ESD TESTS OF SOLAR ARRAY PADDLE ON A POLAR ORBITING SATELLITE

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Abstract

Advanced Land Observing Satellite (ALOS) that will be launched by Japanese Aerospace Exploration Agency in 2005 will carry a large solar paddle of 22mx3m in polar orbit. The wake side of solar paddle can be charged to a highly negative value. Laboratory experiments are carried out to investigate charging and arcing phenomena on the backside of the solar paddle that has exposed bypath diode boards and Silver-Teflon® thermal coating. We irradiate solar panel coupons with an electron beam to simulate charging situation near the North Pole. Surface flashover is observed once the insulator potential exceeds -7kV. Possibility of sustained arc and surge voltage between hot and return ends of power circuit have been investigated.

Introduction

Loss of ADEOS-II (Midori-II) due to power failure[1] resulted from spacecraft charging in aurora zone has made us reinvestigate strength of polar orbiting satellite against spacecraft charging. The risk of charging is indeed increasing for recent polar orbiting satellites that demand more power for spacecraft operation. The increased power means increased risk of catastrophic failure in the power distribution system that was demonstrated unfortunately by the loss of ADEOS-II. The increased power also means increased size of solar array paddle. The polar orbit is a peculiar orbit where low energy but high density ionospheric plasma and high energy but low density aurora particles coexist. As a satellite passes by the aurora zone, combination of plasma wake, non-conductive surface, and aurora particles may lead to severe surface charging of the wake side of the solar paddle.

Figure 1. Illustration of ALOS in orbit

Japan Aerospace Exploration Agency (JAXA) plans to launch ALOS (Advanced Land Observing Satellite) in 2005 to a sun-synchronous orbit of 690km altitude. Aurora charging has

been discussed previously for Freja and DMSP[2,3]. Severe negative charging of satellite body was observed for those satellites when the satellites crossed aurora zone between 65 and 75 degrees of the magnetic latitude and ionospheric ion density decreased as low as the order of $10^9 m^{-3}$. The orbital altitude of ALOS is not as high as Freja or DMSP. Therefore, ion density would not be as low as Freja or DMSP, which makes it unlikely for a satellite at the same altitude of ALOS to suffer charging similar to Feja or DMSP. ALOS, however, will carry a large solar paddle whose size is 22mx3m, that is one of the largest solar paddles ever flown in LEO except ISS. Figure 1 shows an illustration of the satellite.

Near the North and South Poles, the solar paddle surface is perpendicular to the flight direction so that the paddle faces directly to the sun. Plasma wake is formed behind the paddle, where ionospheric ions that flow supersonically relative to the satellite cannot easily enter. On the other hand aurora electrons can enter the wake relatively free because of their high energy of the order of keV or higher. If the wake side has non-conductive surface, the surface can be charged to a highly negative potential, which was pointed out previously via a numerical study by Wang et al[4]. Unless the aurora electron flux becomes extremely high, the satellite body is well grounded to the ionospheric plasma. In that case, the satellite body that is connected the negative end of solar array circuit has a negative potential of the solar array output voltage[5]. Therefore, at the wake side severe differential charging is possible between non-conductive surface and conductive surface that is connected to the satellite ground. Solar paddle has many parts of non-conductive surface, such as coverglass, insulator sheet below solar cells and thermal coating. The differential charging is more severe near the North Pole where the solar paddle back surface that receives no sunlight is in the wake side. Near the South Pole, the front surface (i.e., surface with solar cells) is in the wake side. Therefore, photoelectrons relax the negative charging of the non-conductive surface (i.e., solar cell coverglass) compared to the situation in the North Pole, though differential charging still occurs if the aurora electron flux becomes very high.

The solar paddle of ALOS consists of nine panels that generate a total of 7kW at EOL condition. Each panel has 16 solar array strings. One string has 162 cells connected in series and two strings are connected in parallel sharing block diodes and bypath diodes. Therefore the total number of cells is more than 23,000. One solar array circuit generates 56V to 58V and 2.7A. (For simplicity, in this paper we approximate the solar array output voltage by 60V.) Solar cells are 69mmx36mm Si cells that have no integrated bypath function. The bypath diodes are inserted at every 27 cells. The power control unit regulates the power at 50 V. to 52V in the dayside. The solar paddle is made of CFRP/Aluminum substrate. The backside has Silver-Teflon® thermal coating on CFRP/Aluminum substrate to deal with the Earth's albedo. In addition, there are bypath diode boards at the backside. The bypath diodes are covered by white paint to reject heat. A photograph of a bypath diode board and nearby thermal coating at the paddle

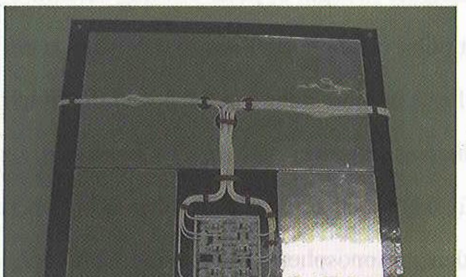


Figure 2. Photograph of back surface of

backside is shown in Fig.2. We took the photograph of a test coupon used in the laboratory experiment that will be discussed later in detail.

