AFRL-RV-PS-
TR-2016-0120

AFRL-RV-PS-
TR-2016-0120

SPACE PARTICLE HAZARD MEASUREMENT AND MODELING

Adrian Wheelock

01 September 2016

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

DTIC COPY

NOTICE AND SIGNATURE PAGE

AFRL-RV-PS-TR-2016-0129 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNED//	//SIGNED//
Adrian Wheelock Program Manager, AFRL/RVBXR	Dr. Thomas R. Caudill, Acting Chief AFRL Battlespace Environment Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-09-2016

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
01 Oct 2007 – 30 Sep 2015

4. TITLE AND SUBTITLE
Space Particle Hazard Measurement and Modeling

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62601F

6. AUTHOR(S)
Adrian Wheelock

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
PPM00004262

5f. WORK UNIT NUMBER
EF004375

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RV-PS-TR-2016-0129

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBXR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited. (OPS-2016-12552 dtd 27 Sep 2016)

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Space Particle Hazard Measurement and Modeling effort within the Space Particles program at AFRL/RVBX performed substantial research and development in the areas of the AE9/AP9/SPM standard radiation belt model, energetic space particle modeling, spacecraft charging, hypervelocity impacts, and sensors/anomaly attribution. This report provides a summary of the work and a directory to the technical details of the research products.

15. SUBJECT TERMS
AE9/AP9, Radiation Belt, Space Environment, Modeling, Spacecraft Charging, Hypervelocity Impact, Satellite Anomaly Attribution

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Adrian Wheelock
Unclassified	Unclassified	Unclassified	Unlimited	24	19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

This page is intentionally left blank.

Table of Contents

List of Figures

Space Particle Hazard Measurement and Modeling: Final Report

1. Introduction

The Space Particle Hazard Measurement and Modeling work unit consisted of the 6.2 work performed within the Space Particle Hazard Specification and Forecast (Space Particles) program. The Space Particles program focused on measuring, specifying, and predicting the natural energetic particle populations, typically in the Earth's magnetosphere, and the impacts of those particles on spacecraft. In 2014 the Space Particles Program was subsumed into the Space System Survivability program (S3) with elements of other AFRL/RVBX space environment programs. The work unit continued until completion as part of the S3 program.

This report covers activities from 1 October 2007 (the beginning of Federal Fiscal Year 2008) through 30 September 2015. During this time, the program went through many changes. At the beginning of the period, the program was located at Hanscom AFB, MA, but due to the 2005 BRAC round the activity was relocated to Kirtland AFB, NM throughout the course of this work unit, with the transition happening primarily in 2010 and 2011. Additionally, with those disruptions, the program took the opportunity to reassess its approach and developed a much more integrated, focused effort on spacecraft anomalies and spacecraft design. While the technical efforts largely remained the same, the research products became much more focused. Finally, during the course of this work unit, the program has had three program managers. Mr. James Metcalf initiated the work unit at Hanscom AFB. Upon Mr. Metcalf's retirement, Lt Col Gail Weaver took over the program at the beginning of FY12 as the program finished the transition to Kirtland AFB. At Lt Col Weaver's retirement in early FY13, Mr. Adrian Wheelock became Space Particles and later Space System Survivability PM. This reflects the work performed throughout the duration of the work unit.

For the purposes of this report, the activities are broken down into five categories: AE9/AP9/SPM standard radiation belt model, Energetic Space Particle Modeling, Spacecraft Charging, Hypervelocity Impacts, and Sensors and Anomaly Attribution. Each activity is individually summarized year-by-year with one or more key publications from that year listed in that section and a complete list of references as citations.

2. AE9/AP9/SPM Standard Radiation Belt Model

The AE9/AP9/SPM Standard Radiation Belt Model was kicked off in 2007 to update the standard model for the natural trapped radiation environment in satellite design. The previous standards (AP8 and AE8) had not been updated since the 1970s and many new datasets covering a broader sampling of solar cycle climatology were now available. In addition, advanced features supporting statistical confidence intervals were developed to meet the design needs of the national security space community.

2007 – Performed an inversion of proton telescope and dosimeter channel count rates into energy spectra and began applying algorithms to TSX-5, HEO-1 & HEO-3 satellites [1]. Cross-calibrated proton instruments on these satellites with NOAA GOES and NASA SAMPEX satellites as standard instruments, using simultaneous observations of solar proton events. This provided the baseline spectra to be incorporated into the AP-9 standard trapped radiation model.

Key Presentation:

- [1] Presentation on proton inversion methods/results: G. P. Ginet, S. L. Huston, T. B. Guild, T. P. O'Brien, Dec. 2008, "Proton spectra in the inner magnetosphere: Measurements from the TSX-5, HEO-1, HEO-3, and ICO satellites," AGU Fall Meeting, abs. U13A-0039.

2009 – Completed documentation of requirements for AE-9/AP-9 [2], continued work on TSX-5, HEO-1, HEO-3, and ICO data sets. Began work on electron data sets with Combined Release and Radiation Effects Satellite/Medium Electron Sensor (CRRES/MEA) and CRRES/High Energy Electron Fluxmeter (HEEF) serving as calibration standard.

Key Publication:

- [2] Requirements documentation released: G.P. Ginet, T.P. O'Brien, AE-9/AP-9 trapped radiation and plasma models requirements specification, Aerospace Technical Report, TOR-2010(3905)-3, 2010

2010 – Released beta version of Ax9. Continued processing of proton data sets, including spectral inversions. Continued work on electron data: completed processing and cross calibration of CRRES/MEA, CRRES/ HEEF, LANL GEO/SOPA data. During electron data set development, identified relationship of electron energy spectral shapes to spatial location relative to plasmapause [3], with these results applied to spectral inversions of some electron data sets. Worked on developing plasma data sets. Identified and addressed artifacts in beta version flux maps.

Key Presentation:

- [3] Electron spectral study results presented in W. R. Johnston, C. D. Lindstrom, and G. P. Ginet, December 2010, Characterization of radiation belt electron energy spectra from CRRES observations, AGU fall meeting 2010, abstract #SM33C-1925.

2011 – Co-developed and tested principal component inversion algorithm for inverting large sets of dosimeter-type sensor data for inclusion in climatology models. Continued cross-calibrations of energetic particle data from multiple space platforms to devise correction algorithms and contamination removal techniques needed to exploit existing data sets. Processed and intercalibrated electron data from GPS/BDD II, TSX-5, HEO-1, HEO-3, and ICO spacecraft. Processed SCATHA/SC3 electron data, used results to calculate electron decay timescales [4]. Developed method to salvage SAMPEX/PET and POLAR/HISTe data where statistics were impacted by background/saturation. Released reprocessed and cross-calibrated version of CRRES/MEA+HEEF electron data sets on the Virtual Radiation Belt Observatory website [5]. Completed release candidates of flux maps.

Key Publication:

- [4] Results of SCATHA electron decay study published: Y.-J. Su, W. R. Johnston, J. M. Albert, G. P. Ginet, M. J. Starks, and C. J. Roth, 2012, SCATHA measurements of electron decay times at $5<L\leq 8$, *JGR*, 117(A8):A08212.

2012 – Developed advanced inversion algorithms to extend low-energy proton measurement range of CEASE instrument on TacSat-4; identified transient elevation of low-energy protons in slot region and consequent displacement damage impacts [6,7,8]. Completed validation/comparison of model to independent data sets. Released AE9/AP9/SPM v1.00.

