Appendix C
Environment, Electron Transport, and Spacecraft Charging Computer Codes

C.1 Environment Codes

Codes are listed below in alphabetical order. Note that some codes do both environments and transport but are listed in one place only.

C.1.1 AE8/AP8

The NASA AE8 (electrons) and AP8 (protons) radiation models are the traditional electron and proton models of Earth's radiation environment. The AE8 predictions for GEO are probably the most used estimates of the average environment. In these codes, the fluxes are long-term averages (~5 years or more). There are two versions of each model—AE8 solar minimum and AE8 solar maximum and AP8 solar minimum and AP8 solar maximum. They do not predict the peak electron fluxes that are necessary for the internal charging calculations recommended in this book. Reference [1] reviews the output and problems with the AE8/AP8 models. (Note: as of publication of this book, the new AE9/AP9 radiation models had just gone out for beta testing—they were expected to be formally released in late 2011.)

C.1.2 CRRES

CRRES monitored Earth's radiation belts in an eccentric orbit for 14 months starting in July 1990. The data from the spacecraft are in the form of electron and proton flux and dose-depth curves as functions of time and altitude. Environment codes from CRRES include CRRESRAD (dose versus depth); CRRESPRO (proton flux energy spectrum); and CRRESELE (electron flux energy spectrum). They are available from the Air Force Research Laboratory

(AFRL). Perform an internet search on af-GEOSPACE; choose fact sheets: AF-GEOSPACE, and select "software request form" at the bottom of that page.

C.1.3 Flux Model for Internal Charging (FLUMIC)

FLUMIC [2], an environments model developed by ESA and part of the Defense Evaluation and Research Agency (DERA) Internal Charging Threat Analysis Tool (DICTAT), is a position-dependent worst-case model of electron fluxes in the outer radiation belt. The FLUMIC code is explained in the DICTAT user's manual that can be downloaded from the web site http://www.spenvis.oma.be/help/models/dictat.html.

C.1.4 GIRE/SATRAD

GIRE and SATRAD environment models are used to estimate the radiation exposure to spacecraft in the out-of-plane radiation environments of Jupiter's and Saturn's magnetospheres, respectively. A time-versus-position trajectory is required as input into the codes. They were developed by NASA/JPL. The source codes and sample inputs/outputs are available from http://www.openchannelfoundation.org/projects/GIRE and /SATRAD.

C.1.5 Handbook of Geophysics and the Space Environment

This document [3] is an excellent and recommended reference for space environments, including plasma environments for Earth. Even though it was done in 1985, it has not been improved on as a single-source and consistent set of information.

C.1.6 L2 Charged Particle Environment (L2-CPE)

The L2-CPE model is an engineering tool that provides free-field charged-particle environments for the distant magnetotail, magnetosheath, and solar wind environments. L2-CPE is intended for use in assessing contributions from low-energy radiation environments (~0.1 keV to few MeV) to radiation dose in thin materials used in the construction of spacecraft to be placed in orbit about the Sun–Earth L2 point. Reference [4] describes the status of the current version of the L2-CPE model, including the structure of the model used to organize plasma environments into solar wind, magnetosheath, and magnetotail environments, the algorithms used to estimate radiation fluence in sparsely sampled environments, the updated graphical user interface (GUI), and output options for flux and fluence environments. Information on the availability of the model can be obtained from J. I. Minow (Joseph.I.Minow@nasa.gov). Other references are [5–7].

C.1.7 MIL-STD-1809, Space Environment for USAF Space Vehicles

Another source of particle estimates is MIL-STD-1809 [8]. This includes electron spectra that can be used in the electron transport codes for estimating IESD. It also has information that supplements Earth environment information in this Handbook.

C.1.8 Geosynchronous Plasma Model

Reference [9] used data from the ATS-5 spacecraft to generate a simple model for analytically simulating the parameters necessary to characterize the geosynchronous plasma. The model is developed in terms of the daily world-wide geomagnetic activity Ap index and local time. Although based on a limited set of ATS-5 data, the simulation adequately models the simultaneous variations in the warm plasma (50 eV to 50 keV) electron and ion populations during injection events. Developed primarily to estimate the varying potentials expected on a shadowed, electrically isolated surface, the simulation can also be employed in a variety of cases where knowledge of the general characteristics of the geosynchronous plasma is necessary. The model has been extended to include data from ATS-6 and the SCATHA spacecraft. Those desiring the latest version of the model should contact Henry Garrett at henry.b.garrett@jpl.nasa.gov (818-354-2644).

