

Space Weather-Induced Charging in The Garuda-1 Satellite Power Failure

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Abstract

This study investigates the relationship between the geostationary space environment and the Garuda-1 satellite power anomaly that occurred on April 5, 2005. To assess potential anomaly mechanisms, GOES-12 electron and proton flux data, geomagnetic indices, solar wind parameters, and SPENVIS-based charging simulations were examined. While proton fluxes and solar X-ray activity remained relatively low during the event period, relativistic electron fluxes increased significantly under disturbed geomagnetic conditions, as indicated by enhanced AE activity, increased solar wind speed, and prolonged southward IMF Bz. Under these conditions, SPENVIS simulations indicate increased spacecraft surface and internal charging susceptibility. The findings suggest that storm-time energetic electron enhancement and associated charging processes in the geostationary environment may have been associated with the reported Garuda-1 anomaly. This work emphasizes the importance of magnetic local time dependence and geomagnetic activity in influencing spacecraft charging risk for geostationary satellites.

Keywords

Garuda-1 Anomaly, Energetic Electrons, Space Weather, Geomagnetic Activity, MLT, Satellite Charging

Received: 5 May 2026, Accepted: 4 September 2026

<https://doi.org/10.26554/sti.2026.11.4.1705-1714>

1. INTRODUCTION

For more than three decades, extensive research has been conducted to understand how the space environment affects satellites and to develop ways to enhance their resistance to these harsh conditions. The impact of the space environment on a satellite varies depending on its orbit and the surrounding environment (Belov et al., 2004; Dorman et al., 2005; Iucci et al., 2005; Ahmad et al., 2026a; Kirov et al., 2024). Satellites in low Earth orbit (LEO) experience high particle density but low particle energy, while polar-orbiting satellites also encounter high-energy particles when passing through the polar regions. In contrast, satellites in higher orbits are exposed to low-density but high-energy particle environments (Ahmad et al., 2018; Surkov and Mozgov, 2021). Geostationary orbit (GSO) satellites, which occupy high orbits with low inclination, are typically positioned near the plasmapause, where particle density is low and particle energy is high. However, during periods of increased solar or geomagnetic activity, the plasmasphere can expand or contract, causing satellites to become

immersed in regions of significantly higher particle density (Lai, 2011). During magnetospheric substorms, magnetic reconnection in the magnetotail accelerates particles in the plasma sheet, driving their inward transport and resulting in energetic particle injections into the GSO region (Li et al., 2005; Ahmad et al., 2025).

Energetic particles such as protons and electrons can interact with satellites through mechanisms that may lead to operational degradation or system failure. These interactions may involve direct penetration of satellite electronics, leading to system failures, or electrostatic charging, which can result in electrical discharges and equipment burnout (Lai, 2011; Garrett and Whittlesey, 2012). For GSO satellites, surface charging is a common disturbance caused by interactions with electrons in the keV energy range (Baker, 2000; Thomsen et al., 2013). While surface charging can lead to mission disruptions over time, more severe and immediate failures are often the result of deep internal charging, where high-energy electrons penetrate spacecraft walls and become trapped within internal

systems (Baker, 2001; Fennell et al., 2001; Lai, 2011; Gubby and Evans, 2002; Pilipenko et al., 2006). Previous Indonesian studies on spacecraft systems exposed to the near-Earth space environment have highlighted the effects of energetic particle populations on satellite subsystem performance, particularly in relation to electronic degradation and in-orbit anomaly occurrence.

The variability of energetic particles in space is closely related to the dynamics of space weather, which are influenced by solar activity and the geomagnetic conditions of the Earth. Various phenomena, such as solar wind variations, solar flares, and coronal mass ejections (CMEs), can trigger changes in particle flux at GSO, which in turn modulate the response of the magnetosphere (Pratiwi et al., 2025). Proton flux variations in GSO are generally associated with SEP events originating from solar activity, although contributions from particles trapped in the radiation belts may also play a role. Meanwhile, electron flux variations are more strongly controlled by geomagnetic activity, such as geomagnetic storms and substorms, which are triggered by the interaction between the solar wind and Earth's magnetosphere (Hua et al., 2023). Thus, the variability of energetic particle flux is an important factor in determining interactions with satellites, including effects such as surface and deep dielectric charging, as well as radiation-induced electronic disturbances. These flux fluctuations directly reflect the conditions of space weather. To characterize the level of such disturbances, NOAA developed disturbance scales known as the NOAA Space Weather Scales, which are widely used to identify potential risks to satellite systems.