Key Presentations:

- [6] C. D. Lindstrom, W. R. Johnston, S. R. Messenger, and S. Huston, July 2012, Enhanced proton levels in slot region and displacement damage effects on TacSat-4, IEEE NSREC conference, abstract #PJ-4L.
- [7] C. D. Lindstrom, S. R. Messenger, S. L. Huston, and W. R. Johnston, December 2012, Enhanced proton levels in slot region and displacement damage effects on solar arrays, AGU fall meeting, 2012, abstract #SM23B-2313.
- [8] W. R. Johnston, C. D. Lindstrom, S. L. Huston, S. L. Young, Dec. 2012, CEASE observations of the radiation belts: Elevated protons in the slot region, AGU fall meeting 2012, abstract #SM23B-2312.

2013 – Moved primary software development portion of project to 6.3 with release of v1.05 [9].

Key Publication:

- [9] G. P. Ginet, et al., "AE9, AP9 and SPM: New models for specifying the trapped energetic particle and space plasma environment," *Space Sci. Rev.*, 179, 579-615 (2013).

2014 – First intercalibration tech reports addressing data set development methods and results [10,11,12]

Key Publications

- [10] W. R. Johnston, 2014, GEO-GEO Cross-Calibration Results for AE9 Development, AFRL-RV-PS-TR-2014-0017, Air Force Research Laboratory, Kirtland AFB, NM, on line at *DTIC* [http://www.dtic.mil/docs/citations/ADA605733]
- [11] W. R. Johnston, C. D. Lindstrom, and G. P. Ginet, 2014, CRRES Medium Electron Sensor A (MEA) and High Energy Electron Fluxmeter (HEEF): Cross-calibrated data set, AFRL-RV-PS-TR-2014-0016, Air Force Research Laboratory, Kirtland AFB, NM, on line at *DTIC* [http://www.dtic.mil/docs/citations/ADA604519]
- [12] Y._J. Su Caton and C. Roth, 2014, SCATHA/SC3 Data Processing and Cross-Calibration with LANL-GEO/CPA for AE9 Development, AFRL-RV-PS-TR-2014-0015, Air Force Research Laboratory, Kirtland AFB, NM, on line at DTIC [http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA604523]

3. Energetic Space Particle Modeling

Modeling the highly variable energetic particle environment has long been the core of the 6.2 program. These efforts to understand the interactions of the physical processes driving, then specify and ultimately predict the state of the energetic particle populations within the magnetosphere are key to understanding sensor information and translating measurements from the measurement location to a different location of interest. The energetic space particle modeling efforts garnered substantial AFOSR and NASA support over the course of the program, augmenting the core 6.2

investment. Many efforts also supported evaluation of models utilized by the Space Weather Analysis and Forecast System (SWAFS) program that currently resides within SMC/RSS.

2007 – Began work on developing a quasi-linear diffusion coefficient description of wave-particle interactions.
2008 – A description of quasi-linear diffusion by broad-band waves in terms of single-wave interactions was used to develop efficient approximations of the full diffusion coefficients [13]. Study of mechanism for loss of transient energetic proton populations important for understanding and modeling the long term stability of these hazards after injection [14].

Key Publication:

- [13] Albert, J. M. (2008), Efficient Approximations of Quasilinear Diffusion Coefficients in the Radiation Belts, J. Geophys. Res., 113, A06208, doi:10.1029/2007JA012936.

2009 – Studied nonlinear interaction of relativistic electrons with EMIC waves. First 3-D simulation of electron diffusion during a magnetic storm, driven by and validated against satellite measurements [15]. The effects of cross diffusion, in addition to pitch angle and energy diffusion, were described [16]. A useful approximation of the resulting precipitation lifetime was developed [17] and exact lifetimes were calculated for realistic wave models [18].

Key Publication:

- [15] Albert, J. M., N. P. Meredith, and R. B. Horne (2009), Three-dimensional Diffusion Simulation of Outer Radiation Belt Electrons During the 9 October 1990 Magnetic Storm, J. Geophys. Res., 114, A09214, doi:10.1029/2009JA014336.

2010 – The single-wave interaction model of quasi-linear diffusion developed in 2008 was shown to be formally exact [19]. Established detailed relationship between diffusion by broadband wave turbulence and diffusion by coherent small amplitude waves. Examined the role of off-equatorial effects in EMIC wave generation [20].

Key Publication:

- [20] McCollough, J. P., S. R. Elkington, and D. N. Baker, The role of Shabansky orbits in compressional EMIC wave generation, *J. Geophys. Res.*, *117*, A01208, doi:10.1029/2011JA016948, 2012.

2011 – Evaluated wave propagation from transmitters in space. Improved computation of wave-particle resonances for narrowband whistler mode waves [21]. Explored nonlinear interaction effects due to large amplitude waves. Developed graphical sensitivity analysis technique for understanding broadband waves in the plasmasphere. Performed inverse analysis of wave scattering power based on satellite observations of loss-cone energetic electrons [22].   Studied Shabansky effects for VLF Chorus wave generation [23].

Key Publication:

- [22] Selesnick, R.S., J.M. Albert, M.J. Starks, Influence of a ground-based VLF radio transmitter on the inner electron radiation belt, *J. Geophys. Res.*, *118*, doi:10.1002/jgra.50095, 2013.

2012 – Continued to refine transport models of nonlinear wave-particle interactions in radiation belts. Single-wave interaction model for broad-band waves causing quasi-linear diffusion was used to characterize effects on particles over a wide range of parameter space [24]. Found that observed high intensity levels of quasi-trapped, low-altitude electrons are caused by non-diffusive, wide-angle scattering of radiation belt electrons in the upper atmosphere. Showed that inward diffusion of trapped electrons can replenish scattering losses [25]. Validated electron flux models and rules-of-thumb regarding spacecraft charging for AFWA [26,27,28].

Key Publications:

- [25] Selesnick, R. S. (2012), Atmospheric scattering and decay of inner radiation belt electrons J. Geophys. Res., 117, A08218, doi:10.1029/2012JA017793.

2013 –Found that the observed rate of increase in radiation belt proton intensity following a storm-time depletion is consistent with the source strength expected from cosmic ray albedo neutron decay, providing direct evidence that this process is a principal source of radiation belt protons [29]. Validated Geomagnetic Index models for AFWA [30,31,32]. Provided Kp Predictor model output to NOAA/NASA for Geospace model validation and transition [33].

Key Publication:

- [29] Selesnick, R. S., M. K. Hudson, and B. T. Kress (2013), Direct observation of the CRAND proton radiation belt source, J. Geophys. Res. Space Physics, 118, doi:10.1002/2013JA019338.

2014 –Continued development of nonlinear wave-particle interactions in the radiation belts. Effects specific to highly oblique waves were investigated with numerous collaborators [34]. Additional single-wave interaction simulations were used to further characterize the effects on particles, extending the parameter space explored [35]. Described a new method of radiation belt proton data anlaysis that provides strong background rejection. The method was applied to data obtained by the Relativistic Electron-Proton Telescopes (REPT) on the Van Allen Probes satellites, providing new high-resolution energy spectra and pitch angle distributions [36].

Key Publication:

- [34] Li, W., D. Mourenas, A. Artemyev, O. Agapitov, J. Bortnik, J. Albert, R. M. Thorne, B. Ni, C. A. Kletzing, W. S. Kurth, and G. B. Hospodarsky (2014), Evidence of Stronger Pitch Angle Scattering Loss Caused by Oblique Whistler-mode Waves as Compared With Quasi-parallel Waves, Geophys. Res. Lett., 41, 6063, doi:10.1002/2014GL061260.

