program Houston 6 (STP-H6) science payload pallet. The host satellites, launch vehicles, and corresponding orbital parameters for the iMESA-R constellation are listed in Table 1. Note that the STPSat-5 iMESA-R operated continuously for nearly a year prior to the end of mission in November 2019, and the remaining instruments in the iMESA-R constellation are operational.

The location and boundary of both the SAA and auroral regions have been mapped using a variety of techniques. Sensitivity to single-event upsets was used as a method to measure the impact of the SAA as demonstrated by an amateur radio communications satellite (UoSAT-2), where the subsequent upset count was used to map the SAA (Underwood, 1990). The anomaly has also been extensively mapped using background count rates recorded by the energetic particle and photometric detectors on-board the Defense Meteorological Satellite Program spacecraft which are susceptible to backgrounds induced by the increased orbital radiation environment (Anderson et al., 2018; Schaefer et al., 2016). The backgrounds were then used

![Figure 3. Dose in Si at the center of aluminum shielding.](image)

### Table 1

| Satellite | Launch vehicle | Launch date | Orbit |
|-----------|----------------|-------------|-------|
| GPIM      | Falcon heavy   | 25 June 2019| 720 down to 300 km, 24° |
| OTB       | Falcon heavy   | 25 June 2019| 720 km, 24°   |
| STPSat-4  | Antares        | 13 January 2020| 400 km, 51.6° |
| STPSat-5  | Falcon 9       | 3 December 2018 (EOM November 2019)| 596 × 578 km, 97.7° |
| STP-H6    | Falcon 9       | 4 May 2019   | 400 km, 51.6°  |
to estimate the local energetic proton flux used to determine the SAA structure. The constellation of iMESA-R instruments uses TID to monitor the radiation environment in LEO and map the SAA. These five sensors, nearly identical to ensure the homogeneity of the collected data set, offer the ability to provide near-real-time mapping of the plasma and radiation environment in LEO. The constellation ensures that an iMESA-R will transit the SAA approximately 40 times per day thus providing unprecedented daily coverage of the SAA. The ground tracks for a single orbit for each instrument in the constellation are shown in Figure 4.

### 3. Radiation Dosimeter

A Teledyne Microelectronic Technologies microdosimeter is used to measure TID and dose rate that the satellite is exposed to during the course of the mission. This specific microdosimeter model was selected for integration with all iMESA-R instruments due to its extensive ground-based testing and flight heritage (Lindstrom et al., 2011; Straume et al., 2016; Tobiska et al., 2015). Of particular interest is the use of the dosimeter for space-based applications such as the Cosmic Ray Telescope for the Effects of Radiation instrument aboard the Lunar Reconnaissance Orbiter (Mazur et al., 2011; 2015; Spence et al., 2010).

The accumulated dose is presented to three DC linear outputs and one pseudo-logarithmic output giving a dose resolution of 14 μRads and a measurement range up to 40 kRads. The dosimeter will integrate the dose absorbed by the silicon detector for energy deposits in the nominal range of 100 keV to 15 MeV. The dosimeter incorporates a silicon detector and a pulse-processing architecture that creates a Gaussian-shaped pulse in response to ionizing radiation. The Gaussian pulse is presented to an integrator which integrates the area under the pulse. The integration continues for each event until a preset limit is reached. When this happens, a quanta of charge are removed from the integrator equal to a value of 14 μRads, and a counter value is incremented (Teledyne Microelectronic Technologies, 2016). The dosimeter channels, ranges, and associated conversion factors are listed in Table 2. When any of the channels reaches its maximum value, the output rolls over and begins stepping from zero. The iMESA-R utilizes a 12-bit ADC, limited to a range of 3,786 counts, to record the signal for each dosimeter channel which allows for the determination of

| Channel | Description | Range           | Manufacturer dose conversion | iMESA-R ADC dose conversion |
|---------|-------------|-----------------|------------------------------|-----------------------------|
| 0       | Low         | 0–3.6 mRads     | 14 μRad/19.5 mV              | 1,051.7 counts/mRad         |
| 1       | Medium      | 0–0.9 Rads      | 3.6 mRad/19.5 mV             | 4,206.7 counts/Rad          |
| 2       | High        | 0–235 Rads      | 0.9 Rad/19.5 mV              | 16.1 counts/Rad             |
| 3       | Log         | 0–100 kRads     | Available upon request to manufacturer | 37.9 counts/kRad |

Figure 4. Ground tracks for a single orbit of the various iMESA instruments on 12 December 2019.
calibration factors listed in Table 2. The channel selected for data measurements will depend on the dose rate experienced by the unit such that when low dose rate and finer resolution are called for Channel 0 will be used and when high dose rate and coarse resolution are required, then Channel 3 will be used for data acquisition.

