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Title: Development of Space Environment Customized Risk Estimation for Satellites (SECURES)

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Abstract

Plasma variations in geospace environment driven by the solar wind-magnetosphere interaction is one of the major causes of satellite anomaly. To mitigate the effect of satellite anomaly, risk of space weather disturbances needs to be known in advance based on space weather forecast. However, risk of satellite anomaly due to space weather disturbances is not the same as each satellite, because the risk depends not only on the space environment itself but also on the design and materials of individual satellite. For the viewpoint of satellite operator, it is not easy to apply general alert level of space environment to the risk of individual satellite. To provide tailored space weather information, we have developed SECURES (Space Environment Customized Risk Estimation for Satellite) by combining models of space environment and those of spacecraft charging. In SECURES, we are focusing on the risk of spacecraft charging (surface/internal) for geosynchronous satellites. For risk estimation of surface charging, we have combined the global magnetosphere MHD model with the satellite surface charging models. For risk estimation of internal charging, we have combined the radiation belt models with the satellite internal charging models. We have developed

prototype products for both types of charging/ESD. The development of SECURES and our achievements are introduced in this paper.

Keywords

Space weather forecasting, Geospace, Satellite anomaly, Satellite charging, Customized risk estimation

Introduction

The space environment around the Earth (geospace) have been used by many kinds of satellites which have various purposes such as telecommunications, broadcasting, earth observation, positioning, and so on. The plasma and electromagnetic environment in geospace changes significantly due to disturbances in geospace, such as substorms and storms caused by the solar-wind – magnetosphere interaction. It can also be affected by high-energy particles, known as solar energetic particle events (SEPs). The disturbances in geospace cause various satellite anomalies, such as charging/discharging and CPU malfunctions. Therefore, satellites will be designed and developed with measures to prevent anomalies due to geospace disturbances during operation period and in the satellite's orbit.

Space weather forecast provide current status and future condition of space environment in geospace based on observation and modeling. If there is a possibility of spacecraft anomalies due to space environment, the following three utilizations of space weather forecast are necessary to improve the stability and safety of satellite operation.

Firstly, when the satellite anomaly occurs, triage determination is the urgent action at the occurrence of satellite anomaly. The satellite operator needs to identify the cause of anomaly (misoperation, manufacturing problem, space environment) for their next action to mitigate the effect of the anomaly. For this purpose, it is necessary to understand the current condition (Nowcast) of the space environment around the satellite in order to determine whether the malfunction/failure is caused by the space environment or other factor (O'Brien et al., 2013).

Secondly, if there is a high possibility that the satellite anomaly is caused by the space environment, post data analysis will be performed to clarify the relationship between geospace disturbances and satellite anomaly. It is necessary to take future measures, and to improve the satellite itself based on the outcome of post data analysis.

Thirdly, in the case of conducting critical operations, such as attitude control and/or rewriting on-board programs, where mistakes and errors can seriously affect the satellite, the satellite operator should refer to the space weather forecast, and to take Go/NoGo decision for critical operation which can reduce the risk of satellite anomaly. In addition, if the risk of satellite anomaly due to space weather disturbance is predicted, stability and continuity of satellite operation can be improved by taking measures such as increasing the number of staff in charge of operation and preparing backup plans. It is possible to realize quick recovery if the satellite anomaly happens.

However, the specific utilization of space weather forecasts in the current satellite operation is still in the developing stage for the following reasons. First, there are many unsolved problems regarding the relationship between space weather disturbances and satellite anomalies. Since the operating satellite is in space, the status of the satellite cannot be directly confirmed, making it difficult to directly investigate the cause of the failure. In addition, there is a situation in which it is difficult for satellite manufacturers and satellite operators to disclose detailed information about satellite anomalies to the public. In order to overcome this situation, the United Nations the Committee on the Peaceful Uses of Outer Space (UN/COPUOS) calls for information sharing about satellite design standards, space weather observations and models implemented in each country, satellite anomalies, and efforts to mitigate the effects of satellite anomalies (UN/COPUOS, 2019).

