Investigation of an Operational Anomaly of the ADEOS-II Satellite

Shirou Kawakita[1, 2*], Hiroaki Kusawake[1], Masato Takahashi[1], Hironori Maejima [1], Tadaaki Kurosaki[1]
Yasushi Kojima[1], Daisuke Goto[1], Yuugo Kimoto[1], Junichiro Ishizawa[1]
Masao Nakamura[3], Jeong-ho Kim[4], Satoshi Hosoda[4], Mengu Cho[4], Kazuhiro Toyoda[5] and Yukishige Nozaki[6],
1. Japan Aerospace Exploration Agency (JAXA), 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan
2. Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokoyama, Kanagawa 226-8503, Japan
3. National Institute of Information and Communications Technology, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795 Japan
4. Kyushu Institute of Technology, 1-1 Sensui Tobata-ku Kitakyushu, 804-8550, Japan
5. Chiba University, 1-33 Yayoicho Inage-ku Chiba, 804-8550, Japan
6. NEC TOSHIBA Space Systems, Ltd., 2-6-3 Shinyokohama Kohoku-ku Yokohama, 222-0033, Japan
*Phone: +81-29-868-4241, Fax:+81-29-868-5969, E-mail: kawakita.shirou@jaxa.jp

ABSTRACT

The ADEOS-II satellite experienced anomalous operation on October 25, 2003. The power generated on the satellite suddenly decreased from 6 kW to 1 kW. We conducted experiments to investigate this degradation of power for the satellite. The multi-layer insulator film that wraps the power cables was charged by low-energy electrons when the satellite passed though the aurora region around the Earth's pole. ESD tests were carried out for the power cables. Trigger arc discharges occurred between the film and cables with cracks produced by thermal cycles. A secondary arc electric discharge subsequently occurred between the cables themselves. This secondary arc caused a sustained arc after several discharges, which burned out the cables. The heat caused by arc tracking between the hot and return cables made them burn out. This was the mechanism of the operational anomaly on the ADEOS-II satellite.

1. INTRODUCTION

Spacecraft charges have caused many significant anomalies in high-altitude spacecraft. This has led to several investigations devoted entirely to the study of spacecraft charging in geostationary Earth orbit (GEO) [1, 2]. Minimal spacecraft charging occurs in low Earth orbit (LEO) since low-temperature plasma around the satellite mitigates the charging effect. However, the existence of some spacecraft charging in LEO is suggested by observed data from DMSP satellites [3]. In addition, the solar paddle of EOS-AM in LEO was apparently damaged by an electrostatic discharge (ESD) [4]. The solar array may have developed a short circuit between the solar cell and the substrate of the satellite due to a sustained arc that occurred via plasma interaction with the solar paddle of the satellite.

The Advanced Earth-Observing Satellite No. 2 (ADEOS-II) was launched on December 14, 2002, from the Tanegashima Space Center. This satellite performed global observations of Earth's environment for about ten months until the operational anomaly. Figure 1 provides an overview of the satellite.

ADEOS-II suddenly stopped observing the Earth's environment at 22:18 (UT) on October 24, 2003 [5]. The satellite shifted to low-load mode because of the greatly degraded electrical power. The satellite was subsequently unable to contact the ground communication center. An analysis of the flight data revealed that the power on the satellite suddenly decreased from 6 kW to 1 kW. Figures 2 and 3 depict the location of the anomaly and power data for the flight.

Figure 4 contains a function diagram of the solar panel and electrical power unit of the ADEOS-II satellite. The solar panel is composed of 64 solar arrays. The electrical power of one solar array is 60V and 2A. The power is transmitted through two electrical power bundles, the paddle driving mechanism (PDM), and two shunt components to the power control unit (PCU). The total power can be estimated from the sum of the currents of SHNT-1, SHNT-2, and the PCU.

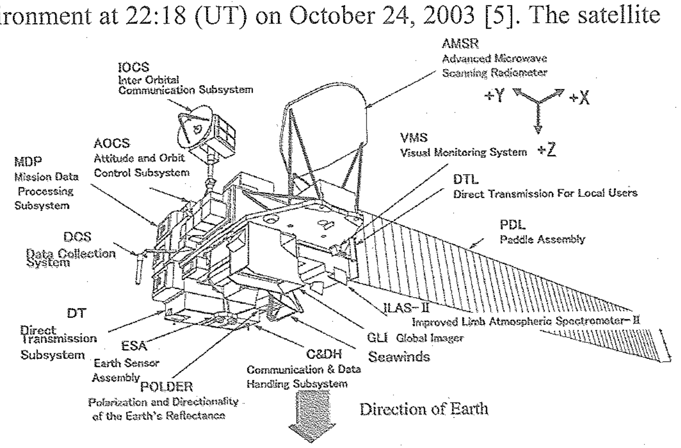


Fig. 1 Overview of ADEOS-II satellite.

