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

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Abstract

Plasma variations in the geospace environment driven by the solar wind–magnetosphere interaction are one of the major causes of satellite anomaly. To mitigate the effect of satellite anomaly, the risk of space weather disturbances predicted by space weather forecasting needs to be known in advance. However, the risk of satellite anomaly owing to space weather disturbances is not the same for all satellites, because the risk depends not only on the space environment itself but also on the design and materials of individual satellites. From the viewpoint of satellite operators, it is difficult to apply a general alert level of the space environment to the risk of individual satellites.

To provide tailored space weather information, we have developed SECURES (Space Environment Customized Risk Estimation for Satellites) by combining models of the space environment and those of spacecraft charging. In SECURES, we focus on the risk of spacecraft charging (surface/internal) for geosynchronous satellites. For the risk estimation of surface charging, we have combined the global magnetosphere magnetohydrodynamics (MHD) model with the satellite surface charging models. For the 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/electrostatic discharge (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 around Earth (geospace) has been used by many types of satellites for
various purposes, such as telecommunications, broadcasting, Earth observation, and
positioning. The plasma and electromagnetic environments in geospace change
significantly owing to disturbances in geospace, such as substorms and storms caused
by the solar wind–magnetosphere interaction. They can also be affected by high-energy
particles, known as solar energetic particle (SEP) events. The disturbances in geospace
cause various satellite anomalies, such as charging/discharging and central processing
unit (CPU) malfunctions. Therefore, satellites are designed and developed with measures to prevent anomalies due to geospace disturbances during operation and in the satellite's orbit.

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

Firstly, when a satellite anomaly occurs, triage determination should be the first action. The satellite operator needs to identify the cause of the anomaly (misoperation, manufacturing problem, or space environment) to decide their next action for mitigating the effect of the anomaly. For this purpose, it is necessary to understand the current condition (nowcast) of the space environment around the satellite to determine whether the malfunction/failure is caused by the space environment or other factors (O'Brien et al., 2013).

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

Thirdly, in the case of conducting critical operations, such as attitude control and/or
rewriting onboard programs, where mistakes and errors can seriously affect the satellite,
the satellite operator should refer to the space weather forecast and make a 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 can be
predicted, the 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 rapid recovery in the event of a satellite anomaly.

However, the specific utilization of space weather forecasts in the current satellite
operation is still in the development 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, it is difficult for satellite manufacturers and satellite operators to disclose detailed information about satellite anomalies to the public. To overcome this situation, the United Nations Committee on the Peaceful Uses of Outer Space (UN/COPUOS) has called for the sharing of information 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).

Another issue is the 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 considerably 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 the geospace environment are driven by solar wind, forecasts with sufficient lead times cannot be realized unless the state of solar wind can be predicted in advance. However, since there are few observations between the Sun–Earth line, the
current status of forecasting lead time is about 1 h ahead using data from the solar wind
observation at the L1 point of the Sun–Earth system. Prediction with longer lead times
is much less accurate.

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

On the basis of this background, we have been developing a charging risk estimation
scheme for satellite operators, called SECURES (Space Environment Customized Risk
Estimation for Satellites), under PSTEP (Project for Solar-Terrestrial Environment
Prediction) (Nagatsuma, 2017). In this paper, we will introduce the outline of
SECURES, the surface charging module, and the internal charging module, and
summarize and discuss our achievements.
Outline of SECURES

Electrostatic discharge (ESD) due to space weather disturbances is one of the major causes of satellite anomalies (e.g., Ferguson et al., 2015). More than half of the satellite anomalies are caused by ESD (Koons et al., 1999). There are two types of charging mechanism that will cause ESD, namely, surface charging and 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 as well as the interior, leading to the charging and discharging of cables and equipment inside the satellite. Owing to variations of the plasma environment in geospace, the electric potential on the surface and inside of the satellite may change, resulting in electrical discharges and leading to malfunctions and failures. Charging and discharging conditions differ depending on the satellite shape and materials even if the
space environment condition is the same. Therefore, it is difficult for a satellite operator
identify the operational risk of an individual satellite using only the general information
of space weather nowcast/forecast. This problem will be reduced by estimating the
charging risk of an individual satellite using satellite charging models while providing
the current and future conditions of the space environment at the position of an
individual satellite using models of space weather forecast.