2015 – Continued development of nonlinear wave-particle interaction models in the radiation belts. Evaluated impact of coulomb collisions on inner belt dynamics through a Monte Carlo model. Computed theoretical electron energy spectra that should result from albedo neutron decay. Showed by Lorentz transformation from the neutron rest frame that the high-energy component has a nearly power-law spectral shape, but with predicted intensity levels below the capabilities of current instrumentation [37]. Van Allen Probe data continued to be evaluated to remove contamination and compared to models. Evaluated the entire 1992-2009 database of electron measurements from the Proton-Electron Telescope on the SAMPEX satellite for the presence of inner radiation belt electrons with kinetic energy above 1 MeV. Found that previous reports had misinterpreted signatures of lower energy electrons, but that a data subset restricted to less-stable regions indicate the presence of trapped electrons up to 1.6 MeV [38]. Evaluated geomagnetic cutoff models for solar proton impacts to energetic particle populations within the magnetosphere for potential transition to decision aids [39,40,41]. Developed algorithm to specify energetic particle flux from multiple spacecraft [42].

Started project to evaluate outer zone electron models to determine what advances need to be made in the current state-of-the-art to support operational space environment specification and forecast for anomaly attribution.

Key Publication:

- [42] Su, Y.-J., J. M. Quinn, W. R. Johnston, J. P. McCollough, and M. J. Starks, Specification of > 2 MeV electron flux as a function of local time and geomagnetic activity at geosynchronous orbit, *Space Weather, 12*, 470–486, doi:10.1002/2014SW001069, 2014

4. Spacecraft Charging

A complex field requiring deep understanding of plasmas, materials, and detailed knowledge of satellite component design, spacecraft charging has been a challenging source of spacecraft anomalies for decades. While most charging concerns have been successfully mitigated through development of design standards over the past few years, as new technologies, materials, and missions are flown, new charging hazards can appear unexpectedly. The Space Particles program maintained a robust laboratory and theoretical research effort comprising both 6.2 (described below) and 6.3 elements. As a founding sponsor of the Spacecraft Charging Technology Conference, the program supports strong participation in these conference events approximately every two years with many program members supporting conference organization. In 2010, the program was the lead technical organization supporting the conference when it was held in Albuquerque, NM.

2008 – Evaluated impacts of secondary and backscattered electrons as well as photoelectrons on critical temperature theory of charging [43].

Key Publication:

- [43] Shu Lai. "Critical Temperature for the Onset of Spacecraft Charging: The Full Story", 39th Plasmadynamics and Lasers Conference, Fluid Dynamics and Co-located Conferences, Seattle, WA, 2008 http://dx.doi.org/10.2514/6.2008-3782

2009 – Evaluated relationship of electron temperature and flux with respect to charging onset [44]. Performed initial tests of braided wire passive discharge technologies [45].
Key Publication:

- [44] Lai, S.T. and Tautz, M., On the anticritical temperature for spacecraft charging, *J. Geophys Res.: Space Physics*, 113, 2156-2202, doi: 10.1029/2008JA013161

2010 – Tested basic concepts for automatic passive discharge technologies for mitigating spacecraft charging with mixed results, both chip-based and braided wire and fiberglass [46]. Modeled effects of coverglass and solar cell geometry on solar array and spacecraft charging [47]. Investigated impacts of surface conditions on charging [48]. Performed analysis of rapid charging events on the International Space Station [49,50]. Supported international efforts to develop an international charging test standard [51].

Key Publication:

- [51] Teppei Okumura, Mengu Cho, Virginie Inguimbert, Denis Payan, Boris Vayner, and Dale C. Ferguson. "International Round-Robin Tests on Solar Cell Degradation Due to

Electrostatic Discharge", Journal of Spacecraft and Rockets, Vol. 47, No. 3 (2010), pp. 533-541.

2011 – Analyzed effects of terrestrial weather on rapid charging events on LEO space platforms when emerging from eclipse to support an international collaborative experiment [52]. Modeled effects of coverglass secondary electron emission on solar array and spacecraft charging [53]. Released with collaborators from Japan and France through the International Standards Organization ISO Standard 11221 with standard solar array charging test criteria [54]. Performed modeling of the Galaxy 15 spacecraft to evaluate potential charging causes for the anomaly causing it to become the "zombie sat" [55]. Shipped and installed >$5M in laboratory facilities from Hanscom AFB, MA to Kirtland AFB, NM as part of the BRAC. Installed the Mumbo calibration chamber and developed next generation calibration control system. Conducted tests of a plasma probe in collaboration with New Mexico Institute of Mining & Technology for a spacecraft launch in 2012.

Key Publication:

- [54] ISO Standard 11221 Space Systems – Space Solar Panels – Spacecraft Charging Induced - Electrostatic Discharge Test Methods, 2011.

2012 – Achieved initial laboratory capability at KAFB [56,57], initiated round-robin test with other national laboratories to investigate "flashover" effect on solar cell electrostatic discharge [58,59]. Began first measurements of charging properties of spacecraft materials with respect to temperature. Investigated the role of potential barriers in spacecraft charging [60]. Evaluated on-orbit arcing experiment in collaboration with international partners [61]. Performed simulations evaluating index conditions to support a spacecraft charging hazard [62] and surface material properties [63]. Enhanced laboratory vacuum facilities to include ions and photons enabling a more complete simulation of the space environment. Designed and executed an experiment to measure the radiation induced conductivity of a James Webb Space Telescope mirror material in collaboration with Utah State University and NASA [64].

Key Publication:

- [62] D.C. Ferguson and S.C. Wimberly, "The Best GEO Daytime Spacecraft Charging Index," 2013, 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine, TX, Jan. 7-10.

2013 – Modeled AEHF spacecraft charging, assisting resolving spacecraft anomalies. Initiated work to define an index for differential surface charging hazard. Performed initial assessment of charging effects on space debris orbital parameters (High Area to Mass Ratio (HAMR) objects) [65]. Examined the possibility of detecting arcs from spacecraft discharges from ground-based optical and radiofrequency sensors [66]. Installed thermal unit in test chamber for thermal testing of spacecraft components. Released ANSI/AIAA Standard S-115 for LEO charging design standard [67]. Published initial results in journals from U.S. Round-Robin plasma expansion tests [68,69] and surface material property experiment [70]. Built high plasma density, high magnetic field vacuum chamber for the investigation of plasma wave propagation. Performed simulation of positive probes in strongly magnetized plasma [71]. Completed charge testing on 3 solar panel cover glass replacement candidates developed by the Advanced Space Power program in AFRL/RVS.

Completed a CRADA with Assurance Technology Corporation for use of the Mumbo calibration facility to support the MPS-LO sensor which would fly on the GOES-R satellite.

Key Publication:

- [66] D.C. Ferguson et al., "On the Feasibility of Detecting Spacecraft Charging and Arcing by Remote Sensing," 2013, 5th AIAA Atmospheric and Space Environments Conference, San Diego, CA, June 24-27.