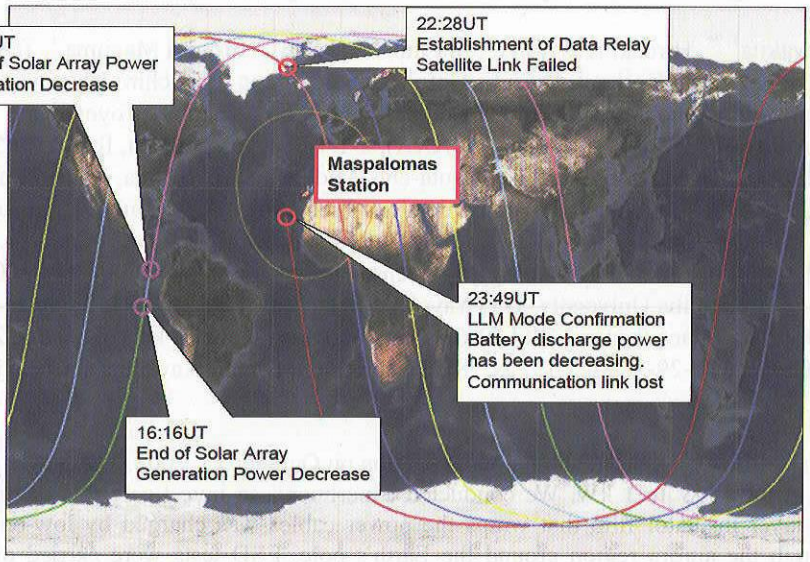


Fig.2 Location of anomaly events.

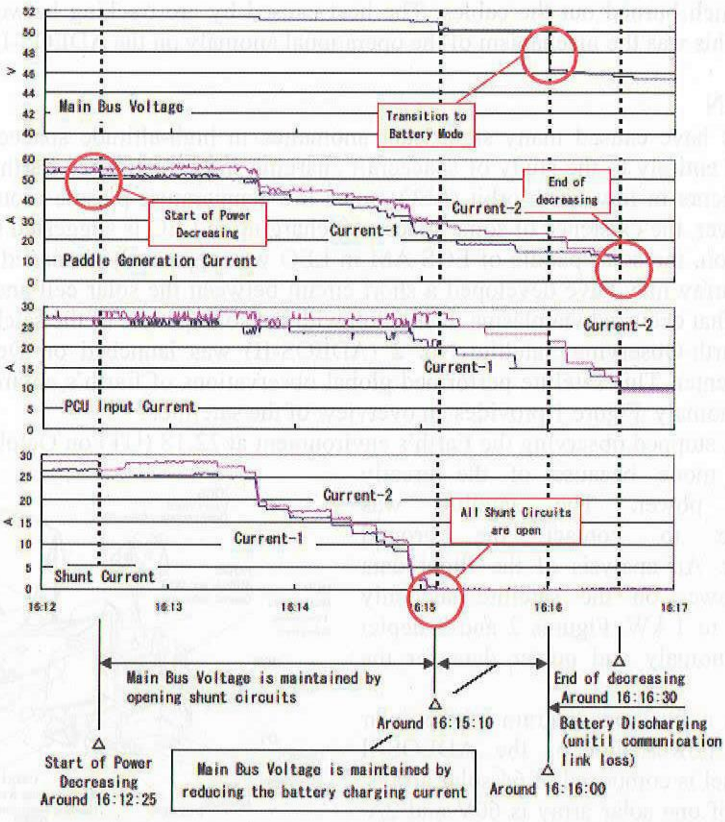


Fig. 3 Flight data of the generated electrical power on operational anomaly.

The currents of SHNT-1 and SHNT-2 decreased at about the 2A step in Fig. 3. The input current of the PCU did not change when the current of the SHNTs decreased. However, the current of the PCU began to decrease when the current of the SHNTs was 0A. The degradation of BUS voltage at 16:16 suggests the discharge of the satellite batteries. The results clearly indicate that the PCU operated normally during degradation of the electric power.

Figure 5 provides the flight data of the attitude of the satellite during the operational anomaly. A change of attitude was observed for five minutes at the same time as the degradation of power. In addition, the altitude of the satellite decreased. This phenomenon was not considered to be affected by space debris or meteoroids, since the attitude