#Insertion of Figure 1

Figure 1 shows the concept of SECURES. Specifically, for each of surface and internal
charging, the 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 the satellite 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 the Global
Magnetohydrodynamics (MHD) model. The information on the simulated space
environment is used to calculate the charging of an individual satellite under a certain
space environment condition using a satellite charging model such as the Spacecraft
Plasma Interaction System (SPIS) (Roussel et al., 2008) or Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT) (Hosoda et al., 2008; Muranaka et al., 2008).

High-energy particles that cause internal charging are predicted by radiation belt simulation. The information on the predicted space environment is used to calculate the internal charging using MUSCAT. Detailed information on the surface charging and internal charging parts of SECURES 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 on the basis of a predesigned satellite model, including information on the shape and materials of the satellite, and the global magnetosphere MHD model, which simulates the plasma environment for the input of charging analysis models. We have developed a prototype surface charging/ESD risk assessment system targeting the geostationary earth orbit (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 using the real-time global magnetosphere

MHD model

The global magnetosphere MHD model used in the surface charging part of SECURES was originally developed by Tanaka (1994) and Tanaka et al. (2010). The message passing interface (MPI) parallelized version of the model is called the 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 their center with sufficiently high spatial resolution and numerical stability. It is shown that the code is sufficiently robust to simulate magnetospheric responses to extreme conditions, such as intense solar wind velocity and density and the high intensity of the interplanetary magnetic field (Kubota et al., 2017). The relationships among the space environment data and surface charging data obtained from the Michibiki-1 satellite, and space environment data obtained from global magnetosphere MHD simulation are examined as a first step (Nagatsuma et al.,
For simplicity, the original code assumes that Earth’s magnetic dipole axis and the rotation axis coincide with each other. Therefore, it does not meet the requirements for practical use and operation as it is, because in the actual solar-terrestrial system, Earth’s rotation axis is inclined with respect to the ecliptic plane, and the magnetic dipole axis is tilted from the rotation axis, completing the precession.

To perform a more realistic simulation, we have improved the model by introducing the inclination and precession of the magnetic dipole axis (Kubota et al., 2019). With this improved model, a real-time global magnetosphere simulation on the High-Performance Computing System at the National Institute of Information and Communications Technology (NICT) is carried out. The real-time simulation is driven by the real-time solar wind data at the L1 point of the Sun–Earth system provided by the 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 Earth’s magnetosphere is about 1 h, and the processing time of the real-time simulation system is about 20 min, the total lead time of the real-time
simulation is about 40 min on average. Figure 2 shows a quick look at 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 using the MHD model.

Nakamura (2012) statistically compared the plasma parameters in GEO simulated using the old version of our global magnetosphere MHD model and those obtained from the 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 has a good correlation with the observed electron pressure. We have applied the same approach of Nakamura (2012) to the current version of our MHD model. We used the plasma moment data of LANL/MPA from February to April in 2006
available via the Coordinated Data Analysis Web (CDAWeb). First, we searched for events in which LANL/MPA observed negative potential in association with the occurrence of isolated substorms, while the satellites were in the nightside. A total of 12 events were selected. For each event, we performed the MHD simulations by using the OMNI solar wind and IMF data (available via CDAWeb) as the input. We extracted the time series of plasma parameters along the satellite orbits from the simulation data, then compared them with the LANL/MPA data.

#Insertion of Figure 3

Figure 3 shows an example of the deep negative satellite charging event during an isolated substorm that occurred at around 10:00 UT on February 15, 2006. The top three panels show the OMNI data: the three components of IMF in the GSM coordinate system, solar wind speed, and solar wind density. The fourth and fifth panels show the cross polar cap potential (CPCP) estimated from PCN index (Troshichev et al., 1996) and AU/AL indices, respectively. The CPCP and AU/AL indices deduced from the simulation are shown by the red lines in each panel. The next three panels show plasma moment data. The observed electron, ion, and simulation data are shown by the solid
black, dotted black, and solid red lines, respectively. Shown from the sixth to eighth panels are, respectively, \(N_e\), \(N_i\), and simulated plasma density \(N_{\text{sim}}\); \(T_e\), \(T_i\), and simulated plasma temperature \(T_{\text{sim}}\); \(P_e\), \(P_i\), and simulated plasma pressure \(P_{\text{sim}}\). The ninth panel shows the satellite potential. The bottom two panels show the satellite orbit in (MLT, L) and in (X, Y, Z) of the GSM coordinate system, respectively. Around the period of the substorm, the LANL satellite, which remained in the midnight sector, observed the enhancements of electron and ion parameters, leading to a deep negative spacecraft potential that reached about \(-6,000\) [V].

