Impact of Space Environment on Geostationary Meteorological Satellite Data Outage

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Abstract  Impact of space environment changes on geostationary meteorological satellite services, such as data outage, incomplete imagery, or quality degradation were investigated using event logs of Himawari-8 and Meteosat (MET-7 and MET-8) in 2015–2017. The event logs show that such failures were caused by anomalies on spacecraft and in ground system half each. On Himawari-8, a total of 11 incomplete imagery occurred due to spacecraft anomaly, and among them about 45% (5 anomalies) occurred during energetic electron enhancement and about 9% (1 anomaly) occurred during energetic proton enhancement. In cases of Meteosat, a total of 84 service alerts occurred due to spacecraft anomaly, and among them 35% (29 anomalies) occurred during electron enhancement and 7% (6 anomalies) occurred during both proton and electron enhancement.

On the basis of statistical analysis, it is found that the probability of spacecraft anomaly occurrence markedly increases when electron fluence exceeds a threshold. The probability of anomaly is less than 10% when the 1-MeV electron fluence is less than \(10^9\) (cm\(^2\) sr eV), whereas it increases to more than 20% above the fluence. Thresholds are also found for electron fluences at other energies from 200 keV to 1.5 MeV. This study clarifies that changes in the space environment, particularly electron fluence enhancement affect geostationary meteorological satellite services.

Plain Language Summary  Space-based meteorological observations are an indispensable part of our social infrastructure, but they are always face the risk of malfunction due to space radiation enhancement. To assess the impacts of space radiation on meteorological imagery observation services, we investigated energetic particle variation during meteorological imagery service alerts, particularly on Himawari-8, MET-7, and MET-8 between 2015 and 2017. We found that about forty percent of the geostationary meteorological satellite anomalies occurred when 24-hr fluence of energetic electrons increased. The occurrence probability of spacecraft anomaly markedly increases when the energetic electron fluence exceeds a threshold value. The results are important for planning safety operation of and developing robust next-generation spacecraft.

1. Introduction

Changes in the space environment, particularly energetic particle enhancement in the radiation belts, solar energetic particles (SEP) arrival, and/or substorm particle injection in association with solar flares, coronal mass ejection (CME), and/or geomagnetic storms, can cause malfunctions of spacecraft in orbit. As investigated in many papers, for example, Koons et al., 1999; Baker, 2000; Iucci et al., 2005; Choi et al., 2011; Ferguson et al., 2011; Lohmeyer & Cahoy, 2013; Loto'aniu et al., 2015, spacecraft malfunctions have been a serious concern since the beginning of the space era and are still difficult to fully mitigate against. In recent society, spacecraft malfunctions can have even more considerable impacts on public users due to service suspension, and stakeholders because of the cost for recovery, for example, by using alternative satellites. Despite modern technology, a spacecraft that is already in space is difficult to repair even if malfunctions are found, and also, we cannot control such hazardous space environment. Therefore, in each phase of spacecraft design, manufacturing, and operation, various measures are required to mitigate the risk of spacecraft malfunctions. To realize the effective measure for mitigating the risk of spacecraft malfunctions in each phase or to minimize anomaly in orbiting spacecraft by operation, it is important to investigate in detail the causes of spacecraft malfunctions that occur in an actual space environment. Frederickson et al. (1992) estimated the rate of electrostatic discharges (ESD) based on the environment from data observed by the internal discharge monitor of the Combined Release and Radiation Effects Satellite (CRRES). Also, Wrenn and Smith (1996) derived probability of the rate of ESD with a complete list of anomalies on two operational spacecrafts. O’Brien (2009) derived various hazard quotients; surface charging, internal charging, single event effects, and total dose effects by variable space radiation environment on the basis of the closed lists and proxies of on orbit anomalies and these are incorporated in the Aerospace Corporation’s
Spacecraft Environmental Anomalies Expert System (SEAES). However, there are few public anomaly lists and sharing between manufacturers is seldom conducted because such detailed reports of spacecraft malfunctions is kept strictly confidential despite the common recognition of their importance (Green et al., 2017). In addition, since space environment monitor is not installed on every spacecraft, in most case causalities between satellite malfunctions and space environment changes are not yet fully understood. It is important to investigate space environment to which a failed spacecraft was directly exposed and understand those causalities.