4. Instrument Calibration

An engineering unit of the iMESA-R was used to measure radiation emitted from an 80 curie Cobalt-60 radioisotope source emitting electron, X-ray, and gamma ray radiation decay products. As mentioned, the microdosimeter is unable to differentiate between the radiation types; however, for the purpose of measuring TID the cobalt source is ideal as the energy level of the gamma rays, approximately 1.3 MeV, is sufficient to penetrate the aluminum housing and induce dose in the silicon detector of the dosimeter (Brown & Tuli, 2013). The iMESA-R was mounted inside a lead and aluminum-lined case in order to prevent lower-energy scattered photons from interacting with the instrument. In order to measure the effect of the iMESA-R aluminum housing with regard to radiation attenuation, a series of measurements at different distances and configurations was conducted. The dosimeter response to the radiation source was measured while directly exposed as shown in Figure 5a and shielded in the nominal configuration as shown in Figure 5b. The nominal configuration is the method that the iMESA-R will be mounted to the host satellite via the baseplate with the laminated analyzer section facing outward. Note that since the radiation testing was not conducted in a cleanroom environment, a Kapton cover was used to prevent particulate contamination from entering the electrostatic analyzer portion of the instrument as evident in Figure 5b.

To provide an independent measurement of dose and dose rate, an air-ionization chamber (AIC) measurement device was mounted next to the iMESA-R as shown in Figure 6. The AIC instrument measures the charges created by direct ionization gas through the application of an electric field between two electrodes. As gas molecules are ionized by incident ionizing radiation, the newly created ion pairs and dissociated electrons are accelerated to the electrodes of opposite polarity. The accumulated charge is proportional to the number of ion pairs created and therefore the radiation dose (Knoll, 1999).

The iMESA-R and AIC were placed in the lead-lined aluminum test apparatus and adjusted so that the test articles and the Cobalt-60 radiation source were at the same height. In the configuration shown in Figure 6, the radiation source is in the direction projected orthogonally into the
photograph. To measure the dosimeter response in the shielded configuration, the iMESA-R was mounted with the Kapton-covered ESA analyzer facing the radiation source. The exposed configuration involved removing the bottom plate of the iMESA-R and rotating the instrument such that the bare dosimeter was facing the source. The process of rotating the instrument resulted in the location of the dosimeter shifting from the upper right to the upper left of the mounting fixture shown in Figure 6 with distances from the AIC of 5 and 10 cm, respectively. The iMESA-R and AIC were then exposed to the radioisotope source at various distances ranging from 3.41 to 1.02 m with the iMESA-R dosimeter in the shielded and exposed configurations.

The test articles were exposed to the source for 5 min durations; however, at the nearest distances of 1.02 and 1.36 m the exposure durations were decreased to 2 min. The collected iMESA-R data are shown in Figure 7 where the counts recorded by each dosimeter channel are plotted as a function of time. The signal response of Channel 1 was used to calibrate the dosimeter due to the high sensitivity of Channel 0 and the low sensitivity of Channels 2 and 3. The low sensitivity of Channel 0 causes the data to appear noisy; however, this is just an effect of the rapid counter rollover each time the full scale of the channel is reached. Due to the higher measurement range of Channel 2 and Channel 3, the plotted data do not show an increase in counts until the instrument is exposed to the greatest amounts of radiation at 1.02 and 1.36 m and even then the response is minimal. The scale factor for the dosimeter Channels 0 through 3 is constant; therefore, calibrating the
dosimeter counts recorded by Channel 1 as a function of the dose measured by the AIC allows for simultaneous calibration of the low, medium, and high channels. During the radiation exposure, Channel 1 can be seen to increment in a linear fashion with the slope increasing, that is, higher dose rate, as a function of decreasing distance from the radiation source. This behavior is apparent when considering Runs 9 and 12, depicted in Figure 7d, where Run 9 was conducted at 3.41 m and Run 12 was conducted at 1.02 m. The time sections Channel 1 data that have a slope of zero are when the source was sealed in its container and the instrument was no longer exposed to the source. Note that Channels 2 and 3 overlap as the total dose is quite low relative to the range of these channels.