Garuda-1, Indonesia's communication satellite, is in a geostationary orbit at 123 °E longitude. Asia Cellular Satellite (ACeS) International, based in Batam, is the operator of this satellite. The satellite was launched on February 12, 2000, at 09:10:54 UTC by the International Launch Service (ILS) using a Proton-K rocket from Baikonur Cosmodrome, Tyuratam, Kazakhstan. With 188 transponders, the Garuda-1 satellite can cover 22 countries: from Japan in the north to Indonesia in the south, from Guam (Philippines) to Papua New Guinea in the east, and Pakistan in the west. Information about the Garuda-1 satellite has been reported by International Launch Services (ILS) and other satellite databases. The Garuda-1 satellite was reported to have unexpectedly lost power on April 5, 2005, without a clearly identified cause (Choi et al., 2011; Rachman and Herdiwijaya, 2014). The malfunction was believed to be associated with disturbances affecting the satellite's solar panels, which serve as its primary source of operational power. Such power degradation may reduce the satellite's operational lifetime compared with its original design expectations (Hanslmeier, 2010).

Rachman and Herdiwijaya (2014) investigated the Garuda-1 anomaly using solar wind and interplanetary magnetic field parameters through a superposed epoch analysis. Their study suggested that the anomaly was associated with a Corotating Interaction Region (CIR) event that generated a moderate geomagnetic storm, indicating that solar wind structures acted

as external drivers of the disturbance. However, their analysis mainly focused on identifying the interplanetary source of the event and did not examine how the resulting geomagnetic disturbance affected the local plasma environment at geostationary orbit where the satellite operated. Consequently, the physical mechanism linking CIR-driven geomagnetic activity to the satellite anomaly remains insufficiently understood.

Furthermore, a comprehensive assessment integrating observational energetic particle analysis, Magnetic Local Time (MLT) dependence, and physics-based spacecraft charging simulations has not yet been carried out. In particular, the relationship between MLT-dependent radiation belt dynamics, storm-time electron enhancement, and possible internal charging processes affecting the satellite remains poorly understood. To address these issues, the present study combines GOES energetic particle observations, geomagnetic and solar wind parameters, MLT analysis, and SPENVIS charging simulations to investigate the potential charging-related mechanisms associated with the reported Garuda-1 anomaly.

2. EXPERIMENTAL SECTION

2.1 Materials

The data were categorized into energetic particle measurements associated with satellite exposure and space weather parameters influencing particle dynamics to analyze the reported Garuda-1 power loss event. Measurements of proton flux ($9 < E < 15$ MeV) and electron flux ($E > 0.6$ MeV and $E > 2$ MeV) were taken using the Energetic Particle Sensor (EPS) channels E1, E2, and P3 on board the GOES-12 satellite. Proton data from the solid-state detector were adjusted to remove cross-contamination and particles outside the detector's aperture, while electron data were corrected for interactions with protons exceeding 32 MeV. X-ray flux in the short-wavelength range of 0.5-3 Å and the long-wavelength range of 1-8 Å was used as an indicator of solar activity, according to Bornmann et al. (1996), Benz (2008), and Fletcher et al. (2011). The measurements were obtained from an ion detector chamber onboard the same satellite. Although affected by Bremsstrahlung contamination from energetic particles, this contamination does not significantly alter the overall temporal patterns and variability of the measured flux. Data for both X-rays and energetic particles were obtained from the NOAA GOES Space Environment Monitor (SEM) data archive available through the National Centers for Environmental Information (NCEI).

Geomagnetic activity indices were used to assess magnetic disturbances around the time of the Garuda-1 satellite anomaly event. Definitive geomagnetic index data were obtained from the World Data Center for Geomagnetism, Kyoto. The SYM-H index reflects variations in the global ring current intensity near the Earth's magnetic equator. The Kp index is a 3-hour planetary geomagnetic index derived from standardized K indices from multiple mid-latitude observatories. The AE index is a measure of auroral electrojet activity, derived from ground-based magnetometer readings in the auroral zone. The dataset was complemented by solar wind plasma velocity and inter-

planetary magnetic field. Solar wind plasma parameters and interplanetary magnetic field data were obtained from the NASA OMNI database and incorporated into the analysis to evaluate interplanetary conditions, which serve as key external drivers of space weather variability.

2.2 Methods and Simulations

The environmental conditions associated with the reported Garuda-1 power loss event were investigated over the period of 2-8 April 2005. A three-day time window is commonly used in space weather research to capture the pre-conditioning, main phase, and recovery phases of geomagnetic disturbances that may lead to satellite malfunctions, due to the typical timescales of interplanetary structures and magnetospheric response.

The Space Environment Information System (SPENVIS) simulations was used in conjunction with observational data to investigate the physical mechanisms behind the anomaly and the impact of the space environment on power loss events on the Garuda-1 satellite. This study employed two SPENVIS modules, EQUIPOT and DICTAT, for this purpose. The EQUIPOT module was used to calculate charging probability and estimate the equilibrium potential on spacecraft surface materials using a simple differential material charging model. The DICTAT module was used to evaluate the potential for electrostatic discharge (ESD) by comparing the maximum electric field with the material's breakdown field (Ahmad et al., 2026b).

The EQUIPOT module uses inputs consisting of plasma environment parameters surrounding the satellite, the properties of the satellite's constituent materials, and the characteristics of the intermediate insulating layer. The plasma environment is divided into two regimes, namely hot plasma and cold plasma. The hot plasma is characterized by an electron density of 0.4 cm^{-3} with a temperature of 15 keV and an ion density of 1 cm^{-3} with a temperature of 15 eV. Cold plasma is defined by an electron density of 0.1 cm^{-3} and an ion density of 1 cm^{-3} , with both species having a temperature of 0.5 eV.