2014 – Defined a candidate index based on particle flux for differential surface charging through extensive modeling and simulation [72,73]. Performed laboratory testing of solar array discharges to determine discharge speed and energy coupling into the arc [74,75]. Conducted spacecraft charging qualification tests on new solar array designs, heat shield materials, and meta materials for NASA, AFRL/RVS, and AFRL/RVE respectively [76]. Performed analysis of spacecraft charging effects of solar array coverglass degradation in severe charging environments [77,78]. Posited solar array contamination from arcing as cause of excess GPS power degradation [79], and the potential for remote observation to confirm this arcing [80]. Developed method for determining energy and charge deposition profiles from isotropically incident electrons for use in spacecraft charging transport codes. Established collaborations with the Satellite Assessment Center at AFRL/RD to transition simulated space-aged material properties into databases supporting operational observations. Completed calibration of an MPS-LO sensor in support of the CRADA with ATC. Negotiated Educational Partnership Agreement with Utah State University to coordinate activities in the areas of spacecraft charging and space environment effects on materials.

Key Publication:

- [72] D.C. Ferguson, R. V. Hilmer, A. T. Wheelock and V. A. Davis, "The Best GEO Daytime Spacecraft Charging Index – Part II," 2014, 52nd AIAA Aerospace Sciences Meeting, National Harbor, MD, Jan. 13-17.

2015 – Continued laboratory testing of solar array discharge voltage thresholds and evaluation of data. Evaluated Roll-Out Solar Array (ROSA) and other photovoltaic technologies in support of AFRL/RVS [81]. Aged polyimide films in simulated space radiation, tested charging properties, and provided to RVS for optical characterization. Developed and performed initial validation of algorithm for deposition of charged particles into dielectric slabs from isotropic sources [82]. Detected RF emission from arcing on GPS satellites using the Arecibo 305m radiotelescope and correlated with on-board sensors. Analyzed sustained arcing events of 1997-2002 and identified new eclipse-related arcing mechanism [83,84]. Transitioned two new materials into MATTER.DAT user database for optical characteristics. Acquired and developed vacuum chamber for long-term charge storage measurements. Evaluated trigger arc thresholds under LEO conditions [85]. Increased electron and ion capabilities in the Mumbo calibration chamber [86] supporting the calibration of a second MPS-LO sensor as part of the CRADA with ATC in addition to in-house sensor development. The MPS-LO sensor will be an operational space environment sensor on the GOES-R spacecraft. Results from prior years were published as peer-reviewed papers for charging index [87] and round-robin/plasma propagation [88,89] activities.

Key Publication:

- [87] D.C. Ferguson, Robert V. Hilmer, and Victoria A. Davis, “The Best Geosynchronous Earth Orbit Daytime Spacecraft Charging Index,” 2015, Journal of Spacecraft and Rockets, Vol. 52, No. 2 (2015), pp. 526-543

5. Hypervelocity Impacts

Energetic particles in the space environment are not limited to electrons, protons, and assorted heavier ions. There are micrometeorites and orbital debris as well, and their velocities and size make them significant hazards. Understanding the signatures of impacts could provide a mechanism for distinguishing natural causes from hostile acts. Current micrometeor impact detectors rely on measuring impacts to specific sensors, which by definition are not going to cause an anomaly to your spacecraft. Detection of impacts on the spacecraft generally would allow much stronger attribution of impacts. Micrometeorites are travelling with such velocity that the projectile vaporizes, creating a plasma. The charged particles within the plasma were theorized to emit a distinctive radiofrequency signature.

2010 **–** Completed a series of hypervelocity impacts to determine if a distinct RF signature could be discerned from micrometeorite impact. The addition of a low-grade vacuum chamber to the experiment resulted in complete suppression of previously-observed impact signatures in the HF and L bands. The conclusion was that these signals resulted from discharge of the projectile to the target in the moments preceding impact.

2011 **–** Continued developing processing techniques for detection of RF signature from hypervelocity impacts. Utilized improved testing apparatus extending diagnostics into the X, K and Ka bands (Figure 1 through Figure 3). No indications of RF emissions were observed. The project was therefore concluded. Figures below: impact at the red line. Spikes much later are from secondary debris impacts that are not part of the experiment [90].