C.1.9 Others

Alternate sources of space radiation data include Severn Communications Corporation, 1023 Benfield Boulevard, Millersville, MD, 21108 (including AP8 and AE8). Use the Severn Communications web site to search and find various environmental papers published by their staff. As described in more detail in Section C.2.9, the Space Environment Information System (SPENVIS) provides an on-line space environment "handbook" at http://www.spenvis.oma.be/.

C.2 Transport Codes

Note that some codes do both environments and transport but are listed in one place only.

C.2.1 Cosmic Ray Effects on MicroElectronics 1996 (CREME96)

CREME96 is a web-based suite of tools hosted at https://creme-mc.isde.vanderbilt.edu/ at Vanderbilt University, Nashville, Tennessee. It incorporates analysis capabilities for the following:

a. Creating numerical models of the ionizing radiation environment in near-Earth orbits:

   (1) Galactic cosmic rays (GCRs).

   (2) Anomalous cosmic rays (ACRs).

   (3) Solar energetic particles (SEPs).

   (4) Geomagnetically trapped particles.

b. Evaluating the resulting radiation effects on electronic systems in spacecraft and in high-altitude aircraft:

   (1) Total ionizing dose (TID).

   (2) Displacement damage dose (DDD).

   (3) Single-event effects (SEEs), including single-event upsets (SEUs).

c. Estimating the linear energy transfer (LET) radiation environment within manned spacecraft.

The TRANS module of the suite is limited to 1-D and aluminum shielding.

C.2.2 EGS4

EGS4 is a Monte Carlo transport code. The suite is used primarily for electron beam experiment simulations. It is easy to use and incorporates validated physics models but is limited in geometry modeling and the space environments included. Recent improvements may have added to its capabilities. References [10], [11], and [12] contain additional information. The web site for this code is http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html at the National Research Council, Institute for National Measurement Standards, Canada.

C.2.3 Geant4

Geant4 is the European counterpart to Monte Carlo N-Particle (MCNP) eXpanded (MCNPX). The Geant family of particle transport codes represents a unique international cooperative effort to model radiation interactions. Many different groups and organizations have contributed specialized analytic components to the basic package. Geant4 is a collection of computer tools for the simulation of the passage of particles through matter. Its areas of application include high-energy, nuclear, and accelerator physics, as well as studies in medical and space science. The two main reference papers for Geant4

are published in *Nuclear Instruments and Methods in Physics Research* [13] and the Institute of Electrical and Electronics Engineers (IEEE) *Transactions on Nuclear Science* [14]. The code and its derivatives make up probably the most sophisticated (and thus complex) modeling package currently available as it covers a much wider range of problems than space radiation effects. As such, it has a steep learning curve. There are special courses and seminars available for learning its many features. The homepage for Geant4 can be found at http://geant4.web.cern.ch/geant4/.

C.2.4 Integrated TIGER Series (ITS)

The ITS code provides electron flux and deposition and has been validated by experiment. It would be the first choice for the electron deposition calculations suggested in this book. Some packages have been simplified to handle simple geometries such as cylinders and slabs. It apparently has no E-field-induced conductivity parameter. Contact: Radiation Shielding Information Computational Center (RSICC), Oak Ridge National Laboratory, Building 6025, MS 6362, P.O. Box 2008, Oak Ridge, TN 37831-6362 (ITS CCC-467). One web page source is http://rsicc.ornl.gov/codes/ccc/ccc4/ccc-467.html. Another is: http://prod.sandia.gov/techlib/access-control.cgi/2004/045172.pdf.

ITS3.0 is a suite of three radiation transport codes that employ a Monte Carlo (mostly forward) technique. The three tools are as follows:

a. TIGER (1-D).
b. CYLTRAN (2-D).
c. ACCEPT (3-D).

The codes handle electrons and photons.

C.2.5 MCNP/MCNPE

MCNP is a radiation transport code that employs a Monte Carlo (mostly forward) technique. The code handles neutrons, photons, and electrons. At one institution, the code is primarily used for neutron/photon transport studies. It incorporates a versatile geometry and input/output options. It is, however, slow for space environment applications.

MCNPX is based on MCNP and has the additional capability of handling neutrons, anti-neutrons, photons, electrons, positrons, muons, anti-muons, electron neutrinos, anti-electron neutrinos, protons, anti-protons, positive pions, negative pions, neutral pions, positive kaons, negative kaons short, neutral kaons long, deuterons, tritons, helium-3s, and helium-4s (alpha particles). It has been used for proton transport where secondary particle generation is important.