The inputs for the DICTAT module are based on a hot plasma environment defined by a 24-hour exposure duration, an isotropic electron flux orientation relative to the satellite, and a range of electron energies. The selected energy range was 0.6-3.8 MeV, with fluxes ranging from 9×10^2 to 1×10^6 electrons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. These parameters were selected based on electron measurements recorded by the GOES satellite over the selected time range corresponding to the satellite power loss event. The dielectric material is assumed to be Mylar, which is widely used in spacecraft multilayer insulation systems due to its favorable dielectric properties, with a thickness of 1.18 cm, a density of 1.4 g/cm^3 , and a dielectric constant of 3. The electrical conductivity of the dielectric is assumed to be $1 \times 10^{-19} \Omega^{-1} \text{ m}^{-1}$ under moderate geomagnetic storm conditions, with a radiation-induced conductivity (RIC) dose rate factor of 1.0×10^{-15} , based on standard parameterizations used in spacecraft charging simulations. The shielding is assumed to consist of aluminum with a thickness of 0.1 cm. Due to the lack of detailed satellite geometry information, the DICTAT

analysis is based on a simplified planar geometry, assuming isotropic electron incidence and a 90° field of view. These assumptions, although simplified, are commonly adopted in preliminary SPENVIS-based charging assessments to estimate first-order charging susceptibility under disturbed geomagnetic conditions. Realistic spacecraft geometries and anisotropic particle distributions can produce different local charging responses, which should be taken into account in future studies once detailed spacecraft engineering data become available.

The electron and proton fluxes used in the simulation are 2×10^6 electrons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and 1×10^6 protons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, respectively, representing a geomagnetically disturbed condition observed during the selected event period. Both fluxes are defined at an effective energy of 1 MeV. The SPENVIS input parameters used in this study are based on GOES-derived electron flux measurements and representative geostationary spacecraft material configurations commonly adopted in spacecraft charging studies. These assumptions provide a first-order representation of GSO space weather conditions during the event period. The material parameters, including structural and patch elements, are assumed to be aluminum, a standard spacecraft structural material due to its favorable mechanical and electrical properties. Secondary electron emission is modeled using the Katz formulation. The intermediate insulating layer is characterized by a relative permittivity of 3, a thickness of 0.001 m, and an electrical conductivity of 10^{-15} S/m , representing typical spacecraft dielectric properties used in multilayer insulation systems. It should be noted that the detailed engineering specifications of the Garuda-1 satellite are not publicly available; several material and geometric parameters were selected based on representative spacecraft charging studies and commonly adopted SPENVIS reference configurations for GSO spacecraft environments. The simulations aim to give first-order estimates of charging susceptibility rather than an exact replication of spacecraft charging conditions.

The overall analytical framework adopted in this study is summarized in Figure 1. The investigation begins with a time-series analysis in Coordinated Universal Time (UTC) to identify the temporal relationships among interplanetary conditions, geomagnetic disturbances, and energetic particle enhancements associated with the anomaly period. After the disturbance interval is identified, the Garuda-1 satellite position is transformed into MLT coordinates to examine the occurrence of enhanced electron fluxes and geomagnetic activity relative to the MLT sector occupied by the satellite, while charging simulations are performed to evaluate surface and internal charging conditions under the observed space environment. The observational and modeling results are subsequently integrated to assess the likelihood that spacecraft charging contributed to the reported Garuda-1 power loss event.

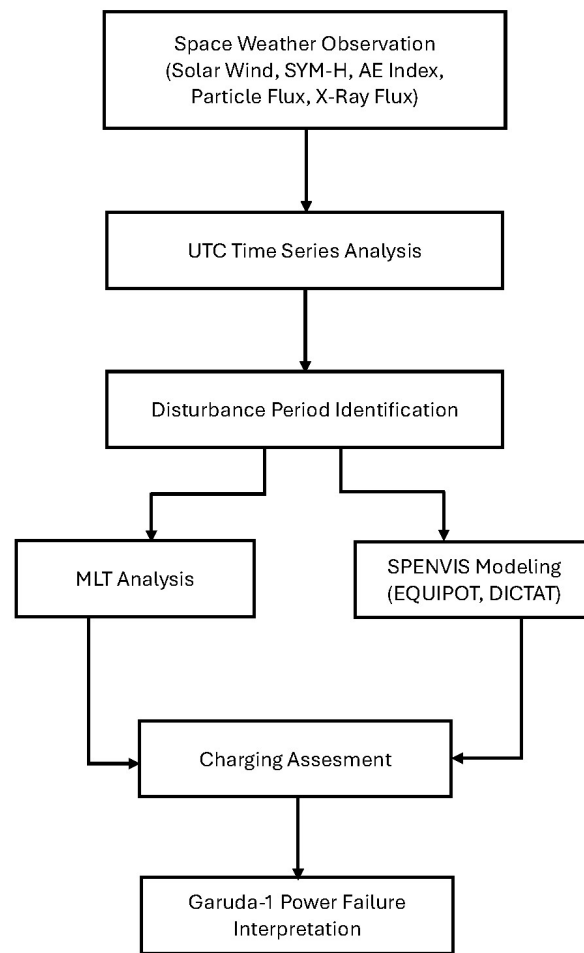


Figure 1. Workflow Combining Space Weather Observations, Energetic Particle Measurements, MLT Transformation, and SPENVIS Charging Simulations (EQUIPOT and DICTAT) for Analysis of the Reported Garuda-1 Anomaly