The calibration factors listed for the iMESA-R in Table 2 were used to convert the counts measured during the instrument calibration runs into dose in units of Rad. Recall that the ADC conversion rate for Channel 1 is 4206.7 counts/rad and was determined by dividing the maximum ADC range of 3,786 by the maximum dose range of the dosimeter of 0.9 Rads. The results for the iMESA-R and AIC measurements for all of the calibration runs are listed in Table 3. The total dose measured by the microdosimeter in the shielded and exposed configurations is 13.7 and 15.3 Rads, respectively, and the attenuation due to the instrument housing and internal components is determined as the ratio of the total dose collected in the shielded versus the exposed configuration is 0.912 ± 0.095. The dose rate for the iMESA-R and AIC was determined as the total amount of dose accumulated over the time length of exposure to the radiation source. Considering the AIC to be the cross-calibration unit of merit, the percent difference between the microdosimeter and AIC is 7%. The dose rate measured at test distances nearest to the source (Runs 11–14) exceeds the data sheet specifications for the maximum dose rate of 10 mRad/s indicating that the device is capable of higher performance than it is specified for.

The calibration data for the microdosimeter in the two configurations (shielded and exposed) are compared with the AIC data for cross-calibration of the instrument and are shown in Figure 8. The data points between 3.41 and 2.04 m represent 5 min of instrument exposure to the radioisotope source, while the data points at 1.02 and 1.36 m represent 3 min of exposure time. At all distances the instrument was operated in a nominal data taking mode at a 1 Hz sampling rate. The error bars are determined as the square root of the standard deviation from the mean over the number of data samples. Note that the data are in close agreement and trend

| Run | Duration (min) | Distance (m) | iMESA-R configuration | iMESA-R dose (Rad) | iMESA-R dose rate (Rad/s) | AIC dose (Rad) | AIC dose rate (Rad/s) |
|-----|----------------|--------------|-----------------------|--------------------|--------------------------|---------------|----------------------|
| 1   | 5              | 3.408        | Shielded              | 0.549              | 0.0016                   | 0.6207        | 0.0021               |
| 2   | 5              | 3.0672       | Shielded              | 0.669              | 0.0022                   | 0.7442        | 0.0025               |
| 3   | 5              | 2.7264       | Shielded              | 0.717              | 0.0024                   | 0.9277        | 0.0031               |
| 4   | 5              | 2.3856       | Shielded              | 0.964              | 0.0032                   | 1.169         | 0.0039               |
| 5   | 5              | 2.0448       | Shielded              | 1.477              | 0.0049                   | 1.575         | 0.0052               |
| 6   | 5              | 2.0448       | Exposed               | 1.627              | 0.0054                   | 3.245         | 0.0052               |
| 7   | 5              | 2.3856       | Exposed               | 1.072              | 0.0036                   | 5.85          | 0.0038               |
| 8   | 5              | 2.7264       | Exposed               | 0.848              | 0.0028                   | 0.959         | 0.0032               |
| 9   | 5              | 3.0672       | Exposed               | 0.637              | 0.0021                   | 0.778         | 0.0026               |
| 10  | 5              | 3.408        | Exposed               | 0.513              | 0.0017                   | 0.655         | 0.0022               |
| 11  | 2              | 1.3632       | Exposed               | 4.384              | 0.0365                   | 1.389         | 0.0289               |
| 12  | 2              | 1.0224       | Exposed               | 6.210              | 0.0517                   | 2.348         | 0.0489               |
| 13  | 2              | 1.0224       | Shielded              | 6.092              | 0.0508                   | 3.473         | 0.0488               |
| 14  | 2              | 1.3632       | Shielded              | 3.310              | 0.0283                   | 5.87          | 0.0277               |

Figure 8. Dose measured by the AIC and iMESA dosimeter in the shielded and exposed configurations as a function of distance from the radiation source.
along an inverse square law as expected. The dosimeter in the exposed configuration measures more dose than in the shielded configuration at all distances except for the 1.02 m distance from the radiation source. The calibration data demonstrate that the microdosimeter within the iMESA-R can accurately monitor dose and suggests that the attenuation due to the instrument housing is negligible for gamma rays as tested in this calibration effort. As discussed previously, the greatest impact the instrument housing has on TID measurement is the lower-energy limit of electrons and protons that can pass through the aluminum walls.