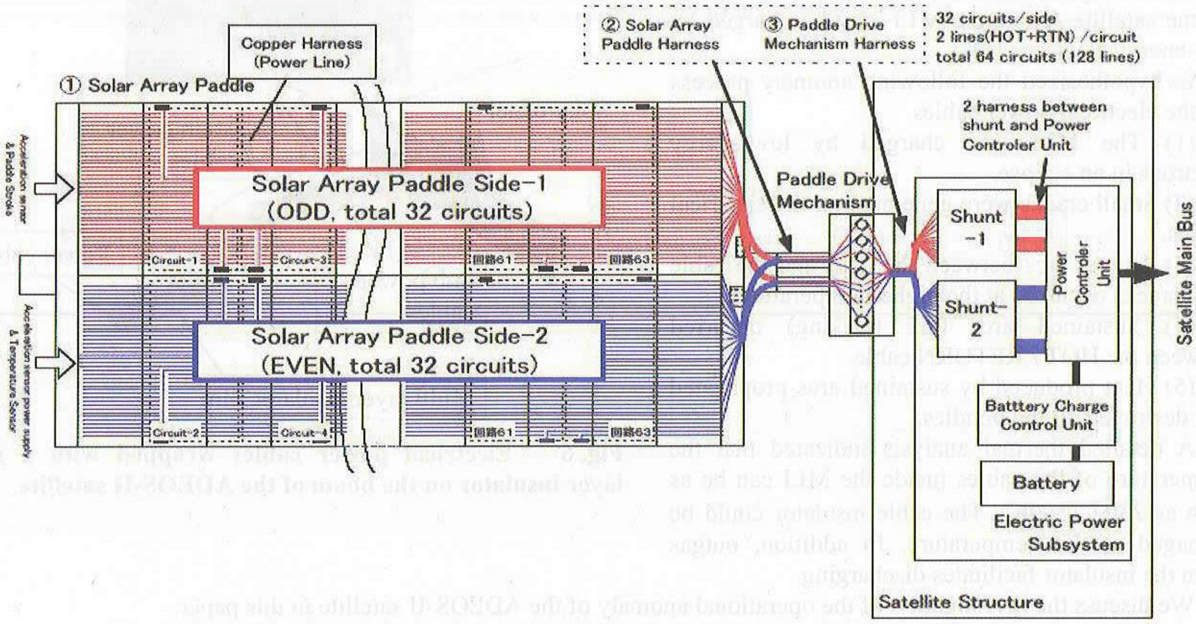


Fig. 4 A Function diagram of PDL and EPS of the ADEOS-II satellite.

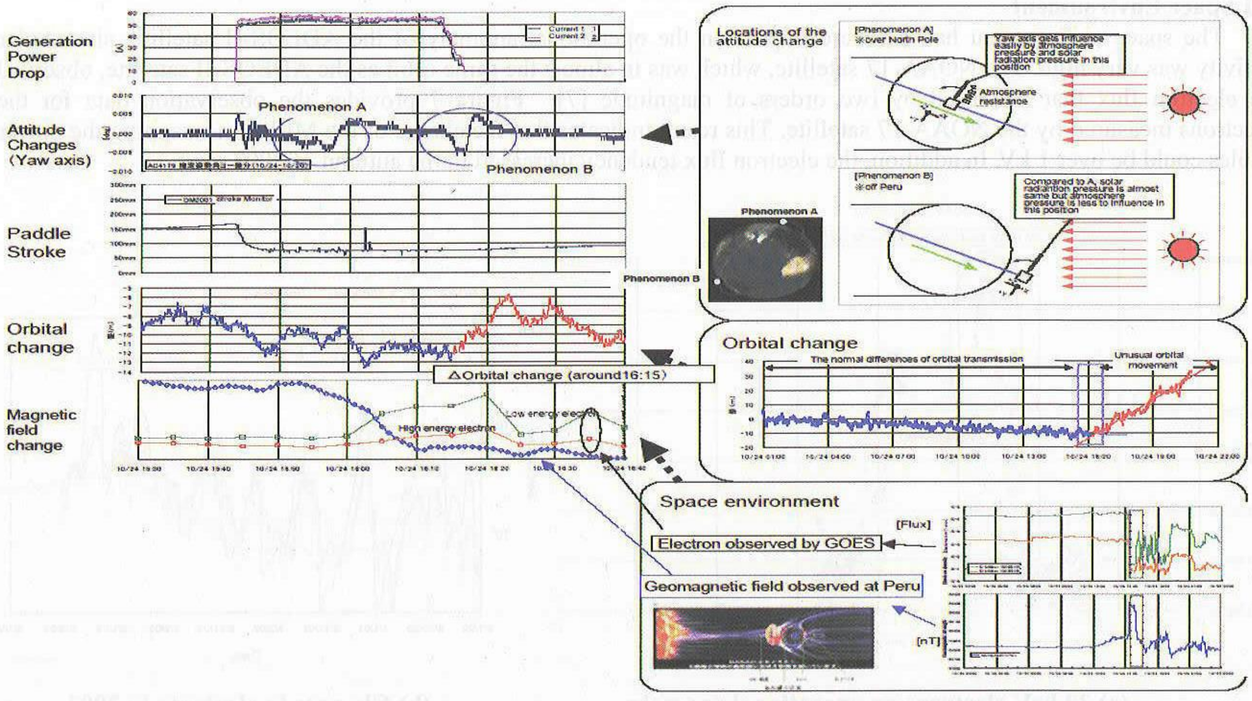


Fig. 5 Changes in attitude of the ADEOS II satellite on operational anomaly.

fluctuation continued for a long time.

This analysis suggests that the electrical power cable of the satellite was the failure point. The cables of ADEOS-II were bound in two parts on the boom. One bundle was composed of 52 cable pairs, corresponding to about 5kW, the other was composed of signal lines and 12 cable pairs, corresponding to about 1kW. An overview of the cables and the boom of ADEOS-II are provided in Fig. 6. The main electrical power of the cables was consistent with the satellite's loss of generated power.

The cables were wrapped in multi-layer insulator (MLI) film. This film prevents the cable temperature from dropping when solar panels are deployed in the first phases of space travel. The film has 12 layers, which are insulator film with evaporated Al. The film floats electrically on the satellite. Thus, the MLI may be charged by low-energy electrons [6].