3. RESULTS AND DISCUSSIONS

3.1 Space Environment Conditions During the Garuda-1 Anomaly

The GOES-12 satellite measurements, which provide a representation of the space environment at GSO altitude where Garuda-1 operated, are shown in Figure 2. The upper panel shows fluctuations in X-ray flux, the red curve representing short-wavelength X-ray flux (XS) and the black curve representing long-wavelength X-ray flux (XL). X-ray flux fluctuations reflect the level of solar activity, particularly flare events. These events may be followed by solar proton events (SPEs), in which high-energy protons are accelerated and emitted into space (Waterfall et al., 2023). These particles can reach Earth's orbit, including geostationary orbit, and increase radiation risks that affect the performance and reliability of satellite systems (Normand, 1994; Tranquille, 1994; Ahmad et al., 2018).

The lower panel of Figure 2 represents the flux of high-

energy particles. The red and black curves represent electron flux variations in the >0.6 MeV and >2 MeV energy channels, respectively, while the blue curve represents proton flux in the 9-15 MeV energy range. The electron flux reflects the dynamics of the outer radiation belt, which generally increases during geomagnetic storms as a result of particle injection from the magnetosphere and acceleration processes through wave-plasma interactions (Horne et al., 2005; Kim et al., 2015; Larsen and Niehof, 2013). On the other hand, fluctuations in proton flux in the 9-15 MeV energy range may originate from contributions of particles in both the inner radiation belt and solar energetic particles (SEPs) produced during enhanced solar activity. To complement the diagnosis of magnetospheric conditions, Figure 3 shows several key parameters. The panels in the figure, from top to bottom, show fluctuations in the interplanetary magnetic field component (Bz) and solar wind speed (V), the global geomagnetic index Kp with a 3-hour resolution, the SYM-H index as an indicator of geomagnetic storm

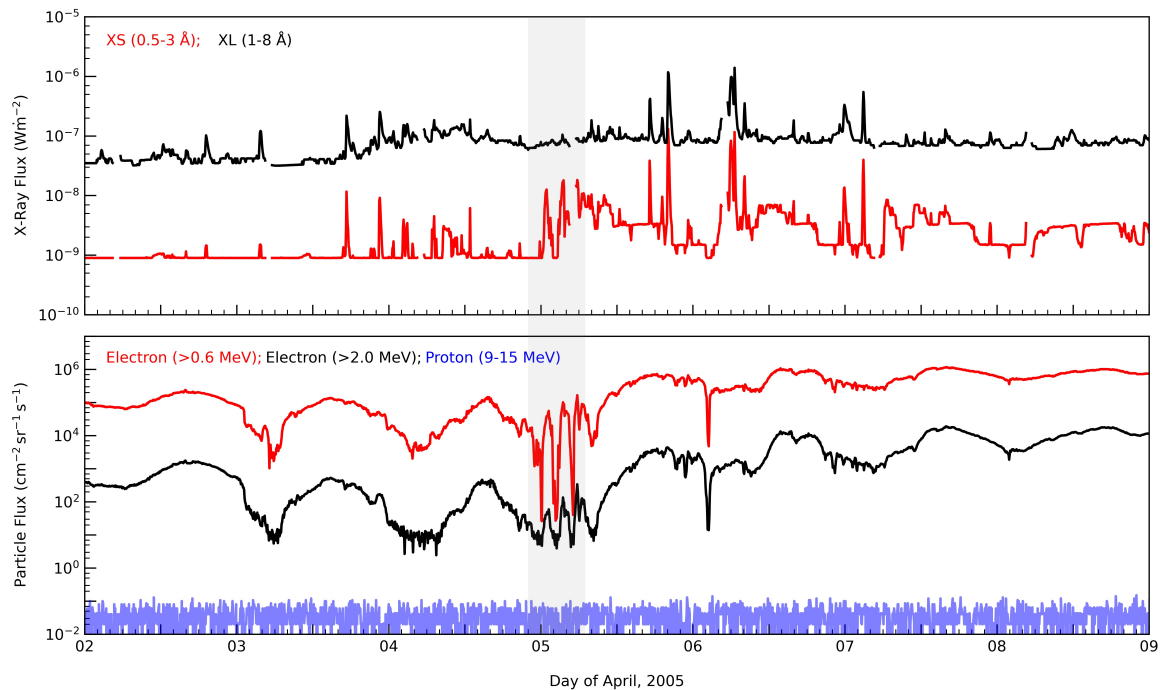


Figure 2. Electron Fluxes ($E > 0.6$ MeV and $E > 2.0$ MeV), Proton Flux ($9 < E < 15$ MeV), and X-Ray Fluxes (XS and XL) from 2-8 April 2005

intensity, and the AE index, which represents auroral electrojet current activity.