Several parameters of space environment, for example, solar X-rays, energetic particles, and magnetic fields, has been continuously monitored by the SMS/GOES series of US meteorological geostationary satellites since 1974, and observation data from these satellites are publicly available on the websites of National Centers for Environmental Information (NCEI) of NOAA <https://www.ngdc.noaa.gov/stp/satellite/goes/> . Japanese geostationary meteorological satellites, GMS-1 (Himawari-1) to GMS-4 (Himawari-4) in 1977–2000, also had monitored energetic particles (Kurino, 1985). Although there was an interruption, space environment data acquisition monitors (SEDA) were installed again in Himawari-8 and Himawari-9 (Bessho et al., 2016; Yokota & Sasaki, 2013). Such space environment monitors are being installed as standard equipment on geostationary meteorological satellites in accordance with the recommendation of the World Meteorological Organization (WMO) (e.g., WMO, 2013). Then, in recent years, many geostationary meteorological satellites, such as Russia's Elektro-L satellite series, China's FY-2 and FY-4 satellite series, and Korea's GEO-KOMPSAT-2A, have also installed space environment monitors. Since the meteorological observations are public service in the world, Coordination Group for Meteorological Satellite (CGMS) recommends that the meteorological satellite operating organizations disclose the observation data obtained from the meteorological satellites to the public, and record and publish the event log for comparison and calibration of the data between the satellites (e.g., CGMS, 2017). In the event log, various events that affect the observation data, such as planned events (data outage due to eclipse period, maneuvers, etc.) and sporadic data outage (data missing, quality degradation, etc.), are recorded. The reason of data outage, such as events at platform, satellite, instruments, and processing level are also recorded. Thus, it has become possible to investigate the relationship between the occurrence of meteorological spacecraft anomalies and changes in the space environment by analyzing space environment data obtained by meteorological satellites and the published history of spacecraft anomalies.

The purpose of this study is to assess impacts of the space environment on meteorological imagery observation by investigating the relationship between space radiation (energetic electron fluence and proton flux) changes and spacecraft anomalies that have affected operational meteorological services. In Section 2, Himawari-8/SEDA observation data, which are used as a proxy of the space radiation environment in geostationary orbit (GEO), are briefly explained. In Sections 3 and 4, spacecraft anomalies on Himawari-8 and those on MET-7 and MET-8 are investigated with space radiation observation data, respectively. A discussion and summary of this study are given in Section 5.

2. High-Energy Particles Observations

In this study, Himawari-8/SEDA data are used as a reference of energetic particles, namely space radiation environment in GEO. Himawari-8 is a Japanese meteorological satellite that was launched on 7 October 2014, and is in GEO at 140.7° East longitude. SEDA has been in operation since 3 November 2014, for the purpose of housekeeping. SEDA consists of two sensors: a proton radiation sensor (SEDA-p) measuring energies from 22 to 81 MeV and an electron radiation sensor (SEDA-e) measuring energies from 0.2 to 4.5 MeV. It is mounted on the eastward side of the spacecraft body and observes protons and electrons with fields of view of ±40° and ±80°, respectively. More details of SEDA were described by Nagatsuma et al. (2017). The observation data of SEDA have been provided through the HIMAWARI/SEDA DATABASE WEB <https://aer-nc-web.nict.go.jp/himawari-seda/> of the National Institute of Information and Communications Technology (NICT), Japan.

In this paper, 5-min average electron and proton fluxes and electron fluence over 24 hr in a UT day are investigated with anomaly databases. Generally, energetic electrons with energies higher than about 0.1 MeV cause internal/deep dielectric charging because they can penetrate spacecraft materials. If charges accumulate beyond the breakdown potential of materials, ESD occurs (Bodeau, 2010; Fennell et al., 2001). Also, energetic protons that can penetrate through the shield, for example, greater than 1 MeV, cause single-event effects (SEEs) and/or total ionizing dose effects (TID). Galactic cosmic rays are normally the main component of energetic proton
in GEO, but the fluxes are very low. Once SEP caused by severe solar flares and/or interplanetary shocks are emitted toward Earth from the Sun, energetic proton flux increases significantly to a severe level for spacecraft operation. Thus, Himawari-8/SEDA observation data can be used as a reference of the environment to determine the factors contributing to ESD, SEEs, and/or TID.