The other thing is accuracy and lead time of space weather forecast. The space environment significantly changes in space and time depending on the solar-wind – magnetosphere interactions. Therefore, the condition of the surrounding space environment may be greatly different depending on the position of the satellite, and the space weather forecast is required to reproduce the difference. In addition, since the conditions of space environment in geospace is driven by the solar wind, forecasts with enough lead times cannot be realized unless the state of the solar wind can be predicted in advance. However, since there are a few observations between the sun – earth line, the current status of forecasting lead time is about one hour ahead using data from the solar wind observation located at the L1 point of the Sun-Earth system. Prediction of longer lead times is much less accurate.

Finally, as will be described later, the risk of satellite anomaly due to the space environment in geospace also varies depending on the materials and structure used for the satellite itself. In other words, it is not easy for satellite operators to judge the risk of individual satellites only with the space weather forecast. Therefore, in order to perform safety and stability of satellite operation, it is necessary to understand not only the status of geospace environment but also the risks of individual satellites.

Based on this background, we have been developing charging risk estimation scheme for satellite operator as SECURES (Space Environment Customized Risk Estimation for Satellites) under PSTEP (Project for Solar-Terrestrial Environment Prediction) (Nagatsuma, 2017). In this paper, we will introduce outline of SECURES, surface charging module, and internal charging module, and will summaries our achievements with discussion.

Outline of SECURES

Electrostatic discharge (ESD) is one of the major satellite anomalies caused by space weather disturbances (e.g. Ferguson et al., 2015). One fourth of the satellite anomalies are caused by ESD (Mazur et al., 2011). There are two types of charging mechanism which will cause ESD. One is surface charging and the other is internal charging. Surface charging is a phenomenon that occurs on the surface of the satellite structure caused by plasma of several tens to several hundred keV. An electric potential is formed on the surface of the satellite by the inflow of ions and electrons from the plasma environment around the satellite and the emission of photoelectrons because of sunlight. Internal charging is a phenomenon that occurs inside the satellite structure. Electrons with energies higher than several hundred keV penetrate the wall of the satellite structure and penetrate the interior, which causes charging and discharging of cables and equipment inside the satellite. Due to variations of plasma environment in geospace, the electric potential on the surface and inside of the satellite may change, resulting in electrical discharges leading to malfunctions and failures. Charging and discharging conditions are different depending on the satellite shape and materials even if the condition of space environment is the same. Therefore, it is not easy to identify the operational risk of individual satellite by satellite operator using general information of space weather nowcast/forecast itself. This problem will be reduced by estimating the charging risk of individual satellite using satellite charging models with providing current and future condition of the space environment at the position of an individual satellite by models of space weather forecast.

#Insertion of Figure 1

Figure 1 shows the concept of SECURES. Specifically, for each of the surface and internal charging, predicted physical parameters in the space environment (electron/ion temperature, density, etc.) at the position of the individual satellite, and the structure and material model of that, are used as input of the satellite charging model to estimate the risk of charging.

The space environment that causes surface charging is simulated by Global Magnetohydrodynamics (MHD) model. The information on the simulated space environment is used to calculate the charging of individual satellite in a certain space environment condition using a satellite charging model such as Spacecraft Plasma Interaction System (SPIS) (Roussel et al., 2008) or Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT) (Hosoda et al., 2008; Munakata et al., 2008). High energy particles which cause internal charging are predicted by radiation belt simulation. The information on the predicted space environment is used to calculate the internal charging by MUSCAT. Detailed information of surface charging part of SECURES and internal charging part of that will be introduced in the following sections.

Surface Charging Part of SECURES

Toward the surface charging/ESD risk assessment, we combine surface charging analysis models (SPIS and/or MUSCAT), which estimate spacecraft potentials based on a pre-designed satellite model including information of shape and materials of the satellite, and global magnetosphere MHD model, which simulates plasma environment for the input of charging analysis models. We have developed a prototype surface charging/ESD risk assessment system targeting on the GEO region. In this section, the global magnetosphere MHD model, charging analysis model, and the overview of the prototype surface charging/ESD risk assessment system are described.