We hypothesized the following anomaly process for the electrical power cables.

(1) The MLI was charged by low-energy electrons in an eclipse.

(2) Small cracks were generated on the electrical cables.

(3) Trigger arcs between the MLI and the cable with cracks occurred at the higher temperature.

(4) Sustained arcs (arc tracking) occurred between the HOT / RETURN cable.

(5) Heat produced by sustained arcs propagated and destroyed all the bundles.

A detailed thermal analysis indicated that the temperature of the cables inside the MLI can be as high as 230℃(500K). The cable insulator could be damaged at this temperature. In addition, outgas from the insulator facilitates discharging.

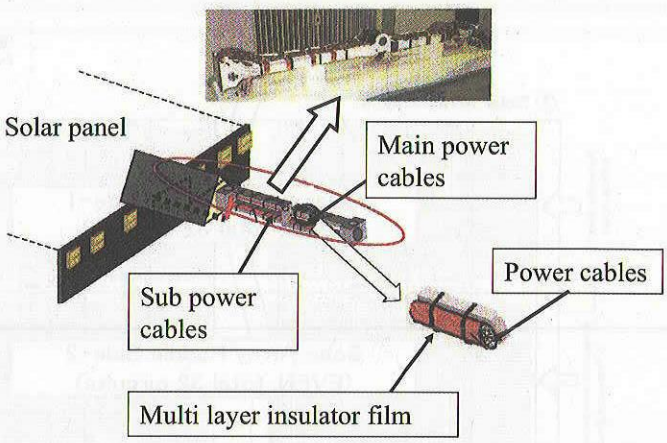


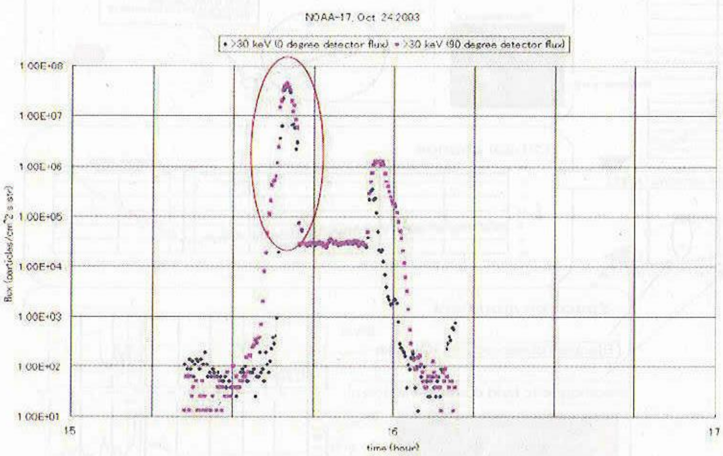
Fig. 6 Electrical power cables wrapped with a multi layer insulator on the boom of the ADEOS-II satellite.

We discuss the investigation of the operational anomaly of the ADEOS-II satellite in this paper.

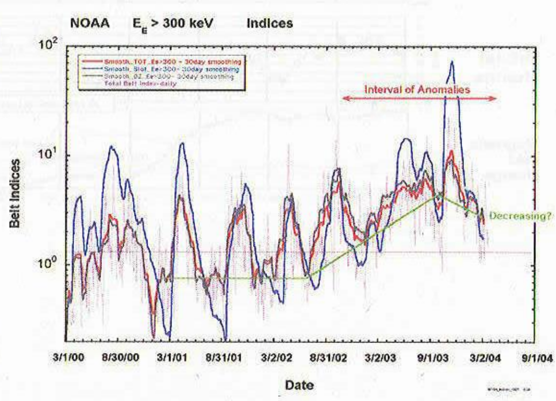
2. EXPERIMENTS AND RESULTS

2.1 Space Environment

The space environment had a severe impact on the operational anomaly of the ADEOS-II satellite, since solar activity was very high. The NOAA-17 satellite, which was in almost the same orbit as the ADEOS-II satellite, observed an electron flux that increased by two orders of magnitude [7]. Figure 7 provides the observation data for the electrons measured by the NOAA-17 satellite. This result indicates that the charge of the MLI film wrapping the power cables could be over 1 kV. In addition, the electron flux tendency increased in the autumn of 2003.



(a) 30 keV electrons on operational anomaly



(b) Changes in electrons in 2003

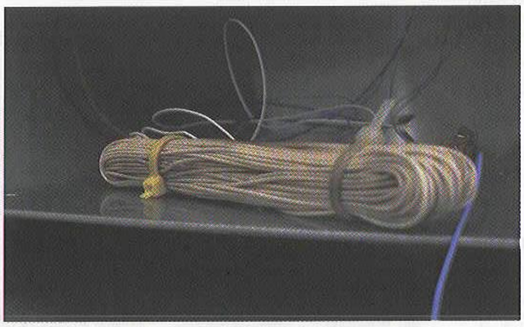
Fig. 7 Flight data of electrons measured by the NOAA-17 satellite.