3. Spacecraft Anomalies on Himawari-8

3.1. Incomplete Imagery of Himawari-8

The operational information of the Himawari-8 imaging observation system have been published on the website of the Meteorological Satellite Center of the Japan Meteorological Agency (JMA). Himawari-8 irregular event logs are reported on the website <https://www.data.jma.go.jp/mscweb/en/oper/event_H8.html> to indicate anomalous period of imaging observation system, information of incomplete imagery, such as quality degradation, unscheduled pause, and data outage that affect meteorological data distribution services to end users. According to information of the incomplete imagery log published on the web, 20 service alerts occurred between July 2015, when Himawari-8 started imaging observation, and December 2017. The causes of anomalies are classified into four categories according to the location of the occurrence. These locations where anomalies occurred are broken down into eight ground system anomalies, three ground system and spacecraft anomalies, eight spacecraft anomalies, and one instrument anomaly, as shown in Figure 1. Anomalies are allocated one of the four categories of most likely cause, but there is no further information on these causes for most cases. So, it is impossible to determine whether the cause of “spacecraft and ground system anomaly” was spacecraft, ground system, or both. Roughly, half of the incomplete imagery occurred in space, whereas the rest occurred on ground systems.

Although the event log of Himawari-8 does not explain the causes of these anomalies, it was found that some spacecraft anomalies occurred when the flux/fluence of energetic electron and/or proton was high. Thus, energetic electron and proton data during spacecraft anomalies on Himawari-8 are examined in this paper. Table 1 lists details of 11 spacecraft anomalies (eight on spacecraft and three on ground system and spacecraft) and energetic particle data on corresponding days. The third column shows the duration of each spacecraft anomaly, with a total of about 17 hr. The fourth column shows the impact of each spacecraft anomaly on imagery observation: “missing” for one case, “quality degradation” for seven cases, and “incomplete” for three cases. The electron fluence and proton flux columns respectively show the 24-hr fluence of energetic electrons (1 MeV) and the daily maximum differential flux of energetic protons (22 MeV) based on Himawari-8/SEDA observations. The average 1-MeV electron fluence measured by SEDA-e from 2015 to 2017 is about 2,000 (/cm² sr eV). Six spacecraft anomalies occurred when the electron fluence was considerably higher than the average. The fluences on the
days of Anomalies 1, 4–7, and 9 were between 9,000 and 20,000 (/cm² sr eV), which were about four to ten times higher than the average. The differential proton flux at the energy of 22 MeV on all days of spacecraft anomalies except for Anomaly 8 was less than 0.01 (/cm² sr s MeV), which is the background level of SEDA-p. On 13 September 2017 (day of Anomaly 8), the proton flux in GEO increased to over 1 (/cm² sr s MeV) owing to the arrival of SEP from the Sun. Daily alert levels of radiation belt electrons and solar protons issued by the Space Weather Forecast Center of NICT, Tokyo, Japan, are shown in the last two columns. Five of the 11 anomalies occurred when the radiation belt electron levels were “extreme” or “high.” The NICT’s alert level of radiation belt electrons are divided into four levels based on 24-hr fluence of electrons with energies higher than 2 MeV observed by GOES. The “low” is less than $3.8 \times 10^7$ (/cm² sr) and “moderate” is higher than $3.8 \times 10^7$ (/cm² sr) and less than $3.8 \times 10^8$ (/cm² sr), “high” is defined as higher than $3.8 \times 10^8$ (/cm² sr) and less than $3.8 \times 10^9$ (/cm² sr), and “extreme” is defined as higher than $3.8 \times 10^9$ (/cm² sr). Anomaly 7 was occurred when the level was moderate according to the definition, but the value of electron fluence was quite close to the high level. One of the 11 anomalies occurred during the event-in-progress level that indicate >10-MeV proton flux observed by GOES was higher than 10 (/cm² sr s). Thus, it is revealed that of the six anomalies occurred during electron fluence enhancement and one anomaly occurred during proton flux enhancement. In the next sections, time evolutions of energetic particles during these anomaly events are reported in detail.