MCNP/MCNPE, a version of MCNP modified to include transport of electrons, can be used to determine electron flux inside complex spacecraft geometries. MCNP does detailed 3-D Monte Carlo modeling of neutron, photon, and electron transport. MCNPE does 3-D modeling of neutron, photon, and electron transport. They have a powerful geometric capability; however, transport to very deep depths can take extremely long computer runs with a large uncertainty in the results. At shallow depths (as much as 600 mil of aluminum thickness), codes like ITS are preferred. The codes have continual upgrades, so looking at the web site is advised for the most recent information. Web site: http://mcnp-green.lanl.gov/index.html. A new version of this code is MCNP-4B [15].

C.2.6 NOVICE

NOVICE is a charged-particle radiation transport code. It uses an adjoint Monte Carlo technique to model particle fluxes inside a user-specified 3-D shield geometry in particular. NOVICE uses an inside-out particle tracking algorithm. The code handles electrons, photons, protons, and heavy ions ($Z \geq 2$). It can handle fairly complex geometries and is fast as well as easy to use; however, it does not work for secondary particles. Contact: Thomas Jordan, Experimental and Mathematical Physics Consultants, P.O. Box 3191, Gaithersburg, Maryland (MD) 20885, phone 301-869-2317. This source may also have codes for electron deposition calculations [16].

C.2.7 NUMIT

NUMIT, originally developed by A. R. Frederickson, is a 1-D computer code for estimating internal charging in dielectrics. It computes the full-time dependent current, voltages, and electric fields in the dielectric by iteratively solving a set of equations for mono-energetic photons/electrons normally incident on one side of a dielectric. Contact: Dr. Wousik Kim, Jet Propulsion Laboratory, Mail Stop 122-107, Pasadena, California (CA), U.S.A. 91109.

C.2.8 SHIELDOSE

SHIELDOSE is a charged-particle radiation transport code that calculates the dose inside slab and spherical shield geometries. It also computes dose absorbed in small volumes of some detector materials under specified aluminum shield geometries. See references [2,17]. Web reference: http://modelweb.gsfc.nasa.gov/magnetos/shield.html.

C.2.9 SPENVIS/DICTAT

This code package is designed for spacecraft internal charging analysis and is available for use on the web at http://www.spenvis.oma.be/spenvis/ and

http://www.spenvis.oma.be/spenvis/help/background/charging/dictat/dictatman.html.

DICTAT [18] calculates the electron current that passes through a conductive shield and becomes deposited inside a dielectric. From the deposited charge, the maximum electric field within the dielectric is found. This field is compared with the breakdown field for that dielectric to see if the material is at risk of an ESD.

SPENVIS, a web-based suite of tools designed for near-Earth analysis, generates either a spacecraft trajectory or a coordinate matrix. In addition to the DICTAT model, it incorporates analysis capabilities for the following:

a. Trapped proton and electron fluxes and solar proton fluences.
b. Radiation doses (ionizing and non-ionizing).
c. Damage equivalent fluences for Si and GaAs solar panels.
d. LET spectra and SEU rates.
e. Trapped proton flux anisotropy.
f. Atmospheric and ionospheric densities and temperatures.
g. Atomic oxygen erosion depths.
h. GIRE, the jovian radiation model

C.2.10 TRIM

TRIM is a radiation transport code that employs a Monte Carlo (forward) technique. It is 1-D and accommodates protons and heavy ions. TRIM is used for proton and heavy-ion beam simulation, and it covers the entire spectrum of heavy ion types. It is limited to 1-D slab geometry, however, and only incorporates coulomb interactions.

C.2.11 Summary

The preceding transport codes are intended to be used in estimating internal charge deposition—a major step in estimating the probability of IESD. Table C-1 provides a comparison of some IESD charging specific parameters for the major analysis codes. Whereas codes like the TIGER, Geant, and MCNPX allow estimates of the flux (and fluence) with depth in the material, the DICTAT and NUMIT codes estimate the buildup of the fields in the material.

Table C-1. Properties of the Major Transport Codes.