Concern over the possibility of charging and arcing at the diode boards arouse from reexamination of the solar paddle design after the ADEOS-II failure. Arcs may occur near the diode boards because of the differential charging across the aurora zone over the North Pole. Not all of diode surface is covered by the white paint to free thermal stress. Therefore, sustained arc may occur between the exposed conductive parts of diodes in a similar way to sustained arc between solar array strings (Ref.5). The purpose of the present study is to investigate the insulation strength of diode boards under charging situation in the aurora zone.

The satellite orbit was analyzed to identify the worst case of charging. Laboratory experiments are carried to investigate the threshold of arc inception, possibility of sustained arc, and surge voltage in the solar array circuit. This is on-going investigation still underway. Therefore, the results presented in this paper, especially experimental results, are only preliminary. In the last part of this paper, we summarize the results that have been known so far.

Worst case orbit

After the launch in 2005, ALOS will be in a sun-synchronous orbit at 690km altitude. The worst charging condition can be identified based on the satellite trajectory. It is known that charging due to aurora particles mainly occur between 60 and 75 degrees of the magnetic latitude. The longer the satellite stays in the aurora zone, the more negatively it is charged. In addition, if the satellite enters the dayside just after the exit from the aurora zone, the combination of the most negative potential and the beginning of power generation makes the situation the worst case. Therefore, we looked for the case when the satellite stays the longest time in the aurora zone in the night side and enter the dayside just after the exit from the aurora zone.

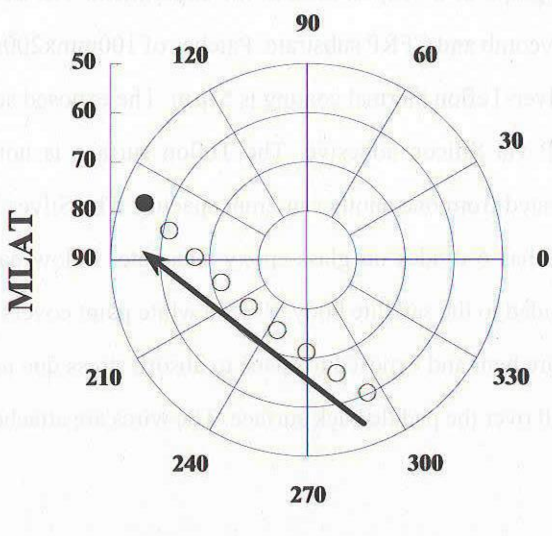


Figure 3. Trajectory of ALOS that flies the aurora zone over the North Pole for the longest

Figure.3 shows an example of satellite trajectory that meets the above-mentioned conditions. This trajectory occurs on January 30th, 2006. The satellite exits the aurora zone at the same time it enters the dayside at 6:10UT, that is denoted by the closed circle in Fig.3. ALOS stays 1200 seconds inside the aurora zone. As we look at 46 days from December 23rd, 2005, there are five such paths over the North Pole where it stays 1200 seconds before it enters the dayside. The example shown in Fig.3 has the highest geographical latitude when the satellite enters the dayside, 86° latitude and 68° longitude, which probably leads to the most severe charging because the plasma density is the lowest. The year 2006 is also near the bottom of 11-year period solar activity, giving the lowest plasma density at the altitude of 690km. Once we know the satellite position where the worst charging condition is expected, we can obtain the plasma conditions from known models of ionosphere. In Table 1, we list the plasma conditions at 68° latitude and 86° longitude at 6:10 UT on January 30th, 2006 that are taken from International Reference Ionosphere(7). We use the plasma conditions listed in Table 1 as the reference values.

Plasma density	$2.0x10^{10}m^{-3}$
Electron temperature	0.2eV
Ion temperature	0.2eV
Averaged ion mass number	13
Orbital velocity	7.2km/s
Nominal aurora current density	$3.2x10^{-8}A/m^2$

Table 1. Plasma parameters assumed for reference value.