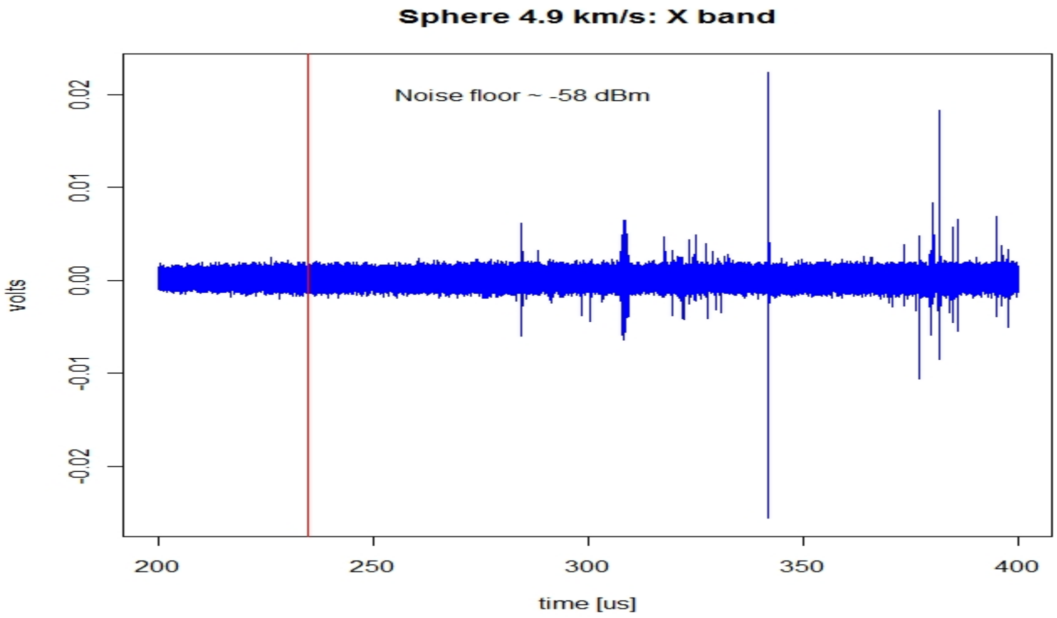

Figure 1: Hypervelocity impact X band emissions

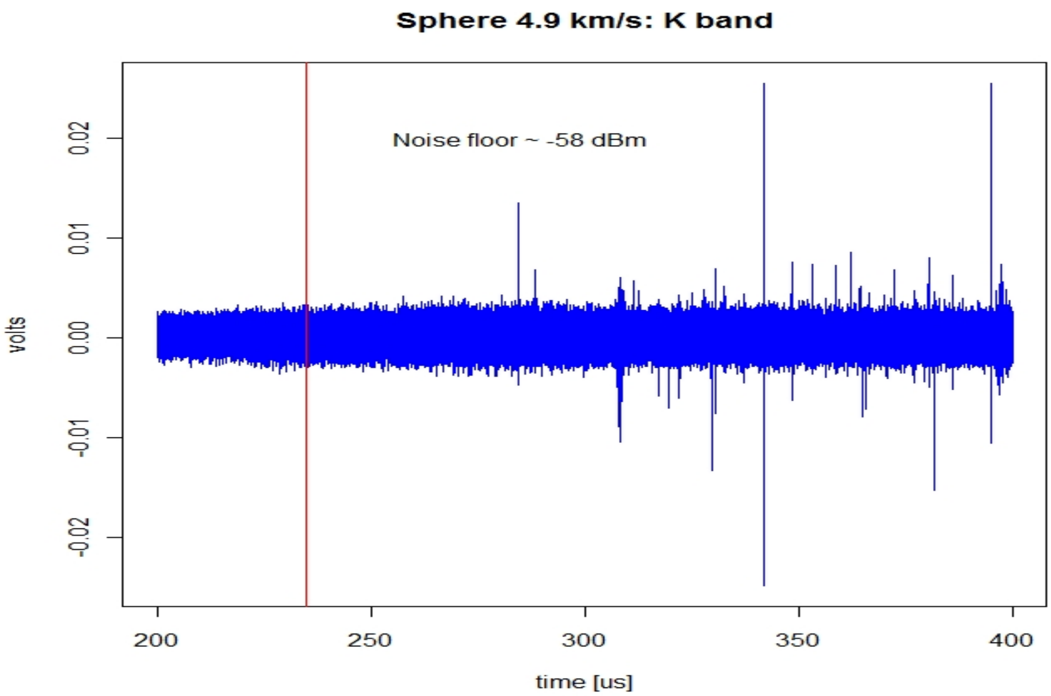

Figure 2: Hypervelocity impact K band emissions

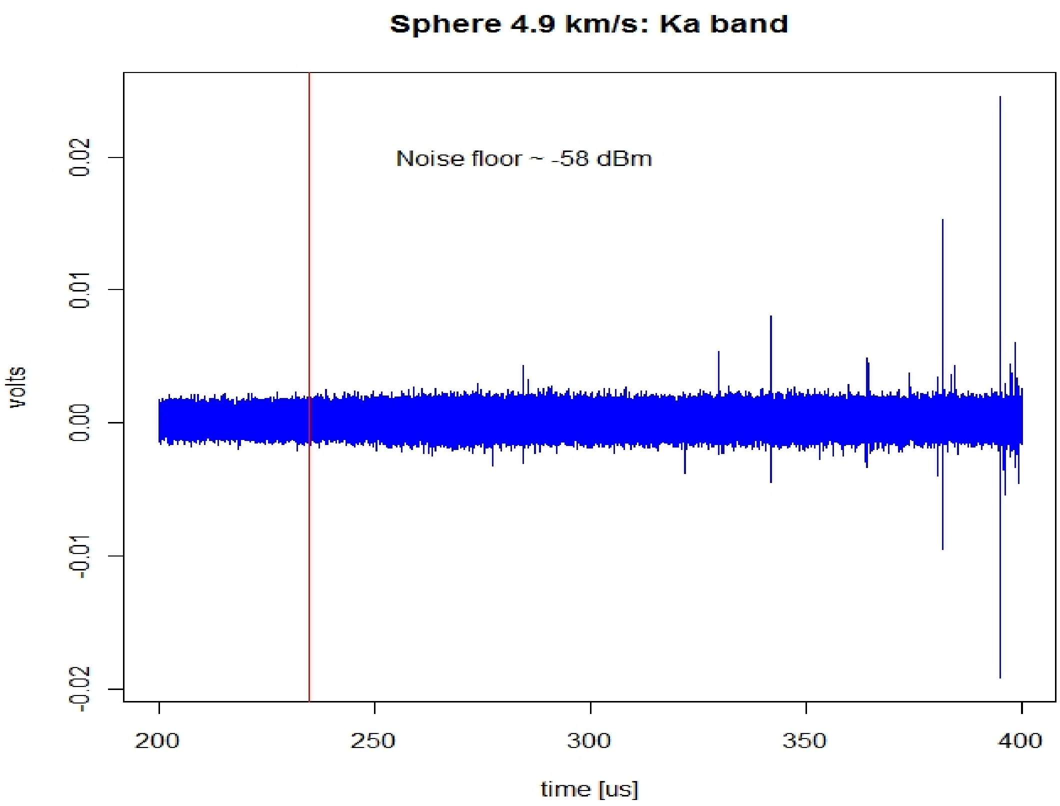

Figure 3: Hypervelocity impact Ka band emissions

6. Sensors/Anomaly Attribution

Throughout its history, the Space Particles program has supported anomaly analyses when requested by spacecraft operators. However, in 2012, the program became aware of research performed at The Aerospace Corporation on computing the relative hazard presented by the environment. In conjunction with the Space Weather Forecast Laboratory program (and later fully incorporated into the S3 program), a new effort to better characterize spacecraft environmental anomalies and produce a useful decision aid was launched. While many aspects of the project were and are 6.3, the 6.2 work involved understanding what requirements would be levied on sensors supporting an architecture supporting actionable environmental SSA, how the data would flow, what the architecture would look like, and perhaps most importantly, what information the users require from any decision aid.

2012 – Modeled C/NOFS and DMSP spacecraft charging, assisting in resolving spacecraft anomalies [63]. Used Nascap-2K to model the wake of the C/NOFS low altitude satellite showing that the wake was not the source of anomalous offsets in the electric field sensing experiment and attributed the anomalies to environment induced changes on Torlon insulators.

2013 – Procured broad-spectrum electron radiation source and built up experimental chamber and apparatus to test space particle detectors and perform material aging studies. Performed study to determine number of space environment sensors required to adequately predict space anomaly hazards for GEO spacecraft. Investigated the possibility of detecting charging and arcing on-orbit by remote sensing [66].

2014 – Provided initial testing of energetic space particle detector concepts with radiation test source. Analyzed spacecraft anomaly data on systems where it has been made available, demonstrating actual environmental susceptibility and performing first attribution of one reported anomaly class. Performed analysis of space environment hazard algorithms utilizing multiple data sources; worked to resolve differences between sensor types and discrepancies in data handling. Leveraged multi-decade environmental data set to understand the applicability of remote observations to environmental anomaly attribution on spacecraft. Anomaly information from actual systems was used as an initial diagnostic. The results indicate reasonably good performance at GEO, producing images such as Figure 4, indicating that anomalies (red) are consistently associated with high levels of the natural environment (blue).

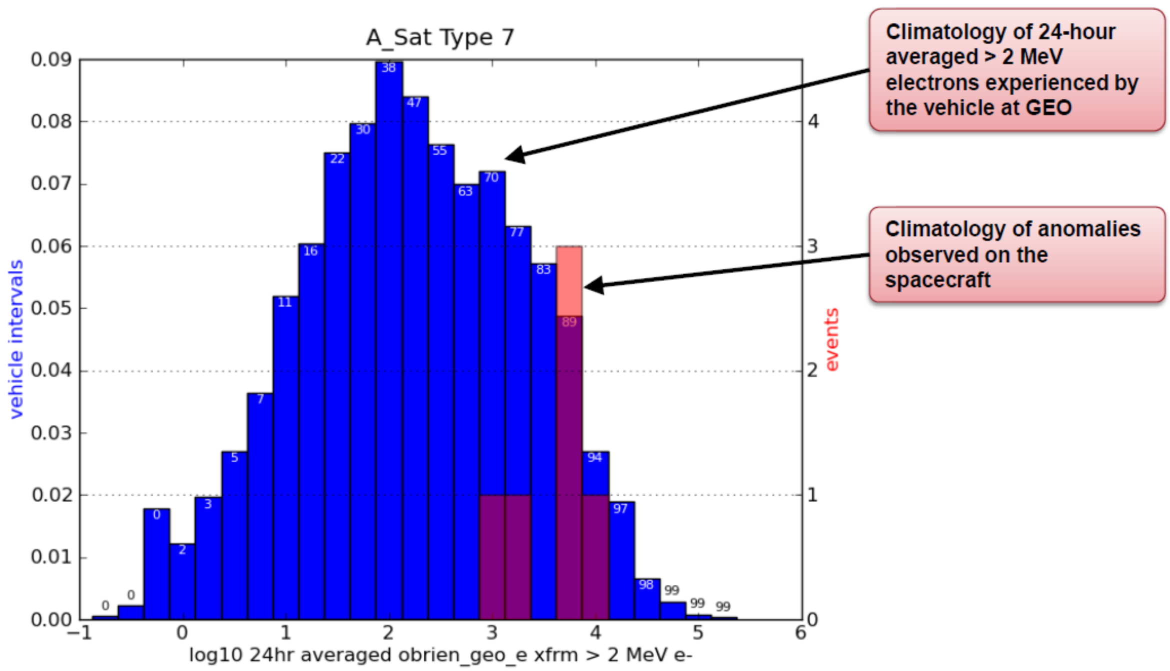

Figure 4: Anomaly event versus driver climatology

Described a new probabilistic analysis method for evaluating the performance of charged particle telescopes, often used in space applications, and for optimal estimation from real data of particle arrival directions and energies [91].