5. On-Orbit Data

The iMESA-R instrument has been successfully integrated as a science payload on the OTB, GPIM, STPSat-4,STPSat-5, and STPT-H6 missions. The STPSat-5 mission was completed in November of 2019 and provides the first data set for the iMESA-R constellation discussed here. The TID of approximately 100 mRad measured by the microdosimeter Channel 1 during the STPSat-5 transit of the SAA on 5 July 2019 is shown in Figure 9a. Note that the inclination of STPSat-5 is 97.7° which results in a retrograde orbit which is illustrated using the latitude, longitude, and direction of the satellite ground track shown in Figure 9b.

Two time series of data from the iMESA-R are shown for context in Figures 10 and 11 showing conditions during the STPSat-5 passage through the SAA and auroral regions, respectively. The data are presented in five panels that display the ESA ion energy spectrograph, radiation dose, latitude, longitude, and altitude. The total dose, as measured using Channel 1, during the two SAA transits shown in Figure 10 is 208 and 364 mRads. The increase in radiation dose shown in Figure 11 corresponds to passage through the auroral region (as indicated by the latitude), and the relatively slow increases in radiation dose correspond to passage through the equatorial region. During periods where the total dose accumulation rate is low, such as through the auroral regions, the use of Channel 0 data would allow for finer resolution.

A preliminary map of the LEO radiation environment constructed using observations from the iMESA-R on-boardSTPSat-5 is shown in Figure 12. The dose rates obtained from approximately 80 full days, at a 1 Hz data rate, between February and August of 2019 are used to map the near-Earth radiation environment. The increased TID rate is binned in 1° latitude × 1° longitude bins and normalized by coverage. The dose rate intensity resulting from passage through the SAA provides a clear image of the spatial boundary and center of the anomaly. The dose rate is also shown to increase at higher latitudes providing a coarse mapping of the auroral regions. The lower resolution is consequence of the
electron energy cutoff of the dosimeter due to the iMESA-R aluminum housing. The precipitating electron flux in the auroral region peaks at energies in the tens of keV (Redmon et al., 2017), well below the 1.5 MeV minimum threshold for the iMESA-R dosimeter; therefore, the dosimeter only registers sparse counts from the high-energy tail of the electron energy distribution.

While the dose measured by the microdosimeter within the iMESA-R does not have the ability to differentiate between electrons and protons, a qualitative comparison with the Relativistic Electron and Proton Telescope integrated little experiment (REPTile) data provides some indication as to the type of particle causing the measured TID (Li et al., 2013). The REPTile instrument is the sole science payload for the Colorado Student Space Weather Experiment which orbits at a highly inclined LEO of 65° with perigee and apogee of 480 km × 780 km, respectively. The detector measures the directional differential flux of electrons ranging between 0.58 and >3.8 MeV and protons ranging between 9 and 40 MeV. For these energies the REPTile data indicate that during periods with no solar energetic particle events, energetic protons are detectable only when the instrument is above the SAA region and not within the auroral regions. Therefore, it can be inferred that the counts detected by the iMESA-R dosimeter in the SAA region are primarily due to protons with a minor contribution from inner belt electrons. The center of the SAA located at 26.9°S and 50.6°W is determined using a Gaussian curve fit to the dose rate measured by the microdosimeter as a function of latitude and longitude. It should be noted that for a given altitude and level of geomagnetic activity, the location

Figure 11. iMESA data product for STPSat-5 as it passes through the auroral regions.

Figure 12. TID rate measurements from the iMESA instrument on-board STPSat-5 between February and August 2019.
of the centroid and size of the SAA will vary significantly as a function of the particle energy band used to map the anomaly (Grigoryan et al., 2005; Jones et al., 2017; Ye et al., 2017). Therefore, future comparisons between the SAA center and drift as determined using the iMESA-R dosimeter data and other instruments should be conducted using similar altitudes and energies.

6. Conclusions
The iMESA-R microdosimeter has been successfully calibrated in a ground-based facility, and initial measurements of TID for the STP-Sat5 instrument are presented. The calibration effort has demonstrated the ability of the microdosimeter to accurately measure dose and subsequent dose rate when compared to the AIC. Additionally, the iMESA-R microdosimeter on-board STP-Sat5 has demonstrated the ability to accurately measure the SAA structure and auroral regions using TID rate due to electrons of $E > 1.5$ MeV and protons of $E > 25$ MeV. The incorporation of dosimetry data from the STP-Sat4-STP-H6, OTB, and GPIM missions will increase the rate and accuracy with which the LEO radiation environment will be mapped. This will allow for the analysis of the SAA structure in terms of spatial variation and intensity on smaller timescales than any previous studies.