Laboratory Experiment

3.1. Experimental method

In order to investigate arcing phenomena on the solar paddle back surface, we have carried out laboratory experiment in a vacuum chamber. We use coupons that represent parts sensitive to arcs, a bypath diode board and Silver-Teflon thermal coating. Coupons are made using the same procedure and material as flight solar paddle. Figure 2 shows a photograph of a coupon used in the experiment. The coupons size is 241mmx220mm made of 25mm thick aluminum honeycomb and CFRP substrate. Patches of 100mmx200mm Silver-Teflon cover most of the back surface. The thickness of Silver-Teflon thermal coating is 51μm. The exposed side is coated by Teflon and the backside is Silver that is attached CFRP via Silicon adhesive. The Teflon surface is not subject to conductive coating. Patches of Silver-Teflon are separated from one another in 2mm spacing. The Silver layer is not grounded to the paddle substrate. The bypath diode board has 6 diodes on glass-epoxy substrate. Below each diode there is a pattern of heat sink. The heat sink is not grounded to the satellite body. Silicon white paint covers the surface of diode board. Each diode has legs made of copper that are bent and exposed to space to absorb stress due to thermal cycles. Electrical wires, Raychem Spec55® AWG24, run all over the paddle back surface. The wires are attached to CFRP via Silicon adhesive through holes in Silver-Teflon.

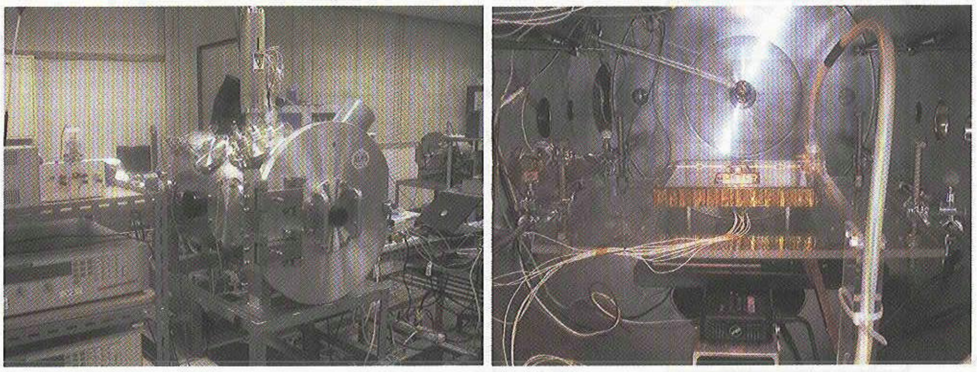


Figure 4. Photograph of vacuum chamber and a coupon panel inside the chamber.

The results of numerical simulation indicate that the paddle back surface suffers severe negative charging while the satellite body is kept to the ionospheric plasma potential. The insulator such as Silver-Teflon patch and diode board paint has a high negative potential with respect to conductor such as CFRP and bypath diodes. This situation corresponds to normal potential gradient where insulator is more negative than adjacent conductors. Once the potential difference exceeds a certain value, arcs may occur. The purpose of the laboratory experiment is to investigate the following points:

- Threshold of arc inception voltage.
- Possibility of sustained arc within the diode board
- Surge current and voltage caused by each arc to the solar array circuit.

Figure 4 shows a picture of vacuum chamber used in the experiment. The chamber is equipped with an electron gun that can generate an electron beam with energy as high as 30keV. The electron gun is equipped with a shutter system. The chamber has a turbo molecular pump and a rotary pump. Typical chamber pressure during experiment is from $2x10^{-4}$Pa ~ $2x10^{-3}$Pa. After a coupon is exposed to atmosphere, it is baked at 70 °C for two hours before experiment. Experiments are carried out at room temperature, 20°C, approximately. Inside the chamber, there is a Trek surface probe mounted on a PC-controlled x-y stage that can scan the area of 90mmx70mm at every 10mm interval in one minute.