Code Name	Calculates Electron Deposition?	Usable for IESD?	Recommended for IESD Calculation?	Calculates E-Field?	Uses RIC or Conductivity?
DICTAT	--	?	Y	Y	--
EGS4	Y	?	N?	--	--
Geant4	Y	Y	N	N	N
ITS	Y	Y	N	N	N
MCNPX	Y	Y	N	--	--
NUMIT	N	N?	Y	Y	Y

C.3 Charging Codes

These codes generally calculate surface charging, potentials, E-fields, and other parameters that are of interest for an overall view of spacecraft charging. Look for one or more that best meets the needs of the project.

C.3.1 Environment Work Bench (EWB)

This code uses simple models of plasma and other space environments and interactions to predict a variety of environmental effects. These include LEO spacecraft floating potentials, as an example. It is International Traffic-in-Arms Regulations (ITAR) restricted. See: http://see.msfc.nasa.gov at Marshall Space Flight Center, Huntsville, Alabama (SEE Products: Electromagnetic Effects & Spacecraft Charging).

C.3.2 Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT)

MUSCAT [19] is a Japanese computer code that predicts potentials, with function similar to the NASA Charging Analyzer Program (NASCAP).

C.3.3 Nascap-2k and NASCAP Family of Charging Codes

Nascap-2k [20,21] is a widely used interactive toolkit for studying plasma interactions with realistic spacecraft in three dimensions. It can model interactions that occur in tenuous (e.g., GEO orbit or interplanetary missions) and in dense (e.g., LEO orbit and the aurora) plasma environments. Capabilities include surface charging in geosynchronous and interplanetary orbits, sheath and wake structure and current collection in LEO, and auroral charging. External potential structure and particle trajectories are computed using a finite

element method on a nested grid structure and may be visualized within the Nascap-2k interface. Space charge can be treated either analytically, self-consistently with particle trajectories, or consistent with imported plume densities. Particle-in-cell (PIC) capabilities are available to study dynamic plasma effects. Material properties of surfaces are included in the surface charging computations. By locating severe surface voltage gradients in a particular design, it is possible to show where discharges could occur. The effect of changes in the surface materials or coatings in those areas on minimizing voltage gradients can then be evaluated.

Nascap-2k is a successor code to NASCAP for Geosynchronous Orbit (NASCAP/GEO), NASCAP for Low-Earth Orbit (NASCAP/LEO), POLAR, and Dynamic Plasma Analysis Code (DynaPAC). NASCAP/GEO has been the standard 3-D tool for the computation of spacecraft charging in tenuous plasmas since 1980. In the following two decades, the fully 3-D computer codes NASCAP/LEO, POLAR, and DynaPAC were developed to address various other spacecraft-plasma interactions issues. Nascap-2k incorporates almost all of the physical and numeric models of these earlier codes. Nascap-2k is available on request to United States citizens only; a web reference with access and other material is http://see.msfc.nasa.gov (SEE Products: Electromagnetic Effects & Spacecraft Charging).

C.3.4 SEE Interactive Spacecraft Charging Handbook

The SEE Interactive Spacecraft Charging Handbook is an interactive spacecraft charging code for the non-expert. It computes spacecraft surface charging for geosynchronous and auroral zone spacecraft along with internal charging related to the deposition of high-energy (MeV) electrons. Eight assessment modeling tools are included: Geosynchronous Environment, Aurora Environment, Trapped Radiation Environment, Material Properties, Single Material Surface Charging, Multi-Material Surface Charging, Three-Dimensional Surface Charging, and Internal Charging. It can be obtained through the web site http://see.msfc.nasa.gov (SEE Products: Electromagnetic Effects & Spacecraft Charging). Contact: barbara.m.gardner@saic.com.

C.3.5 Spacecraft Plasma Interaction System (SPIS)

The SPIS software project aims at developing a software toolkit for spacecraft-plasma interactions and spacecraft charging modeling. SPIS is developing a charging code that includes electrical circuit parameters and can model the time behavior of charging and discharge currents. The project was started in December 2002 and has three major objectives:

a. To build the architecture for the SPIS being developed.

b. To implement the physical routines of the code.

c. To organize and coordinate with the Spacecraft Plasma Interaction Network (SPINE) community.

The overall project has been undertaken within the framework of SPINE. The first development phase of the project has been performed by the French Aerospace Lab (ONERA)/Space Environment Department (DESP), Artenum, and University Paris VII under an ESA contract. Further information is available at: http://dev.spis.org/projects/spine/home/spis.

References

[1] H. B. Garrett, *Guide to Modeling Earth's Trapped Radiation Environment*, vol. AIAA G-083-1999, ISBN 1-56347-349-6, American Institute of Aeronautics and Astronautics, Reston, Virginia, 55 pages, 1999.