From the upper-panel of Figure 2, it can be seen that during the time interval suspected to be associated with the power loss of the Garuda-1 satellite (4-6 April), the X-ray flux remains below the 10^{-7} W/m² level. This condition indicates that solar activity was relatively low and that no significant flares occurred. Accordingly, no significant flare-associated SEP enhancement was identified in the near-Earth environment. Meanwhile, the lower panel of Figure 2 shows relatively large fluctuations in electron flux, while proton flux does not exhibit significant variations over the observation period. These electron flux fluctuations are then followed by an increase in electron flux reaching nearly 10^6 electrons cm⁻² sr⁻¹ s⁻¹ at 20:00 UTC on 5 April. Given that solar activity was in a quiet state, the electron flux fluctuations can be primarily attributed to magnetospheric dynamics driven by the interaction between the solar wind and Earth's magnetosphere, such as particle injection and acceleration processes in the radiation belts (Millan and Thorne, 2007; Thorne, 2010; Rodger et al., 2021). The observed relativistic electron enhancement, approaching a rate of $\sim 10^6$ electrons cm⁻² s⁻¹ sr⁻¹, is comparable to the flux levels previously associated with elevated internal charging risk in geostationary satellites, as reported in previous studies (Baker et al., 1998; Fennell et al., 2001; O'Brien, 2009). Flux levels of this magnitude are consistent with conditions favorable for deep dielectric charging through the penetration of MeV electrons into spacecraft shielding materials and internal dielectric components.

The observed conditions are consistent with those expected during an enhanced magnetospheric activity event, specifically a moderate geomagnetic storm that began at 12:00 UTC on 4 April. The storm reached its maximum intensity when the SYM-H index reached a minimum value of approximately -70 nT and remained at this level for about 4 hours during the 05:00-08:00 UT period on 5 April. The storm intensity began to weaken and eventually returned to pre-storm normal conditions by 10 April after the analyzed interval. During the initial and main phases of the geomagnetic storm, the electrojet current increased in intensity and expanded, with multiple peaks reaching approximately 1300 nT from around 14:00 UT on 4 April to 12:00 UTC on 5 April. The substorm lasted for a relatively long period of time. Global magnetospheric conditions were highly active during this period, with the Kp index reaching a value of 7 in the third panel of Figure 3. Elevated AE electrojet activity further supports the occurrence of intense auroral activity, indicating that substorm processes were dominant during this period.

Substorms can trigger the acceleration and outflow of electrons from the polar ionosphere during enhanced auroral electrojet activity, contributing to fluctuations in high-energy electron flux (Clark and Anger, 1967; Chen et al., 2003; Bland et al., 2022; Wang et al., 2026). The Bz component of the interplanetary magnetic field (IMF Bz) exhibits significant fluctuations during the initial to main phases of the geomagnetic storm, reaching values of approximately -15 nT and maintaining a southward orientation throughout the substorm pe-