| Anomaly No. | Date (UTC) | Duration | Impact on imagery | Energetic particle condition | Electron energy differential fluence 1.0 MeV (/cm² sr eV) | Proton differential flux daily maximum 22 MeV (/cm² sr s MeV) | Radiation belt electron (NICT alert level) >2-MeV electron 24-hr maximum fluence (/cm² sr eV) | Solar energetic proton (NICT alert level) >10-MeV proton flux (/cm² sr s MeV) |
|-------------|------------|----------|------------------|----------------------------|-----------------------------------------------------------|-------------------------------------------------------------|----------------------------------------------------------|---------------------------------------------|
| 1           | 12 Nov. 2015 20:00–24:30 | 4 hr 30 min | Quality degradation | Electron enhancement | 20,000 | <0.01 | High | Quiet |
| 2           | 18 Dec. 2015 07:10–08:30 | 2 hr 20 min | Missing | --- | 3,000 | <0.01 | Moderate | Quiet |
| 3           | 3 Apr. 2016 04:10–05:40 | 1 hr 30 min | Quality degradation | --- | 2,000 | <0.01 | Low | Quiet |
| 4           | 30 Sep. 2016 15:30–16:50 | 1 hr 20 min | Quality degradation | Electron enhancement | 20,000 | <0.01 | Extreme | Quiet |
| 5           | 3 Apr. 2017 10:30–12:20 | 1 hr 50 min | Quality degradation | Electron enhancement | 20,000 | <0.01 | Extreme | Quiet |
| 6           | 3 Apr. 2017 18:40 | Incomplete | Electron enhancement | 20,000 | <0.01 | Extreme | Quiet |
| 7           | 19 Jun. 2017 16:00 | Incomplete | Electron enhancement | 9,000 | <0.01 | Moderate | Quiet |
| 8           | 13 Sep. 2017 10:40–11:30 | 50 min | Quality degradation | Proton enhancement | 1,000 | (>1) | Low | Event in progress |
| 9           | 22 Oct. 2017 13:00 | incomplete | --- | 2,000 | <0.01 | Low | Quiet |
| 10          | 11 Nov. 2017 02:50–04:20 | 1 hr 30 min | quality degradation | Electron enhancement | 10,000 | <0.01 | High | Quiet |
| 11          | 16 Nov. 2017 08:00–11:20 | 3 hr 20 min | quality degradation | --- | 1,000 | <0.01 | Moderate | Quiet |

These were classified as “spacecraft and ground system anomalies.”
3.2. Electron Fluence Enhancement

Figure 2 shows time variations of 24-hr fluence and 5-min average flux of 1-MeV-energy electrons before and after all 11 spacecraft anomalies on Himawari-8 listed in Table 1. Vertical arrows indicate the times of the anomalies. It is found Himawari-8 had been exposed to electrons with fluence higher than $10^4$ for several days before or immediately after the satellite anomalies for all cases, excepting for Anomaly 3. Five anomalies No. 1, 4, 5, 6, and 10 occurred when the electron fluence was $10^4$ (/cm$^2$ sr eV) or higher. Particularly, Anomalies No. 1, 5, and 6 occurred after the spacecraft was exposed continuously to high fluences for several days. Anomaly No. 7 occurred when the fluence was slightly lower than $10^4$ (/cm$^2$ sr eV), whereas it increased to higher than $10^4$ on the following day. In addition, although Anomalies No. 2, 8, 9, and 11 occurred when the fluence was lower than $10^4$ (/cm$^2$ sr eV), it is found that the spacecraft was exposed to high electron fluences of $>10^4$ (/cm$^2$ sr eV) for several days before those anomaly days.

The blue curves in Figure 2 show the differential flux of 1 MeV electrons. Normally, electron flux in GEO shows a diurnal variation because of the asymmetry of the magnetic field intensity around Earth, which is high at dayside and low at nightside. Himawari-8, which is located at a longitude of 140° east, normally experiences its daily maximum flux at around 03 UT as it passes near magnetic noon and its minimum flux at around 15 UT as it passes near magnetic midnight. Although the flux peaks at around 03 UT every day, spacecraft anomalies occur at any local time for both decreasing and increasing periods of electron flux. There seems to be no clear relationship between the temporal variation of 1-MeV electron differential flux and the anomaly occurrences.

In previous studies, Lohmeyer et al. (2015) suggested that in the case of a solid-state power amplifier, anomalies occur at a higher rate when the accumulated fluence over 14–21 days is elevated. ESD can be caused by the accumulation of energetic electrons inside the spacecraft. The occurrence timing of ESD on a particular component
depends on its property, such as volume resistivity, dielectric constant, electrical decay time constant etc. The irregular event log of Himawari-8 does not include details of the affected spacecraft hardware such as shielding, cable electrical parameters etc. Thus, occurrence timing assessment of ESD by accumulated election fluence is impossible and 24-hr fluences on the day of anomalies were simply investigated in this study.