2.2 Evaluation Tests

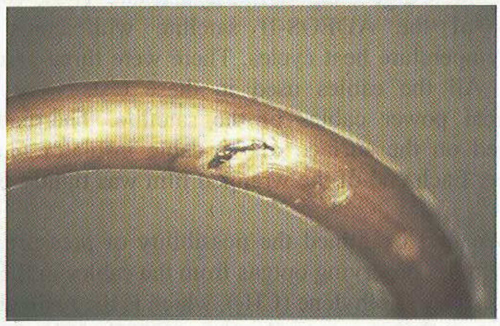
2.2.1 Thermal cycle test for electrical cable

We conducted a thermal cycle test for the electrical power cables to evaluate the generation of cracks on the cable. The cable bundle was set in a vacuum chamber. The temperature of the bundle was controlled to between 100˚C and 230˚C. This thermal condition was estimated from the thermal analysis for the electrical cables of the satellite in space. The test configuration is illustrated in Fig. 8 (a).

Cracks were generated on the cables after about 5000 thermal cycles. Figure 8 (b) depicts the cracked cables after



(a) Sample in the chamber before test



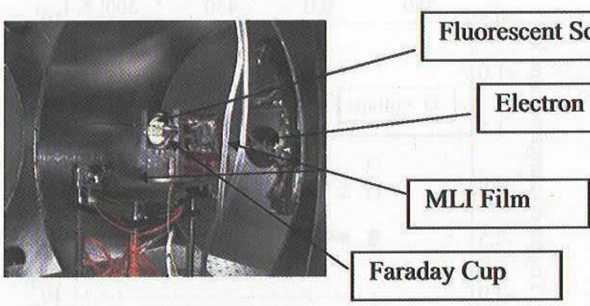
(b) Crack on the cable after test

Fig. 8 A thermal cycle test for the electric power cable bundle. The temperature of the bundle was controlled to between 100°C and 230°C.

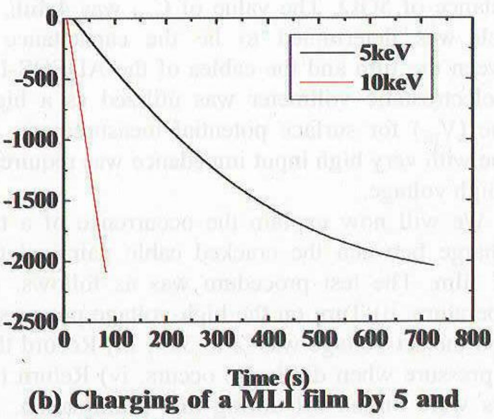
the thermal cycle test. The cracks were produced at the sticking point between the cables caused by thermal stress.

2.2.2 Charging Tests for the MLI film irradiated with electrons.

The MLI film of the ADEOS-II satellite would be charged by electrons while traveling across the aurora region since the film was not grounded to the satellite. We conducted a charging test for the film. Figure 9 depicts the test configuration. Electrons in energy of 5 and 10 keV were irradiated onto the film. The electron flux of 5 keV and 10 keV electrons was 1×10^7 and 1×10^8 electrons/cm^2, respectively. The charging potential of the film was monitored using a potential meter and a PC. The result indicated that the film was charged with enough potential to cause a discharge between the cracked cable and the film. The film charge would not be rapidly mitigated by low temperature plasma after traveling in the aurora region since electrons in a range of 10 keV to 30 keV were able to create an internal charge in the surface polyimide layer of the film [8].



(a) A test configuration



(b) Charging of a MLI film by 5 and 10 keV electrons

Fig. 9 Charging tests of a MLI film irradiated with 5 and 10 keV electrons.

2.2.3 Discharging Tests

We conducted some discharge tests to evaluate hypotheses (3), (4), and (5). The results of the experiments have been reported [9] in detail. This section provides an outline of the result.

The discharge voltage between the cracked cables and the MLI film was measured first. This voltage depended on the temperature in the MLI film, since the pressure in the film increased with increases in the temperature. Figure 10 provides a photograph of the sample. We could apply high voltage to the innermost layer of the MLI through the attached cables. A bundled cable was attached as a heater on the innermost layer of the film. This cable had previously undergone a high temperature heat cycle. These cables simulated the cables of the ADEOS-II satellite with crack damage due to high-temperature heat cycles. There were three pairs of cracks on the cable. All the cables used in these tests were equivalent to the electrical power cables of the satellite. Thermocouples were also attached on the surface of the cable insulator and the film's outer surface. Each end of the wrapped film was tightly bundled by binding wire.

We first examined the possibility of pressure increments in the MLI film by observing outgas from the cables in the film. The primary component was ethylene (CH_2), which is the main chain of an ethylene tetrafluoroethylene copolymer (ETFE:-$[CH_2\text{-}CH_2]_m\text{-}[CF_2\text{-}CF_2]_n$-). This is the major element of the cable insulator. Our result indicated that the cable insulator deteriorated and evaporated at a high temperature. Therefore, the internal pressure of the MLI increased when a large current flowed to the cables due to vaporization of the cable insulator and their own low conductance.