Acknowledgments
The authors wish to thank the Air Force Office of Scientific Research and the Defense Threat Reduction Agency (DTRA) for the funding and support that allowed the successful completion of this research project. Additional thanks to Cobham RAD Solutions for their help and expertise in setting up the calibration test study. Data sets for this research are available in this in-text data citation reference (Maldonado & Cress, 2020).

References
Anderson, P. C., Rich, F. J., & Borisov, S. (2018). Mapping the South Atlantic Anomaly continuously over 27 years. *Journal of Atmospheric and Solar-Terrestrial Physics*, 177, 237–246.
Balthazar, R. L., McHarg, M. G., Enloe, C. L., Mueller, B., Barnhart, D. J., Hoefnffer, Z. W., et al. (2015). Methodology of evaluating the science benefit of various satellite/sensor constellation orbital parameters to an assimilative data forecast model. *Radio Science*, 50, 318–326. https://doi.org/10.1002/2014RS005426
Brown, E., & Tuli, J. K. (2013). Nuclear data sheets for $A = 60$. *Nuclear Data Sheets*, 114, 1849–2022.
Casadio, S., & Arino, O. (2011). Monitoring the South Atlantic Anomaly using ATSR instrument series. *Advances in Space Research*, 48, 1056–1066.
Crabtree, C. M., LaBel, K. A., Stassinopoulos, E. G. & Miller, J. T. (1993). Preliminary SEU analysis of the SAMPEX MIL-STD-1778 microdosimeter flight data. Orlando, Proc. SPIE 1953, photons for space environments.
Cucinotta, F. A., Manuel, F. K., Jones, J., Iszard, G., Murrey, J., Djojonegro, B., & Wear, M. (2001). Space radiation and cataracts in astronauts. *Radiation Research*, 150(5), 460–466.
Dachev, T. P., Tomov, B. T., Matviichuk, Y. N., Koleva, R. T., Semkova, J. V., Petrov, V. M., et al. (1999). Solar cycle variations of MIR radiation environment as observed by the LIULIN dosimeter. *Radiation Measurements*, 30(3), 269–274.
Falguère, D., Boscher, D., Numa, T., Duzzellier, S., Bourdais, S., Ecobef, L., et al. (2002). In-flight observations of the radiation environment and its effects on devices in the SAC-C polar orbit. *IEEE Transactions on Nuclear Science*, 49(6), 2782–2787.
Ginet, G. P., Madden, D., Dichter, B. K. & Brautigam, D. H. (2007). Energetic Proton maps for the South Atlantic Anomaly. *Space Research, 4(1)*, 76–80.
Heynderickx, K. A. (1996). Low altitude trapped radiation model using TIROS/NOAA data. In J. F. Lemaire, D. Heynderickx, & D. N. Baker (Eds.), *Low altitude trapped radiation model using TIROS/NOAA data*. Washington: American Geophysical Union.
Johnson, A. S., Golightly, M. J., Weyland, M. D., Lin, T., & Zapp, E. N. (2005). Minimizing space radiation exposure during extra-vehicular activity. *Advances in Space Research*, 36(12), 2524–2529.
Jones, A. D., Kamekal, S. G., Baker, D. N., Klecker, B., Looper, M. D., Mazur, J. E., & Schiller, Q. (2017). SAMPEX observations of the South Atlantic anomaly secular drift during solar cycles 22-24. *Space Weather, 15*, 44–52. https://doi.org/10.1002/2016SW001525
Knoll, G. F. (1999). *Radiation detection and measurement* (3rd ed.). New York: Wiley.
Li, X., Schiller, Q., Blum, L., Califf, S., Zhao, H., Tu, W., et al. (2013). First results from CSSWE CubeSat: Characteristics of relativistic electrons in the near-Earth environment during the October 2012 magnetic storms. *Journal of Geophysical Research: Space Physics*, 118, 6489–6499. https://doi.org/10.1002/2013JA019342
Lindstrom, C. D., Sullivan, J. D., Dichter, B. K., Hansen, F. A., Cassiow, D., & Galica, G. E. (2011). Characterization of Telędyn microdosimeters for space weather applications. San Diego, California, Proc. SPIE 8148, Solar Physics and Space Weather Instrumentation IV. Maldonado, C. & Cress, R. (2020). iMESA dosimeter calibration and initial results. Retrieved from https://osf.io/7hsak/
Mazur, J. E., Crain, W. R., Looper, M. D., Mabry, D. J., Blake, J. B., Case, A. W., et al. (2011). New measurements of total ionizing dose in the lunar environment. *Space Weather, 9*, 507002. https://doi.org/10.1002/2010SW000641
Mazur, J. E., Zeitlin, C., Schwadron, N., Looper, M. D., Townsend, L. W., Blake, J. B., & Spence, H. (2015). Update on radiation dose from galactic and solar protons at the Moon using the LRO/CRASTER microdosimeter. *Space Weather, 13*, 363–364. https://doi.org/10.1002/2015SW001175
McHarg, G., Neal, P., Taormina, N., Strom, A., & Balthazor, R. (2015). USAFA integrated miniaturized electrostatic analyzer (iMESA)—An undergraduate space weather constellation. *Space Weather, 13*, 827–830. https://doi.org/10.1002/2015SW001284