Electron energy spectra on the day of Himawari-8 spacecraft anomalies are compared with that of the three-year average in Figure 3. The black line and diamond marks indicate the three-year average (logarithmic average) spectrum of energy differential fluence (/cm² sr eV) observed by SEDA-e from 2015 to 2017, and two standard deviations of the average are indicated by dashed lines. Colored lines and triangles show energy differential fluence spectra of electrons on the days of six spacecraft anomalies (Anomaly No. 1, 4, 5, 6, 7, and 10). Energy differential fluences on the days of spacecraft anomalies are higher than those of three-year average in all energy channels of SEDA-e. On 3 April 2017, when two spacecraft anomalies occurred in a day, the high-energy side tends to increase more than the low-energy side.

### 3.3. Proton Flux Enhancement

Figure 4 shows temporal variations of the energetic proton flux at energies of 22 MeV (cyan), 30 MeV (purple), 38 MeV (magenta), and 46 MeV (gray) observed by SEDA-p from 6–16 September 2017. Two SEP events were observed at the Earth’s GEO in September 2017. A spacecraft anomaly on Himawari-8 was reported on 13 September 2017, indicated by a black arrow. The first increase in SEP flux was observed immediately after the X9.3 solar flare at 11:53 UT on 6 September 2017, and the second increase was observed immediately after the X8.2 solar flare at 15:35 UT on 10 September 2017. The X-ray intensity of the second solar flare was relatively lower, but the proton flux increased further after the second solar flare than the first solar flare. The spacecraft anomaly occurred about two and half days after the second SEP arrival. The peak proton flux of the second SEP was about $10^3$ (/cm² sr s MeV) at 22 MeV, then the flux gradually decreased to about $10^0$ (/cm² sr s MeV) at the time of the anomaly, but it was still two orders higher than the normal flux value.

### 4. Spacecraft Anomalies on MET-7 and MET-8

#### 4.1. MET-7 & 8 Service Alerts

The operational information of the geostationary meteorological satellite of EUMETSAT, Meteosat, is also available on the EUMETSAT user notification service website [https://uns.eumetsat.int](https://uns.eumetsat.int). During three years from 2015 to 2017, Meteosat (MET-7 and MET-8) was operated at a longitude of 41.5° east as a part of the Indian Ocean Data Coverage Service (IODC). It is found that a total of 190 service alert events were caused by anomalies on MET-7 and MET-8. The breakdown of the anomalies is shown in Figure 5, that is, 92 cases (320 hr) of “ground segment anomaly”, 84 cases (283 hr) of “spacecraft anomaly”, two cases (2.5 hr) of “instrument anomaly”, and 12 cases (7.5 hr) of “other” reasons. So, the meteorological imagery service in 2015–2017 were affected by these anomalies for 613 hr in total. The numbers of service alerts due to ground segment and spacecraft anomalies were almost the same, as in the case of the incomplete imagery of Himawari-8. There were only two service alerts due to anomalies of the instrument itself, which is very small compared with the numbers due to spacecraft and ground segment anomalies. This trend is also the same as in the case of Himawari-8. Impacts on user service by spacecraft anomalies were “data-degraded” (67 cases, 80%), “data-unavailable” (10 cases, 12%), and “data-interrupted” (7

![Figure 3.](image1.png) Energy differential fluence spectra of electrons observed by Himawari-8/SEDA-e on the days of Himawari-8 spacecraft anomalies. The three-year average spectrum between 2015 and 2017 is shown by the black line and diamonds, and the dotted lines indicate two standard deviations (2σ) of the average.

![Figure 4.](image2.png) Himawari-8/SEDA-p observations of 22 MeV (cyan), 30 MeV (purple), 38 MeV (magenta), and 46 MeV (gray) proton fluxes during SEP events in September 2017. The time of the Himawari-8 spacecraft anomaly is shown by a black arrow.
cases, 8%). Among the 84 service alerts due to satellite anomalies, 79 cases occurred on MET-7 and five cases occurred on MET-8. It is considered that the large difference in the number of satellite anomalies between MET-7 and MET-8 might be related to the difference in the manufacture generation. Meteosat series up to MET-7 belong to the first generation. Unfortunately, information about the hardware changes/differences between the first- and second-generation spacecraft bus systems cannot be found from the public sources.