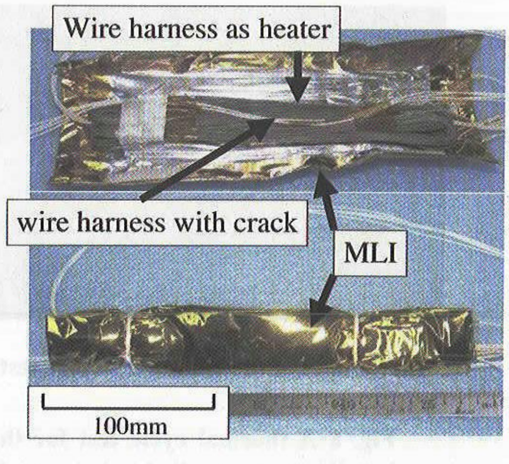


Fig. 10 A test sample which imitates electrical power cables on the boom

We will next explain the results of the discharge test. Figure 11 depicts the experimental set-up. The following two points differed from the above test configuration. The inner surface of the MLI film was biased negatively via a high-voltage power supply, and a cracked cable pair was connected to the external circuit containing a Solar Array Simulator (SAS), which was a DC electrical power supply. The SAS can rapidly respond for switching, because the internal capacitance is less than 50 nF. Thus, the SAS is a suitable for discharge tests. The MLI film's inner surface and capacitance (C_{ext}) were gradually charged by a high-voltage power supply via a limiting resistance of 5GΩ. The value of C_{ext} was 4.4nF, which was determined to be the capacitance between the film and the cables of the ADEOS-II satellite. An electrostatic voltmeter was utilized as a high-voltage probe (V_{p2}) for surface potential measurement. A voltage probe with very high input impedance was required to apply the high voltage.

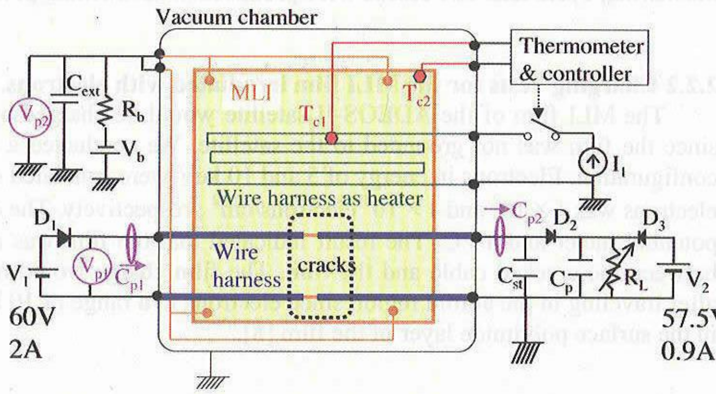


Fig. 11 A schematic drawing of discharge test.

We will now explain the occurrence of a trigger arc discharge between the cracked cable pair and the biased MLI film. The test procedure was as follows. i) Set the temperature. ii) Turn on the high-voltage power supply, for which the set voltage was–2 to 3kV. iii) Record the voltage and pressure when discharge occurs. iv) Return to i). Both SASs were turned off during this examination. Figure 12 illustrates the relationship of the threshold voltage of the trigger discharge and the film's internal pressure with changes in the surface temperature. We confirmed that the threshold voltage of the trigger discharge became lower with increases in the internal pressure of the MLI, as described above. The threshold voltage at 230℃ was -1.0 to 1.5kV, which is a reasonable potential for the film when charged by low-energy electrons in orbit.

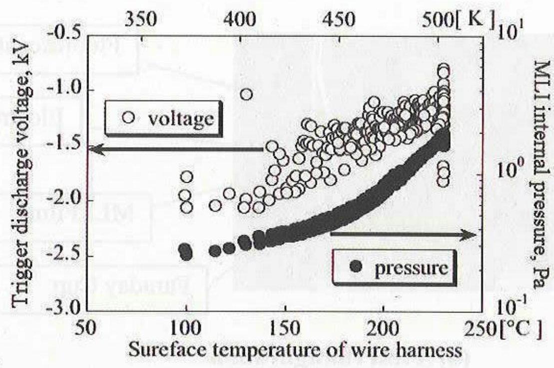


Fig. 12 Variations of the threshold voltage of trigger discharge and the MLI internal pressure.

We next report the occurrence of a secondary arc, which was a sustained arc, its discharge triggered by the discharge between the negatively biased MLI film and cracks in the cable. The external circuit consisted of SASs (V_1, V_2), diodes (D_1 ~ D_3), capacitances (C_{st}, C_p), variable resistance (R_L), and probes. This circuit simulates the actual solar array behavior. The capacitance between each string was C_{st}. The capacitance simulated by the satellite PCU was C_p. The respective capacitance values were 120nF and 18,000μF. Both V_1 and V_2 simulated the voltage of one solar array and provided electrical power to the satellite load (R_L) and PCU (C_p). A potential difference of 60V was applied between each cable by V_1. The voltage of V_1 falls once a secondary arc occurs, and the blocking diode (D_2) acts as a switch that momentarily disconnects current to R_L and changes the current path to an arc discharge. A secondary arc was observed from the measured waveform of the inserted probes.