Similar to the result of Nakamura (2012), \(P_{\text{sim}}\) is well correlated with the observed \(P_e\).

This characteristic is confirmed for all selected events. On the basis of this result, we consider a method for estimating \(N_e\) and \(T_e\) from the simulation data.

For each selected event, we searched for the simulation time when \(P_{\text{sim}}\) showed the peak value within \(\pm 30\) min from the time when \(P_e\) peaked, leading to negative charging, and extracted simulation data and observational data at each timing of the pressure peak. Figure 4 shows the scatter plots of extracted data. Figures 4(a), 4(b), and 4(c) are
the scatter plots of $N_e$ versus $N_{\text{sim}}$, $T_e$ versus $T_{\text{sim}}$, and $P_e$ versus $P_{\text{sim}}$, respectively. Figure 4(d) is the scatter plot of observed $T_i$ versus $T_e$. $P_{\text{sim}}$ has a good correlation with $P_e$. On the other hand, $N_{\text{sim}}$ tends to be much higher than $N_e$, and $T_{\text{sim}}$ tends to be lower than $T_e$.

We focus on the result that the observed $N_e$ is about $1/\text{cm}^3$. Because $P_{\text{sim}}$ is in good agreement with $P_e$, and $N_e$ is almost $1/\text{cm}^3$, we derive $T_e$ from $T_{\text{sim}}$ or $P_{\text{sim}}$ assuming $N_e=1$. The electron temperature $T_{\text{sim}-e}$ estimated in this way is plotted in Fig. 4(b) by orange asterisks. Also, in Fig. 3, we plot $T_{\text{sim}-e}$ by the orange line; $T_{\text{sim}-e}$ well traces $T_e$ better than $T_{\text{sim}}$ itself.

More sophisticated estimation methods may be conceivable. However, we adopt the simplified method at present. As for $T_i$, we multiply the derived $T_{\text{sim}-e}$ by a factor of 1.9. This factor is the average ratio of $T_i$ to $T_e$ in Fig. 4(d). On the basis of these empirical relationships, $N_i$, $T_i$, $N_e$, and $T_e$ from the real-time simulation data for the nightside GEO region are estimated.

Estimating real-time risk of surface charging using SPIS

The surface charging of an individual satellite is calculated using SPIS under space
environment conditions and 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, the surfaces of which are conductive and electrically connected (Stratton et al., 2013). The other is the Michibiki-1 satellite, a typical three-axis stabilized geosynchronous satellite with dielectric materials (Inaba et al., 2009). Figure 5 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 Probes. The absolute charging would have an effect on some scientific observations. We calculate the floating potentials of the surface materials and the local differential charging potentials for the geometric model of the 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.

However, it is impossible to obtain the surface potentials in near real time from real-
time global magnetosphere MHD simulation data because the 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
equilibrium surface potential using precalculated results. The estimation of 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 conditions $N_e=N_i=1/cc$ and $T_i=1.9* T_e$ with $T_e$ as a
single variable. Figure 6 shows an example of the frame (chassis ground) and maximum
surface potentials of the Michibiki-1 satellite model in daylight as a function of $T_e$. In
this case, several frame and maximum surface potentials are calculated for some values
of $T_e$. A polynomial function is fitted for the results of the calculation, and we can
obtain the empirical function of the surface charging potential from several
precalculated results. With these functions, the frame and maximum surface potentials
of the Michibiki-1 satellite can be quickly estimated from real-time simulation data. We
also developed the empirical function for the surface potentials of the Van Allen Probes.

#Insertion of Figure 6
In the case of $N_e=N_i=2/\text{cc}$, the lines of Fig. 6 shift to the right by hundreds of eV but there is little change in their slope. The errors between the estimation method and the charging calculation results are usually a few percent, and even in bad cases, are less than 10 percent when the calculations do not reach equilibrium even after 1 h or more of charging. The details of the estimation method are beyond the scope of this paper.

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 min, we extract the plasma environment data on the sphere of the 6.6 Earth radius ($R_e$), which is identical with GEO, every 5 min. The extracted data are stored in the system. The results of the prototype surface charging/ESD risk estimation system can be browsed with a web viewer. However, the web viewer is for internal use at present.

Since the explanation in the viewer is in Japanese, the content described in the viewer is shown as a schematic snapshot and a table. Figure 7 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 an overview of 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 Re sphere in the geographic coordinate system.

When we open the viewer, the latest condition is shown by default. At the top column, we can select the date and time of our interest. After selecting a specific time period, a 2-h movie from the selected start time can be played by controlling the bottom slider.