Plasma environment at GEO estimated by the real-time global magnetosphere MHD model

The global magnetosphere MHD model used in the surface charging part of SCURES, was originally developed by Tanaka (1994) and Tanaka et al. (2010). The MPI (Message Passing Interface) parallelized version of the model is called REPPU (REProduce Plasma Universe) code (Tanaka 2015). The model is characterized by a triangular unstructured grid system (Nakamizo et al. 2009), which enables us to simulate global systems including fine structures in its center in sufficiently high spatial resolution and numerical stability. It is shown that the code is robust enough to simulate magnetospheric responses to extreme conditions, such as intense solar wind velocity and density, and high intensity of interplanetary magnetic field (Kubota et al. 2017). The relationship among the space environment data and surface charging data obtained from Michibiki-1 satellite, and space environment data obtained from global magnetosphere MHD simulation are examined as a first step (Nagatsuma et al., 2018).

For simplicity, the original code assumes that the earth's magnetic dipole axis and the rotation axis coincide with each other. Therefore, it doesn't meet the requirements for practical uses and operation as it is, because in the actual solar-terrestrial system the earth's rotation axis inclined with respect to the ecliptic plane and the magnetic dipole axis is tilted from the rotation axis, completing the precession.

In order to perform more realistic simulation, we have improved the model by introducing the inclination and the precession of the magnetic dipole axis (Kubota et al. 2019a; Nakamizo 2019). With this improved model, a real-time global magnetosphere simulation (Kubota et al. 2019b) on the High-Performance Computing system at National Institute of Information and Communications Technology (NICT) are developed. The real-time simulation is driven by the real-time solar wind data at the L1 point of the Sun-Earth system provided by National Oceanic and Atmospheric Administration's Space Weather Prediction Center (NOAA/SWPC). Because the average propagation time of the solar wind from the L1 point to the front of the Earth's magnetosphere is about 1 hour, and the processing time of the real-time simulation system is about 20 minutes, the total lead time of the real-time simulation is about 40 minutes on average. Figure 2 is a quick look of the real-time simulation result. Currently the real-time product is used internally for the operational space weather forecast in Japan.

#Insertion of Figure 2

The spacecraft charging analysis model which will be introduced in the next subsection requires the densities and temperatures of ions and electrons (N_i, T_i, N_e, and T_e) as the input parameters of the model. Since MHD models cannot simulate these parameters in principle, the following empirical scheme is introduced for estimating them from the MHD model.

Nakamura et al. (2012) statistically compared the plasma parameters in GEO simulated by the old version of our global magnetosphere MHD model and those obtained from Magnetospheric Plasma Analyzer (MPA) onboard Los Alamos National Laboratory (LANL) satellites. They showed that the simulated MHD pressure, P_{sim}, in the nightside GEO region is in a good correlation with the observed electron pressure.

We have applied the same approach of Nakamura et al. (2012) to the current version of our MHD model (Kubota et al., 2018). Observed plasma moment data of LANL/MPA from February to April in 2006 via Coordinated Data Analysis Web (CDAWeb) and the same period of simulated plasma moment data from our MHD model are compared. According to the comparison between observed electron pressure and P_{sim}, the same tendency of previous study was confirmed. In addition, it was found that the simulated

N tends to be higher than the observed N_e and N_i, which are about $1/cm^3$, and the simulated T tends to be lower than the observed T_e. This means that the current version of our MHD model tends to overestimate/underestimate the density/temperature, although the pressure, the multiplication of them, is reasonably simulated.

Thus, we derive T_e from P_{sim} assuming $N_e=N_i=1/cm^3$. As for T_i, we multiply the derived T_e by the factor of 1.9. This factor is obtained by the average ratio of observed T_i and T_e in our comparison. In summary,

$N_i = N_e = 1/cm^3$

$T_e = P_{sim}/N_e\, k_B$

$T_i = 1.9\, T_e$.

(k_B: Boltzmann constant)

Based on these empirical relationships, N_i, T_i, N_e, and T_e from real-time simulation data for the nightside GEO region are estimated.

Estimating real-time risk of surface charging using SPIS

Surface charging of individual satellite is calculated using SPIS in space environment conditions, the densities and temperatures of ions and electrons (N_i, T_i, N_e, and T_e).