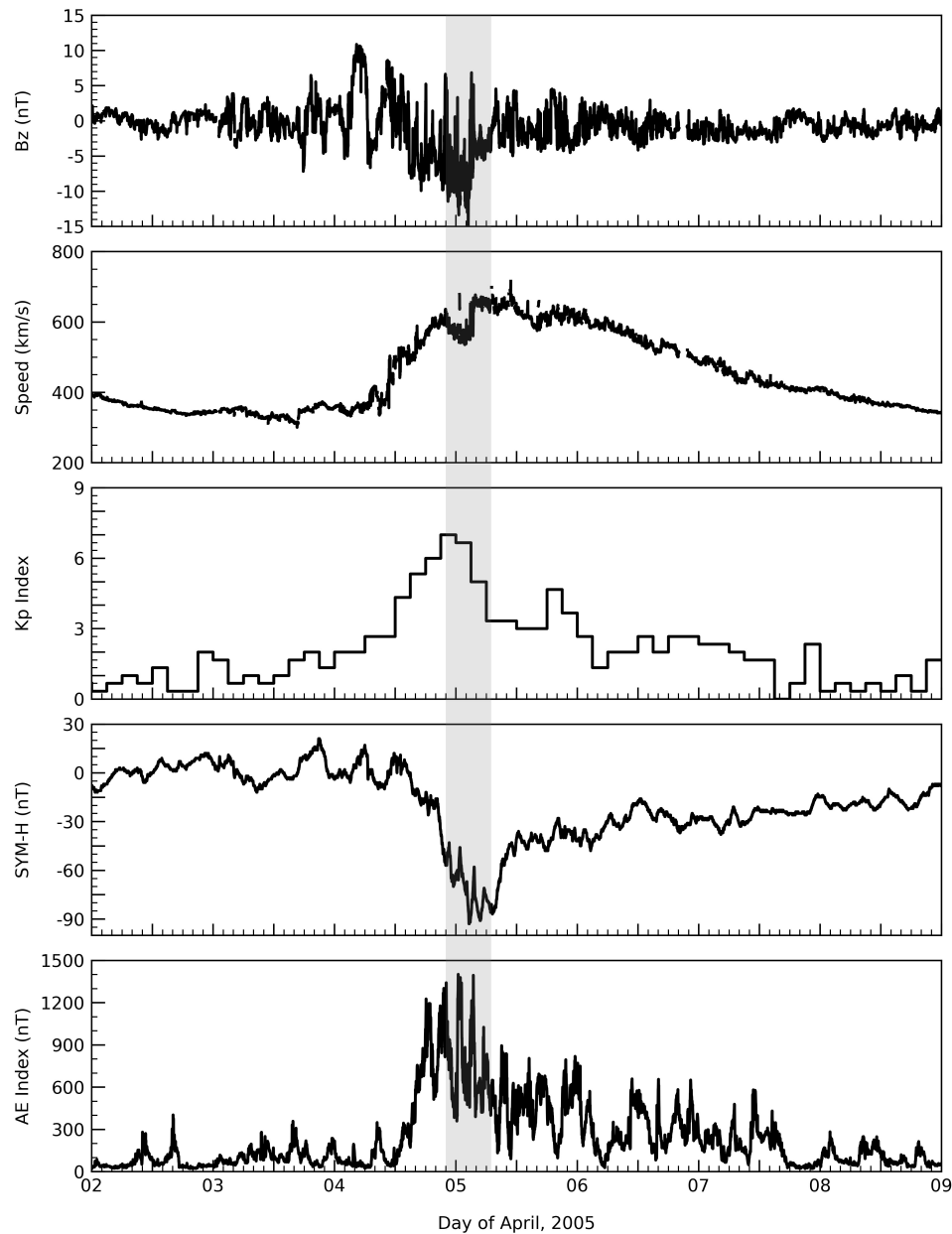


Figure 3. Time Series of the Bz Component of the Interplanetary Magnetic Field (a), Solar Wind Speed (b), Kp Index (c), SYM-H Index (d), and AE Index (e) during 2-8 April 2005

riod. The solar wind bulk velocity exhibits an increasing trend over the same time period. Fluctuations in the southward Bz component and an increase in solar wind speed can modulate ULF waves in the magnetosphere, which then influence wave-particle interactions and contribute to high-energy electron flux dynamics in the radiation belts (Mann et al., 2004; Kilowasid et al., 2014; Baker et al., 2018; Borovsky and Valdivia, 2018; Lara et al., 2025). Strong variations in the 0.6 and 2 MeV electron fluxes coincide with this, suggesting a possible link to energetic particle dynamics in the near-Earth environment

(Reeves et al., 2003; Hands et al., 2018). The exact time of the power loss on Garuda-1 is uncertain. The available reports only mention that the event was identified on 5 April 2005.

The magnetospheric conditions at GSO altitude during the 4-5 April period have been described, and the analysis is further extended by investigating the dependence of energetic electron enhancements and geomagnetic activity on MLT. The left panel of Figure 4 displays the polar representation of electron flux in spacecraft MLT-UT coordinates, whereas the right panel shows the corresponding AE index distribution. In both

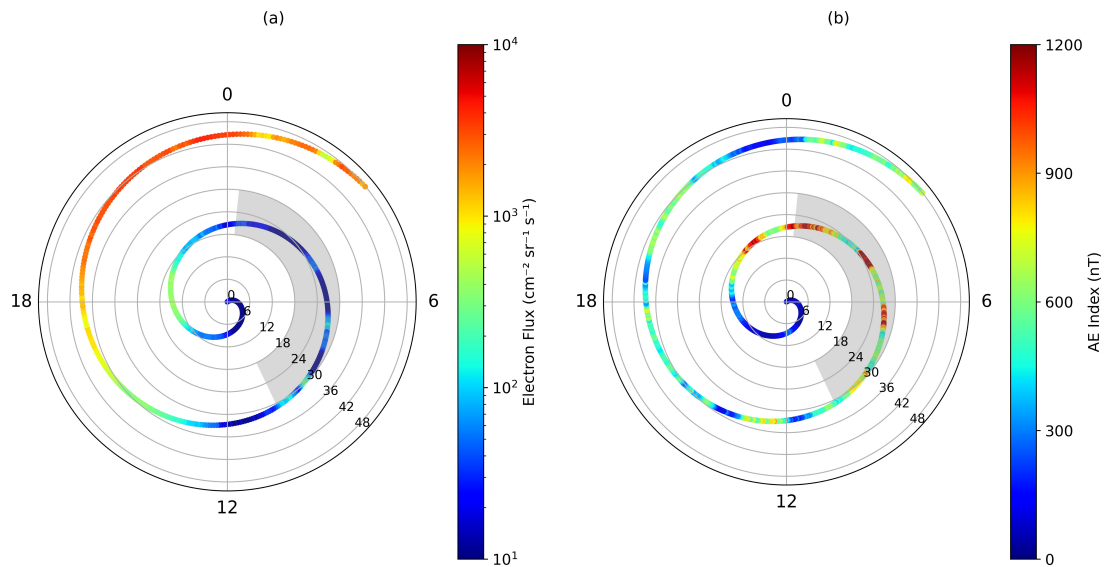


Figure 4. Polar Representation of Energetic Electron flux and AE Index in Spacecraft Magnetic Local Time (MLT) Coordinates during 4-5 April 2005. (a) Electron Flux Distribution. (b) AE Index Distribution