Figure 6 shows (a) 1-MeV electron 24-hr fluence and (b) 22-MeV proton flux observed by Himawari-8/SEDA from 2015 to 2017. Circles indicate the 84 spacecraft anomalies that occurred in MET-7 (red) and MET-8 (magenta). Blue circles indicate the 11 spacecraft anomalies of Himawari-8. The vertical position of each symbol corresponds to the electron fluence or proton flux when the anomaly occurred. From Figure 6a, it is found that the spacecraft anomaly tended to occur when the electron fluence increased. However, there were no simultaneous occurrences of anomalies on Himawari-8 and Meteosat, and anomalies did not always occur when the fluence increased. This means that enhanced electron fluence is a necessary but not sufficient condition for spacecraft anomalies to occur. From 2017, the frequency of spacecraft anomalies on Meteosat were less than in previous years, even when the electron fluence increased and anomalies on Himawari-8 occurred. This is because MET-7, which frequently had spacecraft anomalies, ended its service in April 2017 and went out of orbit.

From Figure 6b, SEP events with proton fluxes greater than $10^8 /\text{cm}^2 \text{sr} \text{s MeV}$ occurred in July 2015 and September 2017. Six spacecraft anomalies occurred on MET-7 when the 22-MeV proton flux increased to $10^{-2} - 10^{-1} /\text{cm}^2 \text{sr} \text{s MeV}$ in July 2015. At the same time, the 1-MeV electron fluence was also observed to increase during this period. Thus, it is difficult to distinguish whether the anomalies were caused by proton enhancement, electron enhancement, or a combination of them both. On Himawari-8 a spacecraft anomaly occurred when the proton flux increased in September 2017, whereas no spacecraft anomaly occurred on MET-7 and MET-8 during this period.

4.2. Probability of Spacecraft Anomaly Occurrence

According to the EUMETSAT user notification service, the number of service alerts caused by spacecraft anomalies on MET-7 and MET-8 was 84 during the three years from 2015 to 2017. Figure 7a shows occurrence distribution of SEDA-e 1-MeV electron 24-hr fluence as a function of $\log_{10}(\text{fluence})$ for the 3 years (gray) and the conditional distribution of that for the 84 days when a spacecraft anomaly occurred (red). The averages of $\log_{10}(\text{fluence})$ for the three years and the anomaly days are 3.40 and 3.76, respectively. It indicates that the spacecraft anomalies tend to occur when the electron fluence is higher than average. Figure 7 clearly shows that the two distributions have different biases. A peak of the $\log_{10}(\text{fluence})$ three-year distribution is at 3.6–3.8 and that of anomaly day distribution is at 4.0–4.2. If the probability of an anomaly had a random uniform distribution across fluence, the anomaly distribution would be same with the fluence occurrence distribution since
Figure 6. (a) Himawari-8/SEDA-e observation of 1-MeV electron 24-hr fluence and (b) SEDA-p observation of 22-MeV proton flux in 2015–2017. Red and magenta circles indicate spacecraft anomalies of MET-7 and MET-8, respectively, and blue circles indicate spacecraft anomalies of Himawari-8. The vertical height of each symbol indicates the electron fluence/proton flux when the anomaly occurred.

Figure 7. (a) Occurrence distributions of SEDA-e 1-MeV electron 24-hr fluence as a function of log\(_{10}\) (fluence) for 3 years (gray) and for 84 days when spacecraft anomalies occurred (red) in 2015–2017. (b) Spacecraft anomaly occurrence rate of Meteosat as a function of log\(_{10}\) (fluence) of 200-keV (purple), 300-keV (blue), 450-keV (green), 650-keV (orange), 1.0-MeV (red), and 1.5-MeV (magenta) electrons.
anomaly would be dependent on the number of days a particular fluence bin was counted. The average and peak fluence differences imply that spacecraft anomaly likelihood distribution is not random against fluence but biased to higher fluence.