Because Figure 7 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 noon corresponds to the dayside cusps. On the other hand, another high-pressure region is seen around midnight. It seems that the pressure enhancement around 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 lists examples of some parameters and estimated spacecraft potentials at the selected point shown as a pink cross in the right panel of Fig. 7. This table is also
browsed within the web viewer. When users mouse over the pink cross cursor on the right panel of Fig. 7, 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 and 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 estimate the absolute/differential potentials as an indication of the charging/ESD risk. Because the critical voltage levels for charging/ESD risk are different in individual satellites owing to the difference in surface material and configuration, the satellite operators should use these potentials as a guide to understanding and evaluating the surface charging/ESD risk for their satellites.

For additional information, we calculated the potentials of a modeled scientific satellite by using the estimated $T_{\text{sim-e}}$ of the February 15, 2006 event shown in Fig. 3. At the time
when \( P_{\text{sim}} \) peaked within 30 min, \( P_{\text{sim}} = 2.26 \) [keV], \( P_{\text{sim}} = 0.96 \) [nPa], and estimated \( T_{\text{sim,e}} = 6.98 \) [keV]. (The observed \( T_e \) was 6.624 [keV].) We obtained the satellite potential of \(-4,032 \) [V] for the ecliptic condition.

Although the estimated potential is lower than the potential observed by LANL/MPA, which reached about \(-6,000 \) [V], this value is in relatively good agreement with the observation within a certain factor. This discrepancy is not significant because the shapes and materials of the modeled and LANL satellites are different from each other.

In other words, even if the space environments are the same, the surface charging conditions are different for individual satellites.

**Internal Charging Part of SECURES**

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

Satellite anomalies that occurred at ESA onboard Kodama (DRTS)

Kodama (DRTS), which was launched on September 10, 2002, started routine operation in January 9, 2003. On March 23, 2003, a satellite anomaly occurred at the ESA onboard Kodama. The ESA shifted from the nominal system (ESA-A) to the redundant system (ESA-B). Afterwards, the same kind of anomaly occurred on April 2, May 27, and June 6, 2003. It was found that the ESA anomaly occurred during the period of increase in the ESA’s noise count. To identify the cause of the anomaly, the relationship between the ESA’s noise count and the high-energy electron flux observed by the 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 Ch.3 of the differential electron flux (0.59–1.18 MeV) observed by SDOM/Kodama (Figure 8). This relationship suggests that the possible cause of the ESA’s anomaly is
internal charging/ESD. Using events of the satellite anomaly that occurred at ESA onboard Kodama, an internal charging/ESD risk assessment system has been developed.

#Insertion of Figure 8

**High-energy electron environment at GEO estimated using radiation belt model**

To evaluate the energetic electron flux at the satellite location, we used the one-dimensional Fokker–Planck equation to describe the radial diffusion (Miyoshi et al., 2004), where \( f \) is the phase space density and \( t \) is time.

\[
\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L} \left( \frac{D_{LL}}{L^2} \frac{\partial f}{\partial L} \right) - \sum \frac{f}{\tau_i}
\]

Here, \( L \) is the L-shell. We used the empirical radial diffusion coefficient \( (D_{LL}) \) formulated by Brautigam and Albert (2000). We consider the electromagnetic coefficients to be parameterized. The time step for calculation is 1 h. The loss terms are described by the lifetimes due to Coulomb collisions \( (\tau_c) \) and wave-particle interactions \( (\tau_{wp}) \) inside the plasmasphere. The lifetime \( \tau_c \) 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 of the phase space...
density $f$, we derived the differential flux $j(E, L, t)$, where $E$ is the electron energy.

Considering the L-shell of Kodama, which varies during a day, we calculated the time variation of $j$ along the Kodama orbit. In this model, we 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 started in 2004 and was completed in 2007 (Hosoda et al., 2008; Muranaka et al., 2008). MUSCAT has the analysis feature of surface charging, and the internal charging simulation function was added in 2010. In the internal charging analysis, the range of the high-energy electrons is calculated by the Monte Carlo method.

The structure and materials of ESA were modeled using the MUSCAT graphical user interface. The external electron energy spectrum was estimated using the 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 using MUSCAT is very small compared with the threshold potential.
of ESD. The structure around the ESA sensor has adequate thickness, which reduces 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 a thin shield, must be considered. An experimental study also suggested that noise produced by ESD could propagate in panels and cables (Kinoda et al., 2018). A detailed quantitative analysis is necessary to clarify the internal charging/ESD of the ESA onboard Kodama, including the development of the detailed structure and material model inside the satellite. However, it is difficult to develop such a detailed model because data on the detailed structure and material are not usually disclosed by the satellite industry.