panels, the circular arcs signify MLT, and the radius of the circle denotes time in UT over a 48-hour period. The center of the circle corresponds to 00:00 UT on 4 April, whereas the outer boundary of the circle corresponds to 00:00 UT on 6 April. The MLT is calculated for the Garuda-1 satellite at a position of 0° latitude and 123° longitude.

Significant fluctuations in electron flux started to occur from 21:00 UT on 4 April and continued until 07:00 UT on 5 April. The Garuda-1 satellite is located within the 0.4-10.3 MLT sector during this interval, covering the pre-dawn to early-morning regions. Geomagnetic activity reached a high level during the same period, with the Kp index peaking at 7, indicating intense geomagnetic storm conditions. This sector thus becomes a key region for electron acceleration processes in the outer radiation belt. A seed electron population can be supplied by particle injections from the plasma sheet associated with previous substorm activity during the pre-dawn phase (approximately 0.4-6 MLT). Electrons then drift eastward due to magnetic field gradient and curvature effects. The intensity of whistler-mode chorus waves typically reaches its maximum in this sector during the same period, making wave-particle interactions highly efficient in accelerating electrons from keV energies to relativistic energies via resonance mechanisms. This results in a significant increase in high-energy electron flux at GSO altitudes.

3.2 Simulation Results of the Radiation Environment

The SPENVIS model was used as a physics-based simulation tool to investigate spacecraft charging effects on Garuda-1 during periods of enhanced substorm activity, and is widely applied in satellite anomaly studies (Heynderickx et al., 2004; Hands et al., 2018). The analysis employs the EQUIPOT and DIC-

TAT modules to evaluate surface potential and internal electric field responses under exposure to high-energy electron precipitation at GSO altitudes. Representative material properties of aluminum structures and dielectric components were included to assess susceptibility to surface charging, ESD, and internal dielectric breakdown. The simulations provide first-order estimates based on simplified spacecraft geometry, homogeneous material properties, quasi-static plasma conditions, and prescribed energetic electron spectra, and therefore should be interpreted as relative indicators of charging risk rather than exact on-orbit voltage or field predictions.

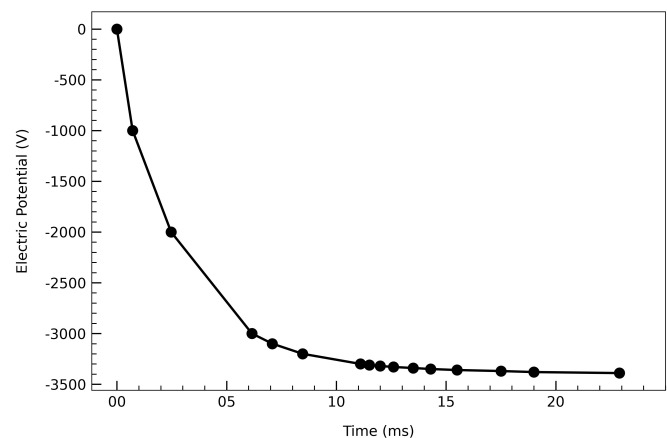


Figure 5. Simulated Spacecraft Surface Potential Obtained from the EQUIPOT Module under Disturbed Geomagnetic Conditions during 4-5 April 2005

The EQUIPOT results (Figure 5) show that the surface

potential decrease reaching approximately -3390 V at ~23 ms, indicating enhanced surface charging under disturbed electron precipitation conditions. In parallel, the DICTAT results (Figure 6) show that the maximum internal electric field in dielectric materials exceeds the assumed breakdown threshold ($\approx 1.0 \times 10^7$ V/m), indicating increased susceptibility to internal charging and ESD processes.

Together, these results suggest that the event conditions were favorable for both surface and internal charging processes, with internal charging representing an important potential risk due to energetic electron penetration into dielectric materials. Severe differential charging conditions in GSO are commonly associated with surface potentials of several kilovolts (Garrett and Whittlesey, 2012), consistent with the magnitude obtained in the EQUIPOT simulation. The presence of enhanced relativistic electron fluxes during the anomaly period provides a plausible environmental driver associated with the simulated charging response, as storm-time magnetospheric dynamics and substorm processes increase spacecraft exposure to energetic particle populations, thereby enhancing both surface and internal charging risk in GSO environments.