[2] D. J. Rodgers, K. A. Hunter, and G. L. Wrenn, "The FLUMIC Electron Environment Model," presented at *The 8th Spacecraft Charging Technology Conference*, Huntsville, Alabama, October 20–24, 2004.

[3] A. Jursa, ed., *Handbook of Geophysics and the Space Environment*, Air Force Geophysics Laboratory, U.S. Air Force, National Technical Information Service Document, Accession No. AD-A167000, 1985. Additional reading for the space environment and interactions with spacecraft. An excellent reference for Earth space plasma environments as well as many other space environments.

[4] J. I. Minow, A. Diekmann, and W. Blackwell, Jr., "Status of the L2 and Lunar Charged Particle Environment Models," presented at *The 45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, AIAA paper 2007-0910, 2007.

[5] J. I. Minow, W. C. Blackwell, Jr., L. F. Neergaard, S. W. Evans, D. M. Hardage, and J. K. Owens, "Charged Particle Environment Definition for NGST: L2 Plasma Environment Statistics," *Proceedings of SPIE 4013, UV, Optical, and IR Space Telescopes and Instruments VI,* pp. 942–953, 2000.

[6] J. I. Minow, W. C. Blackwell, Jr., and A. Diekmann, "Plasma Environment and Models for L2," presented at *The 42nd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, AIAA Paper 2004-1079, 2004.

[7] J. I. Minow, L. N. Parker, and R. L. Altstatt, "Radiation and Internal Charging Environments for Thin Dielectrics in Interplanetary Space," *The 9th Spacecraft Charging Technology Conference*, Tsukuba, Japan, April 2005.

[8] *Space Environment for USAF Space Vehicles*, MIL-STD-1809 (USAF), United States Air Force, 69 pages, February 15, 1991.

[9] H. B. Garrett and S. E. DeForest, "Analytical Simulation of the Geosynchronous Plasma Environment," *Planetary and Space Science,* vol. 27, pp. 1101–1109, 1979.

[10] W. R. Nelson, H. Hirayama, and D. W. O. Rogers, *The EGS4 Code System, SLAC-265*, Stanford Linear Accelerator Center, Stanford University, Stanford, California, December 1985.

[11] J. A. Hableib, R. P. Kensick, T. A. Melhorn, G. D. Valdez, S. M. Seltzer, and M. J. Berger, *ITS 3.0: Integrated Tiger Series of Coupled Electron/Photon Monte Carlo Transport Codes*, The Radiation Safety Information Computational Center, Oak Ridge, Tennessee, November 1994.
Provides additional information on ITS.

[12] A. F. Bielajew, H. Hirayama, W. R. Nelson, and D. W. O. Rogers, "History, Overview and Recent Improvements of EGS4," presented at *Radiation Transport Calculations Using the EGS4 Conference*, Capri, Italy, 1994.

[13] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand, F. Behner, L. Bellagamba, J. Boudreau, L. Broglia, A. Brunengo, H. Burkhardt, S. Chauvie, J. Chuma, R. Chytracek, G. Cooperman, G. Cosmo, P. Degtyarenko, A. Dell'Acqua, G. Depaola, D. Dietrich, R. Enami, A. Feliciello, C. Ferguson, H. Fesefeldt, G. Folger, F. Foppiano, A. Forti, S. Garelli, S. Giani, R. Giannitrapani, D. Gibin, J. J. Gómez Cadenas, I. González, G. Gracia Abril, G. Greeniaus, W. Greineraf, V. Grichinef, A. Grossheim, S. Guatelli, P. Gumplinger, R. Hamatsu, K. Hashimoto, H. Hasui, A. Heikkinen, A. Howard, V. Ivanchenko, A. Johnson, F. W. Jones, J. Kallenbach, N. Kanaya, M. Kawabata, Y. Kawabata, M. Kawaguti, S. Kelner, P. Kent, A. Kimura, T. Kodama, R. Kokoulin, M. Kossov, H. Kurashige, E. Lamanna, T. Lampén, V. Lara, V. Lefebure, F. Lei, M. Liendl, W. Lockman, F. Longo, S. Magni, M. Maire, E. Medernach, K. Minamimoto, P. Mora de Freitas, Y. Morita, K. Murakami, M. Nagamatu, R. Nartallo, P. Nieminen, T. Nishimura, K. Ohtsubo, M. Okamura, S. O'Neale, Y. Oohata, K. Paech, J. Perl, A. Pfeiffer, M. G. Pia, F. Ranjard, A. Rybin, S. Sadilov, E. DiSalvac, G. Santin, T. Sasaki, N. Savvas, Y. Sawada, S. Scherer, S. Sei, V. Sirotenko, D. Smith, N. Starkov, H.