The probability distribution of spacecraft anomalies as a function of $\log_{10}$ (fluence) is shown in Figure 7b. It is simply derived by dividing the number of anomalies by the number of days for every 0.2 $\log_{10}$ (fluence) bin. For example, the total numbers of days and anomaly events are 120 and 25 when the $\log_{10}$ (fluence) range of 1-MeV electron is 4.0–4.2, respectively, thus, the conditional probability of spacecraft anomaly occurrence for $\log_{10}$ (fluence) range of 1-MeV electron is 4.0–4.2 is 20.83%. The probability clearly increases as the electron fluence increases. When the electron fluence of 1-MeV exceeds $10^4$ (cm$^2$ sr eV), it sharply increases to more than 20%, whereas it is less than 10% at a fluence of less than $10^4$ (cm$^2$ sr eV). When the electron fluence of 1-MeV is less than $10^{1.5}$ (cm$^2$ sr eV), the probability of anomaly is almost 0%. Similar conditional probability calculations were performed for electron fluences at other energies of 200 keV, 300 keV, 450 keV, 650 keV, and 1.5 MeV. In the case of 1.5-MeV electrons, the threshold fluence at which the probability of spacecraft anomaly occurrence sharply increases is $10^{3.6}$ (cm$^2$ sr eV). The threshold fluences become higher for lower electron energies and are $10^{4.6}$ (cm$^2$ sr eV) for 650-keV electrons, $10^5$ (cm$^2$ sr eV) for 450-keV electrons, $10^{5.4}$ (cm$^2$ sr eV) for 300-keV electrons, and $10^{5.8}$ (cm$^2$ sr eV) for 200-keV electrons. The threshold fluences of high-energy electrons are lower and those of low-energy electrons are higher, as expected from the shape of the electron energy spectrum. Such thresholds are important for warning an operator of the increased risk of a spacecraft anomaly. This statistical result indicates that there is a clear threshold at which the probability of a spacecraft anomaly increases.

5. Discussion and Summary

In this study, the space radiation environment during the data outage of meteorological imagery service occurred on three geostationary meteorological satellites, Himawari-8, MET-7, and MET-8, from 2015 to 2017 were investigated. A total of 11 incomplete imagery that were caused by spacecraft anomalies on Himawari-8 were reported in the irregular event log between July 2015 and December 2017, whereas a total of 84 service alerts that were caused by spacecraft anomalies on MET-7 and MET-8 were reported during the three years from 2015 to 2017. Simultaneity of occurrences between high-energy particle increase and spacecraft anomalies were investigated based on the observations of energetic electrons and protons by Himawari-8/SEDA. The reports of the irregular event log of Himawari-8 and the user notification service of MET-7&8 include anomaly dates, periods, and simple causes such as, “spacecraft anomaly”, “ground-system anomaly”, or “instrument anomaly” as well as effects on meteorological imaging services. It was found that about forty percent of the data outage were observed when 24-hr fluences of energetic electrons were increased. Simultaneity with energetic particle enhancements implies that ESD after internal/deep dielectric charging or SEE can be considered as root causes of those anomaly. Both reports, however, do not contain detailed information regarding components nor root cause of anomaly. Whereas it is difficult to identify real cause of anomaly so that the forty percent may include the cases happened coincidentally for example, ESD after low-energy electron related surface charging, galactic cosmic ray related SEEs, other causes besides space environments.

Figure 8 shows the percentages of space environment conditions, namely, 1-MeV electron fluence enhancement $>10^4$ (cm$^2$ sr eV), 22-MeV proton flux enhancement $>10^{-2}$ (cm$^2$ sr s MeV), and others, when spacecraft

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Figure 8. Percentage of space environments when spacecraft anomalies occurred on (a) Himawari-8 and (b) MET-7 and MET-8. Electron enhancement indicates that the 1-MeV electron 24-hr fluence was greater than $10^4$ (cm$^2$ sr eV). Proton enhancement indicates that the daily maximum of 22-MeV proton flux (5-min average) was greater than $10^{-1}$ (cm$^2$ sr s MeV). The numbers in brackets indicate the number of spacecraft anomaly events.
anomalies occurred on (a) Himawari-8 and (b) MET-7 and MET-8. In the case of Himawari-8, about 45% of the spacecraft anomalies (five anomalies) occurred during electron enhancement and about 9% occurred during proton enhancement (one anomaly). Thus, 54% of Himawari-8 spacecraft anomalies occurred during energetic particle enhancement. In the case of MET-7 and MET-8, 35% of the spacecraft anomalies (29 anomalies) occurred during electron enhancement and 7% (six anomalies) occurred during both proton and electron enhancement. Thus, 42% of Meteosat spacecraft anomalies occurred during energetic particle enhancement. Spacecraft anomalies in “others” conditions indicate that energetic particle fluence or flux was not high on the anomaly days. But these include cases that fluence or flux was high before and after anomaly days. Since timings of ESD occurrence and spacecraft charging are somewhat different, some cases included in “others” may related to energetic particle variation. These percentages are compared with those in a previous study. According to the analysis results obtained by Tafazoli (2009), the space environment caused 17% of all spacecraft anomalies from 1980 to 2005. In comparison, the percentages derived in this study are higher than that in the previous report. The reasons for the difference are considered to be as follows: (a) the survey period of this study (2015–2017) corresponds to the declining phase of the solar cycle when the energetic electron fluence becomes highest over a cycle, (b) the spacecraft anomaly database of Tafazoli (2009) include spacecraft in low Earth orbit (LEO) where space radiation is less severe than that in GEO, and (c) the anomaly databases of this study are specific because these include only spacecraft anomalies that had affected the meteorological imagery service but excluded others.