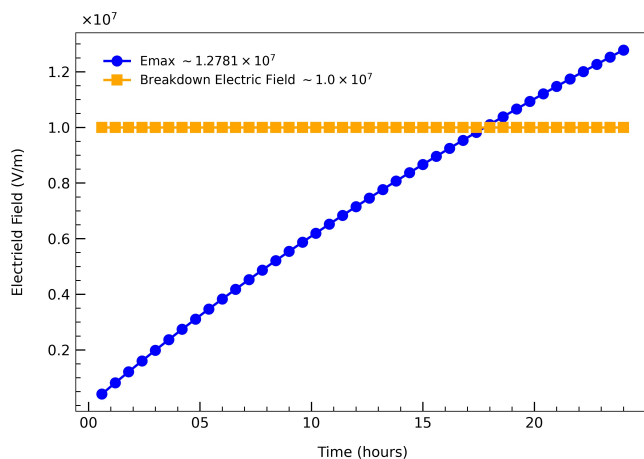


Figure 6. Maximum Internal Electric Field Estimated by the DICTAT Module for Dielectric Materials Exposed to Electrons in the 0.6-3.8 MeV Energy Range

The evolution of electron flux with MLT reflects the changing radiation environment encountered by Garuda-1 from the post-midnight to morning sector. During this interval, enhanced energetic electron populations are associated with increased exposure to charging-related conditions. Variations in plasma density and relativistic electron flux across the dawn-to-morning sector likely contributed to spatial and temporal differences in charging susceptibility. These conditions are indicative of enhanced susceptibility to both surface and internal charging processes.

The coincidence of strong electron flux fluctuations with enhanced electrojet activity during the storm's main phase is consistent with a charging-related scenario that includes increased energetic electron fluxes and disturbed geomagnetic

conditions throughout the event period. The interaction between substorm-driven injections, storm-time magnetospheric dynamics, and increased wave activity reflects conditions conducive to spacecraft charging. Several GSO communication satellites have experienced similar charging-related anomalies under disturbed space weather conditions. An enhanced relativistic electron flux may have contributed to conditions conducive to deep dielectric charging in the Anik E1 anomaly, whereas Telstar 401 and Galaxy 15 experienced operational failures during a major geomagnetic storm with intense MeV electron enhancements, attributed to internal charging and electrostatic discharge processes (Reeves et al., 1998; Saiz et al., 2018). The reported Garuda-1 anomaly occurred under environmental conditions characterized by heightened relativistic electron fluxes, increased geomagnetic activity, and enhanced charging susceptibility indicated by SPENVIS simulations, which are consistent with previously documented space weather conditions associated with charging-related GSO satellite anomalies.

This study has several acknowledged limitations. The exact timing of the Garuda-1 anomaly is not precisely known, and detailed spacecraft engineering characteristics are not publicly available, which limits direct comparison between environmental conditions and spacecraft subsystem responses. No onboard telemetry or diagnostic data were available to verify the specific failure mechanism. The SPENVIS simulations use simplified spacecraft geometry and generalized material parameters because detailed spacecraft engineering specifications are not available. The simulation results should therefore be regarded as first-order estimates of spacecraft charging susceptibility rather than precise reconstructions of the anomaly process. Despite these limitations, this study enhances understanding of the relationship between geomagnetic disturbances, energetic electron dynamics, and spacecraft charging processes in the geostationary environment by integrating observational analysis and physics-based charging simulations for an Indonesian satellite case study.

4. CONCLUSIONS

The reported Garuda-1 anomaly is most consistent with a space weather-driven spacecraft charging scenario dominated by enhanced energetic electron fluxes, while the observed proton flux levels suggest a limited contribution to direct spacecraft effects. Disturbed geomagnetic conditions characterized by strong southward IMF Bz, elevated solar wind speed, and enhanced geomagnetic activity provided favorable conditions for the injection and accumulation of high-energy electrons in GSO. Simulation results indicate that both surface and internal charging processes could have contributed to the reported anomaly, with internal charging representing a potentially important mechanism due to the penetration of energetic electrons into spacecraft dielectric materials under storm-time conditions. The MLT dependence analysis further indicates enhanced charging susceptibility along the spacecraft orbit, with the highest exposure occurring in the nightside to early-

morning sector, where energetic electron enhancements associated with substorm activity are typically strongest. The results suggest that the reported anomaly is consistent with a multi-factor space weather-driven charging scenario, highlighting the importance of integrating energetic electron dynamics, geomagnetic disturbance conditions, charging simulations, and local time effects into a unified framework for spacecraft anomaly diagnosis and risk assessment in GSO.

5. ACKNOWLEDGEMENT

The authors gratefully acknowledge the Research Organization for Aeronautics and Space (ORPA) for funding support, which facilitated the establishment of a topical working team on this subject. The authors also sincerely thank SPENVIS for providing the modeling tools used in this study, as well as OMNIWeb, NOAA/GOES satellite data, and the World Data Center (WDC) for Geomagnetism, Kyoto, for making their space weather and geomagnetic datasets publicly available online, which were essential for the completion of this research.

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