Risk assessment system of internal charging/ESD

The results discussed in the previous subsection suggest that the risk assessment of internal charging based on MUSCAT with the structure model of a specific part is weak for determining the cause of internal charging. Therefore, a risk assessment system of internal charging/ESD has been developed on the basis of a simple analysis method
introduced in the NASA-HDBK-4002A (2017).

The procedure of our risk assessment system of internal charging/ESD is as follows. A 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 9). To estimate the range of incident electron energy into the target material ($d_2$), the lower limit ($E_1$) and higher limit ($E_2$) of incident energy are converted from $d_1$ and $d_1+d_2$. The accumulated current inside the target material is calculated from the differential energy spectrum between $E_1$ and $E_2$ (Figure 9). The differential energy spectrum is obtained from our radiation belt model described in a previous subsection. Alert levels for the risk of internal charging/ESD are set to 0.1, 0.3, and 1.0 pA/cm$^2$ on the basis of NASA-HDBK-4002A in accordance with the ESD Sensitivity Classification of the parts (MIL-STD-883G, 2006). If the circuitry is classes 1 and 2 ESD-sensitive, shield to levels of 0.1 and 0.3 pA/cm$^2$, respectively. If the current exceeds 1 pA/cm$^2$, IESD (Internal ESD) may occur (NASA-HDBK-4002A). A flow chart of the alert system of internal charging is shown in Fig. 10.

#Insertion of Figure 9
An example of stacked plots for the risk assessment of ESA/Kodama’s internal charging/ESD using our system is shown in Fig. 11. In this calculation, $d_1$ and $d_2$ are 0.22 and 0.15 mm of aluminum, respectively. This means that the higher and lower limits of the incident electron energy into the target material are 300 and 250 keV, respectively. Figure 11 shows that this system is capable of sending an alert to the user who set the thickness of the shield and the device in accordance with the ESD risk.

The basic functions of the risk assessment system of internal charging/ESD have been established. With this system, a customized alert for an individual user can be issued on the basis of the user’s selection of the target material, which could be susceptible to internal charging/ESD depending on the design of the operating satellite. If a user inputs the thicknesses of the satellite shield and the devices (target material) that may be susceptible to internal charging/ESD, the risk of satellite anomaly can be estimated on a routine basis using the prediction result of high-energy electron spectra obtained from our radiation belt model, and an alert could be issued in accordance with the excess of
Discussion and Summary

We have been developing SECURES for the risk assessment of surface charging/ESD and internal charging/ESD in GEO combining a space environment model with a satellite charging model. We have confirmed the basic functions of SECURES as prototype products. In principle, these products could be used for practical purposes when we operate these products in near real time. To provide customized risk information for satellite operators, detailed data on the structures and materials of individual satellites are needed. However, as described in the previous subsection, it is difficult to obtain such data because of the nondisclosure from satellite industries. We need to promote further communication with the satellite industry to obtain detailed information on satellite structure and materials. Thus, we will start demonstrating our system based on several sample models of satellites. Prototype products of SECURES will be provided to the public in the near future. These products will be useful for satellite operators and will improve the safety of satellite operation. We will also
consider expanding the target region from GEO to medium and low Earth orbits.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

List of abbreviations

SECURES: Space Environment Customized Risk Estimation for Satellites, MHD: Magnetohydrodynamics, ESD: Electrostatic Discharge, SEP: Solar Energetic Particle, CPU: central processing unit, UN/COPUOUS: United Nations/Committee on the Peaceful Uses of Outer Space, PSTEP: Project for Solar-Terrestrial Environment Prediction, SPIS: Spacecraft Plasma Interaction Software, MUSCAT: Multi-Utility Spacecraft Charging Analysis Tool, GEO: Geostationary Earth Orbit, 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, CPCP: Cross Polar Cap Potential, \( R_E \): 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 obtained from A. Nakamizo upon request. SPIS is available at http://dev.spis.org/projects/spine/home/spis. The geometric model of Van Allen Probes can be obtained from M. Nakamura upon request.
geometric model of the Michibiki-1 satellite cannot be shared because the model includes nondisclosure information. The data obtained from empirical models of estimating the potential of surface charging can be obtained from M. Nakamura upon request. The real-time auroral electrojet indices provided by the 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 the data policy of JAXA. The data obtained from the radiation belt model can be obtained from Y. Miyoshi upon request. 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 a simple internal charging model can be obtained from K. Koga upon request.