Next, the frequency of energetic particle impacts on meteorological satellite services is discussed. On Himawari-8, six service alerts occurred during energetic particle enhancement over about 2.5 years from July 2015 to December 2017. This corresponds to an anomaly occurrence rate of 2.4 events per year. On the first-generation EUMETSAT meteorological satellite MET-7, 33 service alerts occurred from January 2015 to January 2017 (2.1 years) in association with energetic particle enhancements. On the second-generation EUMETSAT meteorological satellite MET-8, only two service alerts occurred in association with electron enhancements when the period it has operated since October 2016 until December 2017 (1.25 years). In the case of MET-7, the occurrence frequency of service alerts due to energetic particles enhancements are about 16 events per year, whereas in the case of MET-8, it is about one to two events per year. The occurrence frequencies of data outage for the three meteorological satellites are summarized as follows.

1. Himawari 8
   - Approx. 2–3 anomalies/year
2. MET 7 (first generation)
   - Approx. 16 anomalies/year
3. MET 8 (second generation)
   - Approx. 1–2 anomalies/year

In this study, the relationships between energetic particle enhancement and data outage of meteorological imagery observation due to spacecraft anomalies that occurred on Himawari-8, MET-7, and MET-8 from 2015 to 2017 were investigated. The findings are as follows.

1. The occurrence frequencies of data outage for meteorological imagery observation, for example, quality degradation, missing, and interruption of data, that are caused by spacecraft anomalies and ground system anomalies are almost the same.
2. A total of 11 incomplete imagery occurred owing to spacecraft anomalies on Himawari-8. In all but one cases, the spacecraft was exposed to 1-MeV electrons with fluence higher than $10^4$ (cm$^{-2}$ sr eV) at the day of (five cases), several days before (four cases), or immediately after (one case) the spacecraft anomaly. There was one case wherein the spacecraft was exposed to SEP (22-MeV proton flux was higher than $10^{-2}$ (cm$^{-2}$ sr s eV)).
3. A total of 84 service alerts occurred owing to spacecraft anomalies on MET-7 (79 cases) and MET-8 (5 cases). Thirty-five spacecraft anomalies among the 84 cases occurred when the 1-MeV electron fluence was higher than $10^4$ (cm$^{-2}$ sr eV). There were six cases among the 35 anomalies wherein the spacecraft was exposed to SEP simultaneously with high electron fluence.
4. Based on statistical analysis, it was found that the probability of a spacecraft anomaly markedly increases when the electron fluence exceeds a certain threshold. The probability of anomaly occurrence is less than 10% at a fluence of less than $10^4$ (cm$^{-2}$ sr eV), whereas it increases to more than 20% at higher fluences. Such thresholds were also found for electron fluences at other energies from 200 keV to 1.5 MeV.

According to the Himawari-8/SEDA observation data and anomaly history, it clarified that the Himawari-8 and Meteosat imaging services fail due to a spacecraft anomaly when energetic particles, particularly electron...
fluences, increases. This analysis is limited to data outages of meteorological satellite operation, but other satellite services also similarly suffer from spacecraft anomalies owing to changes in the space environment. Satellite services are now an indispensable part of our social infrastructure. Thus, a spacecraft and its operation must overcome their vulnerability to the space environment as much as possible. More detailed information of spacecraft anomaly occurrences is important to reveal the direct causality between space environment changes and specific components where anomalies occur. Further studies based on detailed anomaly information are important for developing a resilient system of spacecraft and its operation.

**Data Availability Statement**

The energetic particle data of Himawari-8/SEDA are available from HIMAWARI/SEDA DATABASE of NICT [https://aer-nc-web.nict.go.jp/himawari-seda/](https://aer-nc-web.nict.go.jp/himawari-seda/). The operational information of the Himawari-8 imaging observation system is published on the website of the Meteorological Satellite Center of JMA [https://www.data.jma.go.jp/mscweb/en/oper/event_H8.html](https://www.data.jma.go.jp/mscweb/en/oper/event_H8.html). The operational information of Meteosat is available on the EUMETSAT user notification service website [https://uns.eumetsat.int/](https://uns.eumetsat.int/).

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