In our prototype product, two examples of geometric models are introduced as a test case of our risk estimation, One is Van-Allen Probes, a typical spin-stabilized scientific satellite, all surface of which are conductive and electrically connected (Stratton et al., 2013;). The other is Michibiki-1 satellite, a typical three-axis stabilized geosynchronous satellite with dielectric materials (Inaba et al., 2009). Figure 3 shows geometric models of the Van-Allen Probes and the Michibiki-1 satellite used in the surface charging calculation. We calculate the absolute charging potential for the geometric model of Van-Allen Proves. The absolute charging would have an influence on some scientific observations. We calculate the floating potentials of the surface materials and the local differential charging potentials for the geometric model of Michibiki-1 satellite. The high differential charging potential results in ESD on the satellite surface and would induce spacecraft anomalies. Therefore, the estimation of the differential charging potentials is important for surface charging/ESD risk assessment.

#Insertion of Figure 3

However, it is impossible to obtain the surface potentials in near-real-time from real-time global magnetosphere MHD simulation data because charging calculation of the Michibiki-1 satellite model using SPIS takes hours or days for one space environment condition. Therefore, we have developed a quick estimation method of the surface potential using the pre-calculated results. The estimating the surface potential for the environment parameters, N_i, T_i, N_e, and T_e, as four independent variables is very complicated. However, as shown in the previous subsection, we can calculate the surface charging potentials for the condition of N_e=N_i=1/cc and T_i=1.9* T_e with T_e as a single variable. Figure 4 shows an example of the frame and maximum surface potentials of the Michibiki-1 satellite model in daylight as a function of T_e. In the case, several frame and maximum surface potentials are calculated for some values of T_e. A polynomial function is fitted for the results of calculation, and we can obtain the empirical function of the surface charging potential from the proper several pre-calculated results. Using the functions, the frame and maximum surface potentials of the Michibiki-1 satellite are quickly estimated from real-time simulation data. We also developed the empirical function for surface potentials of the Van-Allen Probes, too.

#Insertion of Figure 4

Surface charging/ESD risk assessment system for GEO satellites

The outline of the prototype surface charging/ESD risk assessment system is as follows. From the real-time simulation data per one minute, we extract the plasma environment data on the sphere of the 6.6 Earth radius (R_E), which is identical with GEO, in every five minutes. The extracted data are stored in the system. The results of prototype surface charging/ESD risk estimation system can be browsed from a web viewer. However, the web viewer is also for the internal use now.

Since explanation in the viewer is in Japanese, the content shown in the viewer is described as a schematic snapshot and a table. Figure 5 is a schematic snapshot of the web viewer of the system which is taken at 09:00 UT on July 05, 2020 as an example. The left panel shows overview of the Earth's magnetosphere. The pressure and the bulk flow velocity distributions on the equatorial plane in the Solar Magnetic (SM) coordinate system are shown by color and arrows, respectively. The right panel shows the pressure distribution on the 6.6 R_E sphere in the geographic coordinate system. When we open the viewer, the latest condition is shown as default. At the top column, we can select date and time according to our interest. After selecting specific time period, two hours movie from the selected start time can be played by controlling the bottom slider.

Because figure 5 is taken at 09:00 UT, the local times of noon and midnight are at longitude 45° and 225°, respectively in the right panel. The high-pressure region around the noon corresponds to the dayside cusps. On the other hand, another high-pressure region is seen around the midnight. It seems that the pressure enhancement around the midnight is caused by magnetospheric activity in the nightside associated with a substorm. Real-time auroral electrojet indices show that the magnetosphere was in the expansion to recovery phases of a moderate substorm. The AL index was about 500 nT at this time.

Table 1 is a schematic example of some parameters and estimated spacecraft potentials at the selected point shown as a pink cross mark in the right panel of Figure 5. This table is also browsed within the web viewer. When users mouse over the pink cross mark cursor on the right panel of Figure 5, the system returns the information of geographic latitude and longitude, daylight/eclipse flag, simulated pressure, density, and

T_e, at the selected point. At the same time, the system calculates the spacecraft potentials using the empirical functions with plasma parameters described in the previous subsection. The results are instantaneously shown in the table inside the web viewer. Using this function, the satellite operators can select the position of their own satellite to understand the risk of surface charging/ESD.