National Institute of Standards and Technology (2019). ESTAR—Stopping power and range tables for electrons. [Online] Available at: https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html [Accessed 23 December 2019].

NOAA space weather prediction center (2019). Solar Cycle Progression. [Online] Available at: https://www.swpc.noaa.gov/products/solar-cycle-progression

Pu, Z. Y., Xie, L., Jiao, W. X., Fu, S. Y., Fang, X. H., Zong, Q. G., & Heynderickx, D. (2005). Drift shell tracing and secular variation of inner zone high energy proton environment in the SSA. *Advances in Space Research, 36*, 1973–1978.

Redmon, R. J., Denig, W. F., Kilcomons, L. M., & Knipp, D. I. (2017). New DMSP database of precipitating auroral electrons and ions. *Journal of Geophysical Research: Space Physics, 122*, 9056–9067. https://doi.org/10.1002/2016JA023339

Schaefer, R. K., Paxton, L. J., Selby, C., Ogorzalek, B., Romeo, G., Wolven, B., & Hsieh, S. Y. (2016). Observation and modeling of the South Atlantic Anomaly in low Earth orbit using photometric instrument data. *Space Weather, 14*, 330–342. https://doi.org/10.1002/2016SW001371

Schwadron, N. A., Baker, T., Blake, B., Case, A. W., Cooper, J. P., Golightly, M., et al. (2012). Lunar radiation environment and space weathering from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER). *Journal of Geophysical Research, 117*, E00H13. https://doi.org/10.1029/2011JE003978

Spence, H. E., Case, A. W., Golightly, M. J., Heine, T., Larsen, B. A., Blake, J. B., et al. (2010). CRaTER: The cosmic ray telescope for the effects of radiation experiment on the lunar reconnaissance orbiter mission. *Space Science Reviews, 150*(1-4), 243–284.

Straume, T., Mertens, C. J., Lushy, T. C., Gersey, B., Tobiska, W. K., Norman, R. B., et al. (2016). Ground-based evaluation of dosimeters for NASA high-altitude balloon flight. *Space Weather, 14*, 1011–1025. https://doi.org/10.1002/2016SW001406

Teledyne Microelectronic Technologies (2016). UDOS001 micro dosimeter datasheet. [Online] Available at: http://www.teledynemicro.com/product/radiation-dosimeter [Accessed 30 November 2019].

Tobiska, W. K., Atwell, W., Beck, P., Benton, E., Copeland, K., Dyer, C., et al. (2015). Advances in atmospheric radiation measurements and modeling needed to improve air safety. *Space Weather, 13*, 202–210. https://doi.org/10.1002/2015SW001169

Underwood, C. I. (1990). In-orbit radiation effects monitoring on the UOSAT satellites. Logan, Utah, Proc. 4th Annual AIAA/USU Conf. On w.

Ye, Y., Zou, H., Zong, Q., Chen, H., Wang, Y., Yu, X., & Shi, W. (2017). The secular variation of the center of geomagnetic South Atlantic Anomaly and its effect on the distribution of inner radiation belt particles. *Space Weather, 15*, 1548–1558. https://doi.org/10.1002/2017SW001687