Key Publication:

- [91] Selesnick, R. S. (2014), Optimal performance of charged particle telescopes in space, Nucl. Instrum. Methods Phys. Res., Sect. A, 761, 34-38, doi:10.1016/j.nima.2014.05.109.

2015 – Continued evaluation of additional spacecraft anomaly data. Supported evaluation of methods to use USNDS data to support SSA. Supported DSX science meeting to support integration of sensor data into operations plans.

References

[1] Ginet, G. P., et al., Proton spectra in the inner magnetosphere: Measurements from the TSX-5, HEO-1, HEO-3, and ICO satellites, AGU Fall Meeting, San Francisco, CA, abstract #U13A-0039, Dec 2008.
[2] Ginet, G. P. and T.P. O'Brien, AE-9/AP-9 trapped radiation and plasma models requirements specification, TOR-2010(3905)-3, The Aerospace Corporation, El Segundo, CA, 2010.
[3] Johnston, W. R., C. D. Lindstrom, and G. P. Ginet, Characterization of radiation belt electron energy spectra from CRRES observations, AGU Fall Meeting 2010, San Francisco, CA, abstract #SM33C-1925, Dec 2010.
[4] Su, Y.-J., et al., SCATHA measurements of electron decay times at $5<L\leq8$, *JGR*, 117(A8):A08212, 2012.
[5] Virtual Radiation Belt Observatory, http://virbo.org, referenced 3 Sep 2016.
[6] Lindstrom, C. D., et al., Enhanced proton levels in slot region and displacement damage effects on TacSat-4, IEEE NSREC Conference, Miami, FL, abstract #PJ-4L, Jul 2012.
[7] Lindstrom, C. D., et al., Enhanced proton levels in slot region and displacement damage effects on solar arrays, AGU fall meeting, 2012, San Francisco, CA, abstract #SM23B-2313, Dec 2012.
[8] Johnston, W. R., et al., CEASE observations of the radiation belts: Elevated protons in the slot region, AGU Fall Meeting 2012, San Francisco, CA, abstract #SM23B-2312, Dec 2012.
[9] Ginet, G. P., et al., AE9, AP9 and SPM: New models for specifying the trapped energetic particle and space plasma environment, Space Sci. Rev., 179, pp. 579-615, 2013.
[10] Johnston, W. R., GEO-GEO Cross-Calibration Results for AE9 Development, AFRL-RV-PS-TR-2014-0017, Air Force Research Laboratory, Kirtland AFB, NM, on line at DTIC [http://www.dtic.mil/docs/citations/ADA605733], 2014.
[11] Johnston, W. R., C. D. Lindstrom, and G. P. Ginet, CRRES Medium Electron Sensor A (MEA) and High Energy Electron Fluxmeter (HEEF): Cross-calibrated data set, AFRL-RV-PS-TR-2014-0016, Air Force Research Laboratory, Kirtland AFB, NM, on line at DTIC [http://www.dtic.mil/docs/citations/ADA604519], 2014.
[12] Su Caton, Y.-J. and C. Roth, SCATHA/SC3 Data Processing and Cross-Calibration with LANL-GEO/CPA for AE9 Development, AFRL-RV-PS-TR-2014-0015, Air Force Research Laboratory, Kirtland AFB, NM, on line at DTIC [http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA604523], 2014.
[13] Albert, J. M., Efficient Approximations of Quasilinear Diffusion Coefficients in the Radiation Belts, J. Geophys. Res., 113, A06208, doi:10.1029/2007JA012936, 2008.
[14] Young, S. L., et al., Magnetic field line curvature induced pitch angle diffusion in the inner magnetosphere, J. Geophys. Res., 113, A03210, doi:10.1029/2006JA012133, 2008.
[15] Albert, J. M., N. P. Meredith, and R. B. Horne, Three-dimensional Diffusion Simulation of Outer Radiation Belt Electrons During the 9 October 1990 Magnetic Storm, J. Geophys. Res., 114, A09214, doi:10.1029/2009JA014336, 2009.
[16] Albert, J. M., The Coupling of Pitch Angle and Energy Diffusion, J. Atmos. Sol.-Terr. Phys., 71, 1664, doi:10.1016/j.jastp.2008.11.014, 2009.
[17] Albert, J. M. and Y. Y. Shprits, Estimates of Lifetimes Against Pitch Angle Diffusion, J. Atmos. Solar-Terr. Phys., 71, 1647, doi:10.1016/j.jastp.2008.07.004, 2009.
[18] Meredith, N. P., et al., Relativistic Electron Loss Timescales in the Slot Region, J. Geophys. Res., 114, A03222, doi:10.1029/2008JA013889, 2009.
[19] Albert, J. M., Diffusion by One Wave and by Many Waves, J. Geophys. Res., 115, A00F05, doi:10.1029/2009JA014732, 2010.