A secondary arc was observed at a temperature of 160℃. A very short duration (~1μs) trigger discharge current flowed into the cables. The peak current was about 50A. The voltage of V_1 fell after several trigger discharges and the discharge current rose rapidly. The measured discharge voltage of the secondary arc was 30V. This secondary arc was sustained for more than 1.5 ms. A microscope photograph of the cracked cable before and after the test is provided in Fig. 13. Formation of arc tracking on the cable insulator was observed near the cracks. This tracking had an electrical resistance of about 20 MΩ. The arc tracking formation was limited at the points where it adjoined each crack.

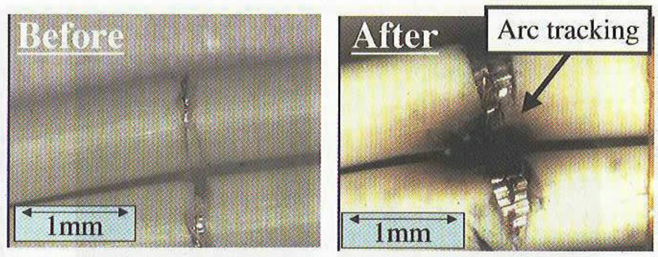


Fig. 13 The waveform of the secondary arc at the temperature of 160°C.

We next investigated the effect of damage by a sustained arc of an electrical cable with cracks to the cables without cracks in order to verify hypothesis (5). The sample was composed of one cable pair with cracks and nine cable pairs without cracks. An external high-voltage bias was supplied to the MLI film. The temperature of the film was controlled by a heater. Trigger arcs occurred between the cables and the film when more than -1kV was applied to the blanket. A sustained arc occurred after several trigger arcs. The heat from the sustained arc greatly affected the electrical power cables surrounding the cables with cracks. Figure 13 presents a photograph of the sample during the sustained arc. Plasma generated from the cables spouted out of the sample. This plasma accelerated the sample.

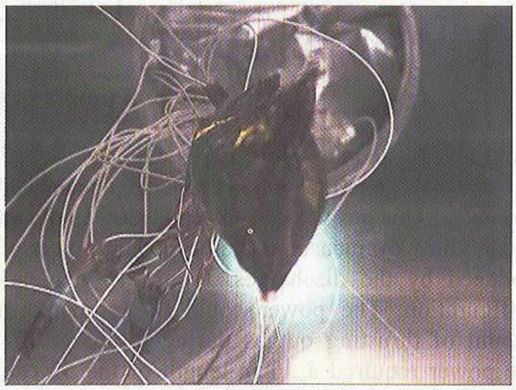


Fig. 14 Plasma from the hole of the MLI destroyed by ESD.

Photographs of the cables wrapped with the MLI before and after the experiment are provided in Fig. 15. This figure indicates the immense damage to the cables by the sustained arcs. Consequently, all electrical power cables were shorted or opened. This phenomenon is in good agreement with the degradation of the electrical power generation of the ADEOS-II satellite.

(a) Before **(b) After**

Fig. 15 Pictures of the electrical power cables (a) before and (b) after the effect of damage by a sustained arc of the cables with cracks to the cables without cracks.

2.2.4 Changes in the Attitude

The attitude of the ADEOS-II satellite changed during the operational anomaly. The amount of torque and the point of action were calculated from the flight data. The point of action was the boom between the solar panel and the

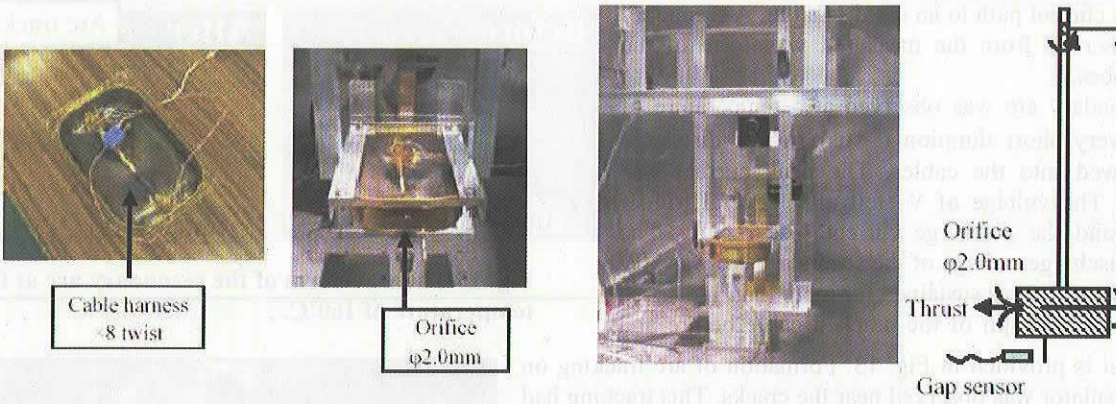


Fig.16 Propellant power test generated by outgases from discharging cables.

satellite body, and the impulse was 4.9 Ns.

Gas was generated when discharges occurred between the cables. This gas would cause a change in the attitude of the satellite. We measured the propellant power of the gas produced by the discharges. Figure 16 depicts the test configuration. The power could be estimated from the amount of thrusting outgas during discharge in Fig. 17. The power required a 10 m length of the 52 cable pairs, which corresponds to the number of electrical cables wrapped in the bundle on the boom. This value was almost the same as the length of the cables on the boom of the ADEOS-II satellite. Therefore, these results can explain the phenomenon.