Stoecker, J. Sulkimo, M. Takahata, S. Tanaka, E. Tcherniaev, E. S. Tehruig, M. Tropeano, P. Truscott, H. Uno, L. Urban, P. Urban, M. Verderi, A. Walkden, W. Wander, H. Weber, J. P. Wellisch, T. Wenaus, D. C. Williams, D. Wright, T. Yamada, H. Yoshida, and D. Zschiesche., "Geant4-A Simulation Toolkit," *Nuclear Instruments and Methods in Physics Research,* vol. A, no. 506, pp. 250–303, 2003.

[14] J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce Dubois, M. Asai, G. Barrand, R. Capra, S. Chauvie, R. Chytracek, G. A. P. Cirrone, G. Cooperman, G. Cosmo, G. Cuttone, G. G. Daquino, M. Donszelmann, M. Dressel, G. Folger, F. Foppiano, J. Generowicz, V. Grichine, S. Guatelli, P. Gumplinger, A. Heikkinen, I. Hrivnacova, A. Howard, S. Incerti, V. Ivanchenko, T. Johnson, F. Jones, T. Koi, R. Kokoulin, M. Kossov, H. Kurashige, V. Lara, S. Larsson, F. Lei, O. Link, F. Longo, M. Maire, A. Mantero, B. Mascialino, I. McLaren, P. Mendez Lorenzo,. K. Minamido, K. Murakami, P. Nieminen, L. Pandola, S. Parlati, L. Peralta, J. Perl, A. Pfeiffer, M. G. Pia, A. Ribon, P. Rodrigues, G. Russo, S. Sadilov, G. Santin, T. Sasaki, D. Smith, N. Starkov, S. Tanaka, E. Tcherniaev, B. Tomé, A. Trindade, P. Truscott, L. Urban, M. Verderi, A. Walkden, J. P. Wellisch, D. C. Williams, D. Wright, and H. Yoshida, "Geant4 Developments and Applications," *IEEE Transactions on Nuclear Science,* vol. 53, no. 1, pp. 270–278, 2006.

[15] J. F. Briesmeister, ed., "MCNP-4B: A General Monte Carlo N-Particle Transport Code, Version 4B," Report Number LA-12625-M, Los Alamos National Laboratory, New Mexico, March 1997.

[16] T. M. Jordon, *NOVICE: A Radiation Transport/Shielding Code; User's Guide*, Experimental and Mathematical Physics Consultants, Gaithersburg, Maryland, January 2, 1987.

[17] S. M. Seltzer, *SHIELDOSE: A Computer Code for Space-Shielding Radiation Dose Calculations*, NBS Technical Note 1116, National Bureau of Standards (now National Institute of Standards and Technology), U.S. Government Printing Office, Washington, District of Columbia, 1980.

[18] J. Sorensen, D. J. Rodgers, K. A. Ryden, P. M. Latham, G. L. Wrenn, L. Levey, and G. Panabiere, "ESA's Tools for Internal Charging," *IEEE Transactions on Nuclear Science,* vol. 47, no. 3, pp. 491-497, June 2000. A published reference for DICTAT.

[19] S. Hosoda, S. Hatta, T. Muranaka, J. Kim, N. Kurahara, M. Cho, H. Ueda, K. Koga, and T. Goka, "Verification of Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT) via Laboratory Test," presented at *The 45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 8–11, AIAA 2007–278, 2007.

[20] M. J. Mandell, V. A. Davis, B. M. Gardner, I. G. Mikellides, D. L. Cooke, and J. Minor, "Nascap-2k—An Overview," *Transactions on Plasma Science,* vol. 34, no. 5, pp. 2084–2093, 2006.

[21] V. A. Davis, M. J. Mandell, B. M. Gardner, I. G. Mikellides, L. F. Neergaard, D. L. Cooke, and J. Minow, "Validation of Nascap-2k Spacecraft-Environment Interactions Calculations," presented at *8th Spacecraft Charging Technology Conference*, Huntsville, Alabama, in NASA Technical Reports Server, 2004.