[20] McCollough, J. P., S. R. Elkington, and D. N. Baker, The role of Shabansky orbits in compressional EMIC wave generation, J. Geophys. Res., 117, A01208, doi:10.1029/2011JA016948, 2012.
[21] Albert, J. M., The Whistler Mode Refractive Index as a Function of Gyrofrequency, Physics of Plasmas 18, 084503, doi:10.1063/1.3622653, 2011.
[22] Selesnick, R.S., J.M. Albert, and M.J. Starks, Influence of a ground-based VLF radio transmitter on the inner electron radiation belt, J. Geophys. Res., 118, doi:10.1002/jgra.50095, 2013.
[23] McCollough, J. P., et al., Shabansky Orbits and High Latitude Chorus, Invited Presentation at the Inner Magnetosphere Conference II, Los Angeles, CA, 19-23 Mar 2012.
[24] Albert, J. M., Dependence of Quasilinear Diffusion Coefficients on Wave Parameters, J. Geophys. Res., 117, A09224, doi:10.1029/2012JA017718, 2012.
[25] Selesnick, R. S., Atmospheric scattering and decay of inner radiation belt electrons, J. Geophys. Res., 117, A08218, doi:10.1029/2012JA017793, 2012.
[26] Perry, K. L., J. P. McCollough, and S. L. Young, Validation of AFWA Electron Forecasting Rules of Thumb, AFRL-RV-PS-TP-2012-0001, Air Force Research Laboratory, Kirtland AFB, NM, 2012.
[27] McCollough, J. P. and S. L. Young, Real-Time Validation of the REP Model, AFRL-RV-PS-TR-2013-0195, Air Force Research Laboratory, Kirtland AFB, NM, 2013.
[28] Young, S. L. and J. P. McCollough, Validation of the RBE Model, AFRL-RV-PS-TR-2014-0193, Air Force Research Laboratory, Kirtland AFB, NM, 2014.
[29] Selesnick, R. S., M. K. Hudson, and B. T. Kress, Direct observation of the CRAND proton radiation belt source, J. Geophys. Res. Space Physics, 118, doi:10.1002/2013JA019338, 2013.
[30] McCollough, J. P. and S. L. Young, Real-Time Validation of the Kp Analysis Model, AFRL-RV-PS-TR-2014-0019, Air Force Research Laboratory, Kirtland AFB, NM, 2014.
[31] McCollough, J. P., S. L. Young, and W. R. Frey, Real-Time Validation of the Kp Predictor Model, AFRL-RV-PS-TR-2014-0117, Air Force Research Laboratory, Kirtland AFB, NM, 2014.
[32] McCollough, J. P., S. L. Young, E. J. Rigler, and H. A. Simpson, Real-Time Validation of the Dst Predictor Model, AFRL-RV-PS-TR-2015-0073, Air Force Research Laboratory, Kirtland AFB, NM, 2015.
[33] Glocer, A., et al., Community-wide validation of geospace model local K-index predictions to support model transition to operations, Space Weather, 14, pp. 469-480, doi:10.1002/2016SW001387, 2016.
[34] Li, W., et al., Evidence of Stronger Pitch Angle Scattering Loss Caused by Oblique Whistler-mode Waves as Compared With Quasi-parallel Waves, Geophys. Res. Lett., 41, 6063, doi:10.1002/2014GL061260, 2014.
[35] Ripoll, J.-F., J. M. Albert, and G. Cunningham, Electron Lifetimes From Narrowband Wave-particle Interactions Within the Plasmasphere, J. Geophys. Res., 119, doi:10.1002/2014JA020217, 2014.
[36] Selesnick, R. S., et al., Observations of the inner radiation belt: CRAND and trapped solar protons, J. Geophys. Res. Space Physics, 119, doi:10.1002/2014JA020188, 2014.
[37] Selesnick, R. S., High-energy radiation belt electrons from CRAND, J. Geophys. Res. Space Physics, 120, doi:10.1002/2014JA020963, 2015.
[38] Selesnick, R. S., Measurement of inner radiation belt electrons with kinetic energy above 1 MeV, J. Geophys. Res. Space Physics, 120, pp. 8339-8349, doi:10.1002/2015JA021387, 2015.
[39] Young, S. L., et al., A Space Weather Utility Study of POES Environmental Observations – Mapping to higher altitudes, DTIC publication in progress, Submitted to SMC/SWAFS, 2016.
[40] Young, S. L., et al., A Space Weather Utility Study of POES Environmental Observations – Polar Cap Absorption, Submitted to SMC/SWAFS, 2016.

[41] Young, S. L., et al., Comparison of Solar Energetic Particle Flux Mapping Models, https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/60486, 2015.
[42] Su, Y.-J., et al., Specification of > 2 MeV electron flux as a function of local time and geomagnetic activity at geosynchronous orbit, Space Weather, 12, pp. 470-486, doi:10.1002/2014SW001069, 2014.
[43] Shu Lai., Critical Temperature for the Onset of Spacecraft Charging: The Full Story, 39th Plasmadynamics and Lasers Conference, Fluid Dynamics and Co-located Conferences, Seattle, WA, http://dx.doi.org/10.2514/6.2008-3782, 2008.
[44] Lai, S.T. and M. Tautz, On the anticritical temperature for spacecraft charging, J. Geophys Res.: Space Physics, 113, pp. 2156-2202, doi: 10.1029/2008JA013161.
[45]Wheelock, A., D. L. Cooke, and M. Knoll, Plasma Testing of IProSEC Cathode Devices, AIAA 2009-6735, AIAA SPACE 2009 Conference & Exposition, Pasadena, California, 14-17 Sep 2009.
[46] Wheelock, A.T., Cooke, D.L, and Geis, M. Ion Proportional Surface emission Cathode Development: Electron Emission for Electrodynamic Tether Applications, 11th Spacecraft Charging Technology Conference, Albuquerque, NM, 20-24 Sep 2010.
[47] D.C. Ferguson, Space Solar Cell Edge, Interconnect, and Coverglass Designs and Their Effect On Spacecraft Charging And Plasma Interactions, IEEE Photovoltaic Specialists Conference, Honolulu, HI, 21-25 Jun 2010.
[48] Shu T. Lai., Importance of Surface Conditions for Spacecraft Charging, Journal of Spacecraft and Rockets, Vol. 47, No. 4, pp. 634-638, 2010.
[49] Ferguson, D.C., Paul Craven and Joseph Minow, The Effects of Eclipse-Exit Weather and Magnetic Latitude on ISS Rapid-Charging Events, 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, AIAA-2010-332, 4-7 Jan 2010.
[50] Ferguson, D.C., Detailed Analysis of a Complex ISS Rapid Charging Event, 2nd AIAA Atmospheric and Space Environments Conference, Toronto, Ontario, Canada, 2-5 Aug 2010.
[51] Okumura, T., et al., International Round-Robin Tests on Solar Cell Degradation Due to Electrostatic Discharge, Journal of Spacecraft and Rockets, Vol. 47, No. 3, pp. 533-541, 2010.
[52] Okumura, T., et al., On-Orbit ESD Experiment on Solar Cell Performance: Experiment Overview, 9th European Space Power Conference, Saint Raphael, France, 5-10 Jun 2011.
[53] Ferguson, D.C., Secondary Electron Emission from Solar Cell Coverslides and Its Effect on Absolute Vehicle Charging, 9th European Space Power Conference, Saint Raphael, France, 5-10 Jun 2011.
[54] ISO Standard 11221 Space Systems – Space Solar Panels – Spacecraft Charging Induced - Electrostatic Discharge Test Methods, 2011.
[55] Ferguson, D.C., William F. Denig, and Juan V. Rodriguez, Plasma Conditions During the Galaxy 15 Anomaly and the Possibility of ESD from Subsurface Charging, 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, AIAA 2011-1061, 4-7 Jan 2011.
[56] Hoffmann, R., et al., The Spacecraft Charging and Instrument Calibration Laboratory: A New Frontier in American Spacecraft Charging R&D, In 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, p. 716, Nashville, TN, 9-12 Jan 2012.
[57] Hoffmann, R., et al., The AFRL Spacecraft Charging and Instrument Calibration Laboratory, 12th Spacecraft Charging Technology Conference, Kitakyushu, Japan, 4-9 Apr 2012.
[58] Ferguson, D.C., et al., First Preliminary Results from U.S. Round-Robin Tests, 12th Spacecraft Charging Technology Conference, Kitakyushu, Japan, 14-18 May 2012.