#Insertion of Figure 5

#Insertion of Table 1

Internal Charging Part of SECURES

To assess the risk of internal charging/ESD, anomalies of Earth Sensor Assembly (ESA) onboard Kodama (DRTS: Data Relay Test Satellite) are examined as a test case. The quantitative assessment of internal charging of ESA have been done by using MUSCAT with the ESA’s structure and material model. The results of our assessment suggest that detailed quantitative analysis is necessary to clarify an internal charging/ESD. Thus, we have developed risk assessment system of internal charging/ESD based on the simple analysis method. Our achievements in detail are described in the following subsections.

Satellite Anomalies occurred at ESA onboard Kodama (DRTS)

Kodama (DRTS), which was launched on September 10, 2002, have started routine operation since January 9, 2003. On March 23, 2003, a satellite anomaly occurred at the ESA on board Kodama. The ESA shifted from the nominal system (ESA-A) to the redundant system (ESA-B). Afterwards, the same kind of anomaly was occurred on April 2, May 27, and June 6, 2003. It was found that the ESA’s anomaly was occurred during the period for the increase of the ESA’s noise count. To identify the cause of the anomaly, the relationship between ESA’s noise count and the high energy electron flux observed by Standard Dose Monitor (SDOM) onboard Kodama (Matsumoto et al., 2001) was examined. It was found that there is a relationship between the ESA’s noise counts and the Ch.3 of differential electron flux (0.59-1.18 MeV) observed by SDOM/Kodama (Figure 6). This relationship suggests that the possible cause of the ESA’s anomaly is internal charging/ESD. Based on the satellite anomaly occurred at ESA onboard Kodama, Internal charging/ESD risk assessment system have been developed.

#insertion of Figure 6

High energy electron environment at GEO estimated by radiation belt model

In order to evaluate energetic electron flux at the satellite location, we used the 1-dimensional Fokker-Planck equation for describing the radial diffusion (Miyoshi et al., 2004), where f is the phase space density and t is time.

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) - \sum_i \frac{f}{\tau_i}$$

where L is the L-shell. We used the empirical radial diffusion coefficient (D_{LL}) which was formulated by Brautigam and Albert (2000). We consider electromagnetic coefficients parameterized. The time step for calculation is 1 hour. The loss terms are described by the lifetimes due to Coulomb collisions (τ_c) and wave-particle interactions (τ_{wp}) inside the plasmasphere. The lifetime τ_c is given by Wentworth et al., (1959). Three different wave sources inside the plasmasphere are included: plasmaspheric hiss, lightning whistler, and VLF transmitters. After the calculation about the phase space density f, we have derived the differential flux $j(E, L, t)$ where E is the electron energy. Considering the L-shell of Kodama that varies during a day, we calculate time variation of j along the Kodama orbit. In this model, we have used the empirical radiation belt model AE-8 (Vette, 1991) as an initial condition.

Internal Charging Estimation using MUSCAT

MUSCAT is the charging analysis tool for satellite design. The development of MUSCAT has started in 2004, and was completed in 2007 (Hosoda et al., 2008; Munakata et al., 2008). MUSCAT has the analysis feature of the surface charging, and the internal charging simulation function is added in 2010. In the internal charging analysis, the range of the high energy electron is calculated by the Monte Carlo method.

The structure and materials of ESA was modeled using MUSCAT Graphical User Interface. External electron energy spectrum was estimated using radiation belt model described in the previous subsection, and the electrostatic potential of the ESA was calculated using MUSCAT. It was found that the variation of ESA’s electrostatic potential calculated by MUSCAT is very small compared with a threshold potential of ESD. The structure around the ESA sensor has adequate thickness which reduce the electron flux, so the charge accumulation is very small. This result suggests that the possibility of internal charging/ESD with other devices or cables, which are located under thin shield, needs to be considered. Some experimental study also suggests that noise produced by ESD could propagate panels and cables (Kinoda et al., 2018). The detailed quantitative analysis is necessary to clarify an internal charging/ESD of the ESA onboard Kodama including the development of the detailed structure and material model inside of the satellite. However, it is not easy to develop such a detailed model because information of detailed structure and material are not disclosed from satellite industry in usual.