Competing interests
The authors declare that they have no competing interests.

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**Authors’ contributions**

TN led the development of SECURES and edited the paper. AN and YK improved the global magnetosphere MHD model and prototype surface charging/ESD risk assessment system. MN developed the empirical functions of surface charging estimation by SPIS. KK examined the internal charging risk by MUSCAT and developed the prototype internal charging/ESD risk assessment system based on a simple analysis method. YM developed the 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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Wentworth RC, MacDonald WM, and Singer SF (1959) Lifetimes of trapped radiation belt particles determined by Coulomb scattering, Phys. Fluids, 2, 499–509.
Figure Captions

Figure 1 A conceptual picture of SECURES.

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

Figure 3 Time series data of LANL/MPA and global MHD simulation for a deep surface charging event during an isolated substorm that occurred around 10:00 UT on February 15, 2006. The top three panels show the OMNI data: the three components of IMF (in the GSM coordinate system), solar wind speed, and solar wind density. The fourth and fifth panels shows the cross polar cap potential (CPCP) estimated from PCN index (Troshichev et al., 1996) and AU/AL indices (simulation data are shown by red lines). The sixth to eighth panels respectively show $N_e$, $N_i$, and simulated plasma density $N_{sim}$; $T_e$, $T_i$, and simulated plasma temperature $T_{sim}$; $P_e$, $P_i$, and simulated plasma pressure $P_{sim}$. (The observed electron, ion, and simulation data are shown by the solid black, dotted black, and solid red lines, respectively.) The ninth panel shows the satellite potential. The bottom two panels show the satellite orbit in (MLT, L) and in (X, Y, Z) of the GSM coordinate system, respectively. The orange line in the seventh panel shows the estimated electron temperature $T_{sim-e}$.
Figure 4 Extracted observational data at the time when $P_e$ peaked, leading to negative charging timing of pressure peak, and simulation data at the simulation time when $P_{sim}$ showed the peak value within $\pm 30$ min from the time when $P_e$ peaked. Scatter plots of (a) $N_e$ versus $N_{sim}$, (b) $T_e$ versus $T_{sim}$, (c) $P_e$ versus $P_{sim}$, and (d) observed $T_i$ versus $T_e$.

Figure 5 Geometric models of Van Allen Probes (left) and Michibiki-1 satellite (right).

Figure 6 Frame and maximum surface potentials estimated by SPIS with the geometric model of Michibiki-1 satellite under daylight condition.

Figure 7 Schematic snapshot of the web viewer of the system, which was taken at 09:00 UT on July 05, 2020. At present, the viewer is only in 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. A 2-h movie from the selected start time in the right panel can be played by controlling the bottom slider. The pink cross mark on the right panel of Figure 5 can be moused over to examine the parameters and estimated satellite potentials. The result is instantaneously shown in the table inside the viewer. A schematic table is separately
shown in Table 1.

Figure 8 Daily noise counts of ESA and daily mean differential electron flux of SDOM (Ch.3: 0.59–1.18 MeV) from Jan. 2003 to Jun. 2003 are plotted by blue and red lines, respectively. The occurrence of ESA satellite anomaly is shown by arrows.

Figure 9 (left) A simple structure model for internal charging. The thicknesses of the satellite shield (d₁) and target material (d₂) can be provided upon request. (right) Charge (Q) of the d₂ region calculated from energy spectrum.

Figure 10 Flow chart of the alert system of internal charging.

Figure 11 An example of stacked plots for the risk assessment of the internal charging/ESD. From top to bottom: differential electron flux observed by Ch.3 (0.59–1.18 MeV) of SDOM/Kodama, and differential electron flux estimated using the radiation belt model, current accumulated inside the target material (d₂), and daily mean of current accumulated inside the target material (d₂). The three dotted lines show the current levels of 0.1, 0.3, and 1.0 pA/cm² in accordance with the ESD risk. The arrow shows the anomaly event of ESA that occurred on April 2, 2003.
Table 1 A schematic example of some parameters and estimated spacecraft potentials at the selected point shown as a pink cross in the right panel of Figure 5. This table is shown in the web viewer of the surface charging/ESD risk assessment system.

| Long. [deg.] | Lat. [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  | Surface potential Φ  |
|           |            | sc[V]                | MAX[V]               |
| 1         | −87,000    | −56,000              | −81,000              | 250,000      |

Differential potential [V]