[59] Ferguson, D.C., et al., Further Results from the U.S. Round-Robin Experiment on Plasma Expansion Speed, 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine, TX, 7-10 Jan 2013.
[60] Ferguson D.C. and H. Brandhorst, The Role of Electrical Potential Barriers in LEO Spacecraft Charging, 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, AIAA-2012-717, 9-12 Jan 2012.
[61] Ferguson, D. C. et al., Cumulative Effects of Primary Arc Electrostatic Discharges on Solar Cell Performance: Initial On-Orbit Results, 12th Spacecraft Charging Technology Conference, Kitakyushu, Japan, 14-18 May 2012.
[62] Ferguson, D.C. and S.C. Wimberly, The Best GEO Daytime Spacecraft Charging Index, 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine, TX, 7-10 Jan 2013.
[63] Ferguson, D.C. et al., Ram/Wake and Oxide Layer Effects on DC Electric Field Measurements in LEO, 12th Spacecraft Charging Technology Conference, Kitakyushu, Japan, 14-18 May 2012.
[64] Dennison, J. R. and Ryan Hoffmann, Competing Mechanisms for Temperature-Dependant Electron Relaxation in Disordered SiO2 Layers Under Electron Irradiation, APS March Meeting, Vol. 1, Baltimore, MD, 2013.
[65] Ferguson, D.C., et al., Passive Electrostatic Charging of Near-Geosynchronous Space Debris HAMR Objects and its Effects on the Coupled Object Dynamics, Proc. AAS Space Flight Mechanics Meeting, Santa Fe, NM, Advances in the Astronautical Sciences 01/2014, 152, pp. 3121-3137, Jan 2014.
[66] Ferguson, D. C., et al., On the Feasibility of Detecting Spacecraft Charging and Arcing by Remote Sensing, 5th AIAA Atmospheric and Space Environments Conference, San Diego, CA, 24-27 June, 2013.
[67] Atmospheric and Space Environment Committee, Standard: Low Earth Orbit Spacecraft Charging Design Standard Requirement and Associated Handbook (ANSI/AIAA S-115-2013), AIAA Standards http://dx.doi.org/10.2514/4.102462.001, 2013.
[68] Ferguson, D.C., et al. First Preliminary Results from U.S. Round-Robin Tests, IEEE Transactions on Plasma Science, Vol. 41, Number 12, pp. 3310-3322, Dec 2013.
[69] Ferguson, D.C. and B.V. Vayner, Flashover Current Pulse Formation and the Perimeter Theory, IEEE Transactions on Plasma Science, Vol. 41, Number 12, pp. 3393-3401, Dec 2013.
[70] Ferguson, D.C., et al., Ram/Wake and Surface Layer Effects on DC Electric Field Measurements in LEO, IEEE Transactions on Plasma Science, Vol. 41, Number 12, pp. 3459-3470, doi: 10.2514/1.A32959, Dec 2013.
[71] Heinrich, J.R. and D. L. Cooke, Dynamics of positive probes in underdense, strongly magnetized, E×B drifting plasma: Particle-in-cell simulations, Phys. Plasmas 20, 093503, doi: 10.1063/1.4821070, 2013.
[72] Ferguson, D.C., et al., The Best GEO Daytime Spacecraft Charging Index – Part II, 52nd AIAA Aerospace Sciences Meeting, National Harbor, MD, 13-17 Jan 2014.
[73] Davis, V.A., et al., Semi-analytic and PIC (Particle-in-cell) Methods for Quantifying Charging in Dense, Cold Plasma, 13th Spacecraft Charging Technology Conference, Pasadena, CA, 23-27 Jun 2014.
[74] Hoffmann, Ryan, et al. AFRL Round-Robin Test Results on Plasma Propagation Velocity, 13th Spacecraft Charging Technology Conference, Pasadena CA, 10-15 Jun 2014.
[75] Ferguson, D.C., et al., Solar Array Operation in HCT Plume: Electrostatic Discharge Generated Plasma Expansion Velocity Measurements, 13th Spacecraft Charging Technology Conference, Pasadena, CA, 23-27 Jun 2014.

[76] Ferguson, D. C., et al., A New Study in Electron Trap Modification as a Result of Insulating Materials Exposure to Space Weather, 13th Spacecraft Charging Technology Conference, Pasadena, CA, 23-27 Jun 2014.
[77] Ferguson, D.C., et al., Conductive Space Solarcell Coverglass Replacement Technology, SPIE West, San Francisco, CA, 4-6 Feb 2014.
[78] Ferguson, D.C., Effect of Space Coverglass Degradation on GEO Spacecraft Charging, 13th Spacecraft Charging Technology Conference, Pasadena, CA, 23-27 Jun 2014.
[79] Ferguson, D.C. and B. Vayner, Anomalous GPS Power Degradation from Arc-Induced Contamination, SPRAT XXIII, 29-30 Oct 2014.
[80] Ferguson, D.C., et al., Feasibility of Detecting Spacecraft Charging and Arcing by Remote Sensing, Journal of Spacecraft and Rockets, Vol. 51, No. 6, pp. 1907-1913. doi: 10.2514/1.A32958, 2014.
[81] Hoffmann, R., et al., Changes of the Electrical and Optical Character of Polyimide Films (and the Chemistry that Drives Them) Due to Exposure to High Energy GEO-like Electrons, Advanced Maui Optical and Space Surveillance Conference, Maui, HI, 20-23 Sep 2015.
[82] Barton, D.A., B. P. Beecken, and R. M. Hoglund, Determination of energy and charge deposition profiles in elemental slabs from an isotropic equivalent electron source using Monte Carlo simulations, IEEE Transactions on Plasma Science, Vol. 43, No. 9, pp. 2861-2868, Sep 2015.
[83] Ferguson, D.C., R. Hoffmann, and R. Cooper, 1997-2002 Solar Array String Failures Revisited, Space Power Workshop, Manhattan Beach, CA, 11-14 May 2015.
[84] Ferguson, D.C., R. Hoffmann, and R. Cooper, 1997-2002 Solar Array String Failures Revisited, Photovoltaic Technical Conference, Aix-en-Provence, France, 27-29 May 2015.
[85] Ferguson, D.C., et al., The Trigger Arc Voltage Threshold under LEO Sustained Arcing Conditions, AIAA SPACE 2015 Conference and Exposition, SPACE Conferences and Exposition, (AIAA 2015-4511), Long Beach, CA, 2015.
[86] Cooper, R. and R. Hoffmann, Jumbo Space Environment Simulation and Spacecraft Charging Chamber Characterization, AFRL-RV-PS-TP-2015-0012, Air Force Research Laboratory, Kirtland AFB, NM, 2015.
[87] Ferguson, D.C., Robert V. Hilmer, and Victoria A. Davis, The Best Geosynchronous Earth Orbit Daytime Spacecraft Charging Index, Journal of Spacecraft and Rockets, Vol. 52, No. 2, pp. 526-543, 2015.
[88] Ferguson, D.C., et al., AFRL Round-Robin Test Results on Plasma Propagation Velocity, IEEE Transactions on Plasma Science, Vol. 43, No. 9, p. 3006, Sep 2015.
[89] Hoffmann, Ryan, et al., AFRL Round-Robin Test Results on Plasma Propagation Velocity, IEEE Transactions on Plasma Science 43.9, pp. 3006-3013, 2015.
[90] Starks, M.J., et al., Radio Frequency Emissions from Hypervelocity Impacts: Detecting Micrometeroid Impacts to Spacecraft, URSI USNC Radio Science Meeting, Boulder, CO, Jan 2008.
[91] Selesnick, R. S., Optimal performance of charged particle telescopes in space, Nucl. Instrum. Methods Phys. Res., Sect. A, 761, pp. 34-38, doi:10.1016/j.nima.2014.05.109, 2014.

DISTRIBUTION LIST

DTIC/OCP 8725 John J. Kingman Rd, Suite 0944 Ft Belvoir, VA 22060-6218	1 cy
AFRL/RVIL Kirtland AFB, NM 87117-5776	2 cys
Official Record Copy AFRL/RVBXR/Adrian Wheelock	1 cy