Risk assessment system of internal charging/ESD

The result of previous subsection suggests that risk assessment of internal charging based on MUSCAT with structure model of specific part which suggested to be weak for the cause of internal charging. Therefore, a risk assessment system of internal charging/ESD has been developed based on simple analysis method introduced in the NASA-HDBK-4002A.

The procedure of our risk assessment system of internal charging/ESD is as follows.

The simple structure model is used for our system. In this model, the thicknesses of the satellite shield (d_1) and the target material (d_2) are defined on request (Figure 7). To estimate the range of incident electron energy into the target material (d_2), lower limit of incident energy (E_1) and higher limit of incident energy (E_2) are converted from the thickness of d_1 and d_1+d_2. The accumulated current inside the target material are calculated from the differential energy spectrum between E_1 and E_2 (Figure 7). The differential energy spectrum is provided from our radiation belt model described in previous subsection. Alert levels for the risk of internal charging/ESD are set to 0.1, 0.3 and 1.0 pA/cm^2, respectively based on the NASA-HDBK-4002A according to the ESD Sensitivity Classification of the parts (MIL-STD-883G, 2006).

#Insertion of Figure 7

An example of stacked plots for the risk assessment of ESA/Kodama's internal charging/ESD based on our system are shown in Figure 8. In this calculation, the thickness of satellite shield (d_1) and that of target material (d_2) are 0.22 mm and 0.15 mm of aluminum, respectively. This means that the higher and lower limit of incident electron energy into the target material are 300 keV and 250 keV, respectively.

#insertion of Figure 8

The basic functions of the risk assessment system of internal charging/ESD have been established. Using this system, a customized alert for individual user will be issued based on the user's selection of the target material which could be weak for internal charging/ESD according to the design of operating satellite. If a user inputs the thickness of the satellite shield and the devices (target material) that could be weak for internal charging/ESD, risk of satellite anomaly will be estimated on routine base using the prediction result of high energy electron spectra obtained from our radiation belt model, the alert could be issued according to the excess of three threshold levels.

Discussion and Summary

We have been developing SECURES for risk assessment of surface charging/ESD and internal charging/ESD in GEO combining space environment model with satellite charging model. We have confirmed the basic functions of SECURES based on the prototype products. In principle, this product could be used for the practical purpose when we operate these products in near-real time. To provide customized risk information for satellite operator, the detailed information of individual satellite structure and materials are needed. However, as described in the previous subsection, it is not easy to get such information because of non-disclosure from satellite industries. We need to consider more communication with satellite industry to get detailed information of satellite structure and materials. So, we will start demonstrating our system based on the several sample models of satellites. Prototype products of SECURES will be provided to the public in the near future. It will be useful for the satellite operator and will improve the safety of the satellite operation. We will also consider expanding the target region from GEO to Medium Earth orbit, and Low Earth Orbit.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

List of abbreviations

SEPs: Solar Energetic Particle events, UN/COPUOUS: the United Nations / the Committee on the Peaceful Uses of Outer Space, MHD: Magnetohydrodynamics, SPIS: Spacecraft Plasma Interaction Software, MUSCAT: Multi-Utility Spacecraft Charging Analysis Tool, MPI: Message Passing Interface, REPPU: REProduce Plasma Universe, NICT: National Institute of Information and Communications Technology, NOAA/SWPC: National Oceanic and Atmospheric Administration’s Space Weather Prediction Center, MPA: Magnetospheric Plasma Analyzer, LANL: Los Alamos National Laboratory, CDAWeb: Coordinated Data Analysis Web, R_E: Earth radius, SM: Solar Magnetic, ESA: Earth Sensor Assembly, DRTS: Data Relay Test Satellite