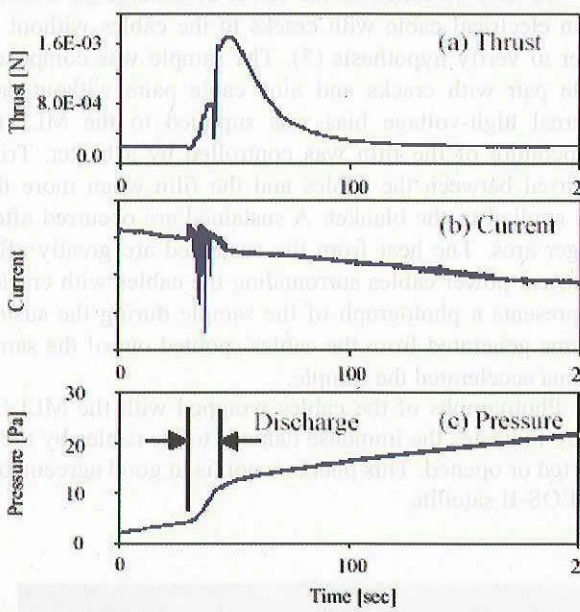


Fig. 17 Changes in thrust from the hole of the orifice and the chamber pressure during discharging of the cables.

3. CONCLUSION

Our hypothesis for the anomaly process of the electrical power cables was verified in ground tests. The degradation of the electrical power of the ADEOS-II satellite was caused by damage to the electrical power cables on the boom produced by discharges between cracked cables and the ungrounded MLI film while traveling in the aurora region. The process of the operational anomaly can be described as follows.

■ Before operational anomaly

1) The thermal cycles caused cracks in the electrical cables in the MLI film.
2) The film was negatively charged by electrons in the aurora region.
3) Trigger arc discharges occurred between the cracked cables and the charged film.
4) Some secondary arc discharges occurred between the hot and return electrical cable pair due to the plasma generated by trigger arc discharges.
5) These discharges damaged the cables. The discharges produced arc tracking between the hot and return cable pair.

■ On operational anomaly

1) Electron flux in the aurora region was two orders of magnitude greater than that in normal conditions since sun activity was very high.
2) The film was highly charged.
3) A great trigger arc discharge occurred the between the cracked cables and the negatively charged film above the offing of Peru.
4) The discharge caused a secondary arc discharge between the hot and return cable pair.
5) The discharge produced arc tracking between the hot and return cable pair.
6) A sustained arc discharge produced heat. The energy of the heat corresponded to the generated power of one solar array (about 100 W).

7) The heat destroyed other cables that surrounded the cables that discharged the sustained arc.
8) Finally, all cables in the film were burned out and the power generated though the bundle in the film on the boom could not be transmitted to the satellite.

4. AKCNOWLEGEMNT

The authors wish to thank the ADEOS-II satellite operational anomaly investigation team, students of Kyushu Institute of Technology, and various companies for their great cooperation and helpful suggestions during this study.

REFERENCES

[1] Crofton, M. W., Francis, R. W., "Electrostatic Discharge Measurements on Solar Cell Coupons in a Simulated GEO Environment", AIAA-99-01-2634, 1999

[2] Takahashi, M., Nishimoto, H., Kawakita, S., Cho, M., Nozaki, Y., Fujii, H., Murakami, Y., Ozaki, T., Onodera, N., "ETS-VIII Solar PDL Plasma Interaction Problem Approach", 7th Spacecraft Charging Technology Conference, April. 23-27, 2001, ESA-ESTEC, Noordwijk, The Netherlands

[3] Cooke, D. L., "Simulation of an Aurora Charging Anomaly on the DMSP Satellite", AIAA-98-0385, 36th Aerospace Science Meeting & Exhibit, January 12-15, 1998, Reno, NV

[4]Davis, S., Stillwell, R., Andiario, W., Snyder, D., Katz, I., "EOS-AM Solar Array Arc Mitigation Design", AIAA-99-01-2582, 1999

[5]Maejima, H., Kawakita, S., Kusawake, H., Takahashi, M., Nakamura, M., Goka, T., Kurosaki, T., Cho, M., Toyoda., K., Nozaki, Y., Okada, K., "Investigation of Power System Failure of a LEO Satellite", AIAA-2004-5657

[6] Anderson, P. C., Koons, H. C., "Spacecraft Charging Anomaly on a Low-Altitude Satellite in an Aurora", *J. Spacecarft and Rokets*, Vol. 33, No. 5, 1996, pp. 734, 738.

[7] M. Nakamura, ***" ***", in this conference

[8] Derek, V., "Electrostatic Discharging Behavior of Kapton Irradiated with Electrons", 3rd Spacecraft Charging Technology Conference, pp. 99-114, 1980

[9] Kawakita. S, Kusawake. H, Takahashi. M, Maejima. H, Kim. J, Hosoda. S, Cho. M, Toyoda. K, Nozaki. Y, "Sustained arc between primary power cables of a satellite" AIAA-2004-5656