Availability of data and materials

The real-time solar wind data at the L1 point provided by NOAA/SWPC are available at https://www.swpc.noaa.gov/products/real-time-solar-wind. LANL/MPA data provided by NASA/CDAWeb are available at https://cdaweb.gsfc.nasa.gov/index.html. The data obtained from global magnetosphere MHD simulation can be shared on request to A. Nakamizo. SPIS is available at http://dev.spis.org/projects/spine/home/spis. The geometric model of Van-Allen Probes can be shared on request to M. Nakamura. The geometric model of Michibiki-1 satellite cannot be shared because the model includes non-disclosure information. The data obtained from empirical models of estimating potential of surface charging can be shared on request to M. Nakamura. The real-time auroral electrojet indices provided by World Data Center for Geomagnetism, Kyoto are available at http://wdc.kugi.kyoto-u.ac.jp/ae_realtime/index.html. SDOM/Kodama data are available at http://sees.tksc.jaxa.jp/fw/dfw/SEES/index.html. ESA/Kodama’s anomaly data cannot be shared because of its data policy of JAXA. The data obtained from the radiation belt model can be shared on request to

Y. Miyoshi. MUSCAT Space Engineering Co., Ltd. (MUSE: http://astro-muse.com/) sells MUSCAT software and provides related support. Currently, services are domestically provided. The data obtained from simple internal charging model can be shared on request to K. Koga.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

TN leaded the development of SECURES and edited the paper. AN and YK improved global magnetosphere MHD model and prototype surface charging/ESD risk assessment system. MN developed empirical functions of surface charging estimation by SPIS. KK examined internal charging risk by MUSCAT and developed prototype internal charging/ESD risk assessment system by simple analysis method. YM developed radiation belt model. HM provided satellite anomaly data of ESA/Kodama and supervised the project of SECURES. All authors read and approved the final manuscript.

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Real-time solar wind data at L1 point are provided by NOAA/SWPC. Observed plasma moment data of LANL/MPA are downloaded from NASA/CDAWeb. The real-time auroral electrojet indices are provided by World Data Center for Geomagnetism, Kyoto.

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Figure Captions

Figure 1 A conceptual picture of SECURES

Figure 2 A quick look of the real-time global magnetosphere MHD simulation result.

Figure 3 Geometric models of the Van Allen Probes (left) and the Michibiki-1 satellite (right).

Figure 4 The frame and maximum surface potentials estimated by SPIS with the geometric model of Michibiki-1 satellite under the daylight condition.

Figure 5 A schematic snapshot of the web viewer of the system which is taken at 09:00 UT on July 05, 2020. The viewer is presently only for Japanese. The left panel shows the pressure and bulk flow velocity distributions on the equatorial plane in the SM coordinate system. The right panel shows the pressure distribution on the 6.6 R_E sphere in the geographic coordinate system. Specific date and time can be selected at the top column. Two hours movie from the selected start time in the right panel can be played by controlling the bottom slider. The pink cross mark cursor on the right panel of Figure 5 can be moused over to examine the parameters and estimated satellite potentials. These information can be seen in the The result is instantaneously shown in the table inside the viewer. Schematic table is is separately shown in Table 1.

Figure 6 Daily noise counts of ESA and the daily mean differential electron flux of SDOM (Ch.3: 0.59-1.18 MeV) during Jan. 2003 to Jun. 2003 are plotted by blue and red lines, respectively. The occurrence of ESA's satellite anomaly are shown by arrows.

Figure 7 (left) A simple structure model for internal charging. the depth of satellite shield (d_1) and thickness of the target material (d_2) can be defined on request (right) Charge(Q) of d_2 region calculation method from energy spectrum

Figure 8 An example of stacked plots for the risk assessment of the internal charging/ESD. From top to bottom: the differential electron flux observed by Ch.3(0.59-1.18 MeV) of SDOM/Kodama, the differential electron flux estimated by the radiation belt model, current accumulated inside the target material (d_2), daily mean of current accumulated inside the target material (d_2).

Table 1 A schematic example of some parameters and estimated spacecraft potentials at the selected point shown as a pink cross mark in the right panel of Figure 5. This table is shown in the web viewer of surface charging/ESD risk assessment system.

Lat. [deg.]	**Long. [deg.]**	**Density [/cc]**	**Temperature [keV]**	**Pressure [nPa]**
220.0	-18.0	1.00	1.62	11.1
Eclipse=1 Daylight=0	**Scientific Satellite**	**Commercial Satellite**		
	Surface potential Φ_{SC}[V]	Surface potential Φ_{MAX}[V]	Frame potential Φ_{FRAME}[V]	Differential potential [V]
1	-87,000	-56,000	-81,000	250,000

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