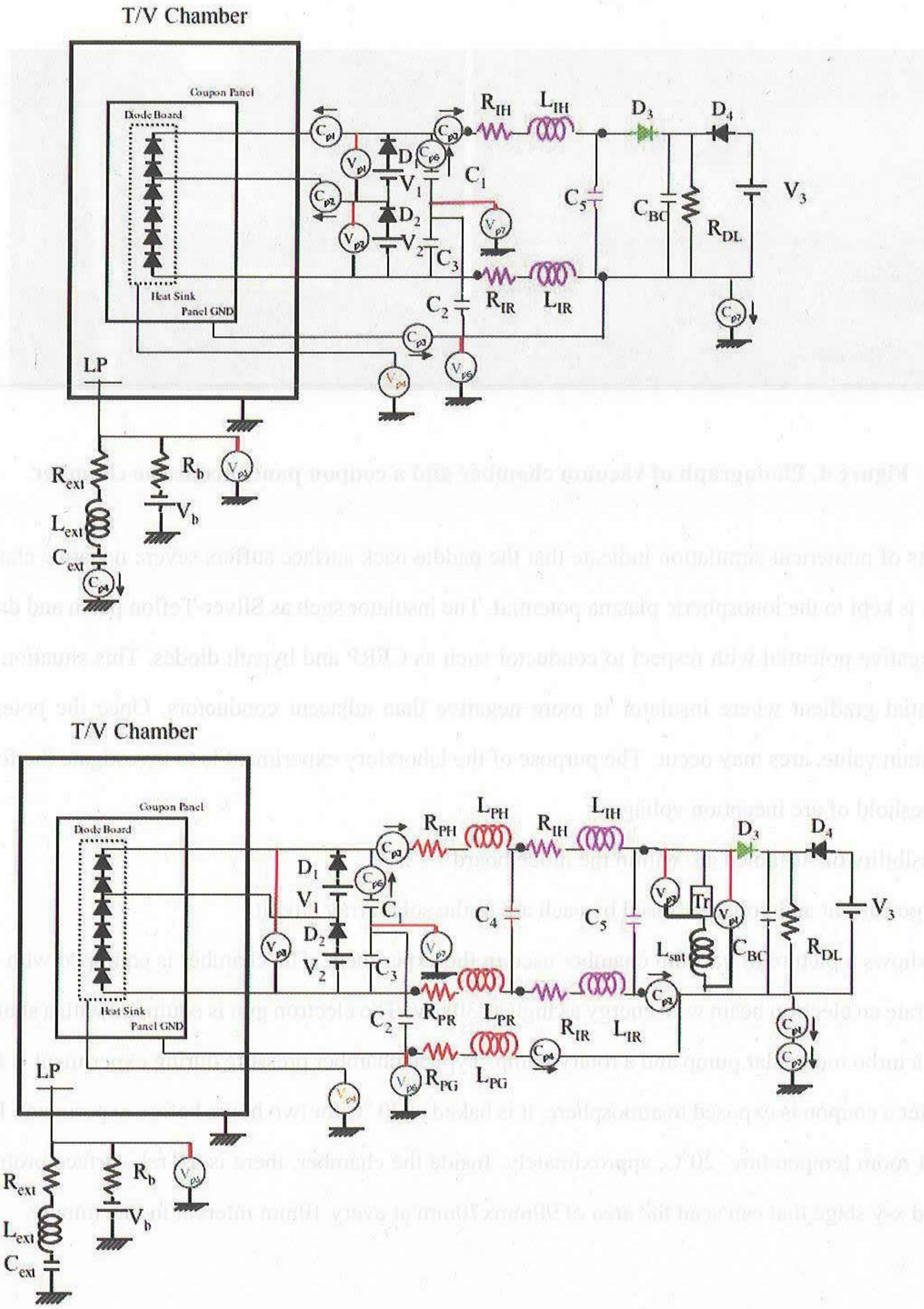


Figure 5. External circuit set-ups for shunt-off configuration (top) and shunt-on configuration (bottom).

We have tested two types of external circuit configuration that are shown in Fig.5. The Shunt-OFF circuit corresponds to solar array circuit that is closest to the satellite body. The purpose of shunt-off configuration is to test sustained arc and surge current. The circuit simulates the innermost solar array circuit that is closest to the satellite body. Therefore, inductance, resistance and capacitance associated with power line of solar array are smallest. The Shunt-ON circuit corresponds to solar array circuit at the far end of the solar paddle. The purpose is to test surge voltage between hot and return lines of the array circuit and power electronics devices such as a shunt-on transistor. The circuit simulates the outermost solar array circuit that is the most distant from the satellite body. The inductance, resistance and capacitance associated with power and ground lines are largest. The additional inductance, resistance and capacitance corresponds to 22m parallel lines. Because there are two pairs of hot and return lines, we used a parallel set of hot and return lines of 11m length made of AWG 22 wire. Threshold measurement is carried out by switching off all the power supplies connected to the external circuit to avoid the risk of discharge between the Trek probe head and one of the diodes.

The power supply V_1 and V_2 are E4351B solar array simulators that simulate the solar cells connected by the bypath diodes. Strictly speaking, we should connect a solar array simulator to each bypath diode. The main purpose is, however, to investigate the possibility of sustained arc between diodes that has the highest potential difference (40V). Therefore, for simplicity, we used only two solar array simulators. The voltages of power supply V_1 and V_2 are set to 20V and 40V, respectively. The power supply V_3 simulates other solar array circuits. The resistance R_{DL} simulates the satellite load and the capacitance C_{BC}(=18000μF) simulates the bus capacitance. Once secondary arc occurs for significant duration, the voltage between the hot and return lines collapses. Then, the diode D_4 is turned on to keep the voltage across the load resistance constant. On the other hand, the diode D_3 works to prevent the current from the power supply V_1 and V_2 flowing to the load resistance. The diodes D_1 and D_2 are used to protect the power supply. The capacitance C_1, C_2 and C_3 simulate the capacitance between solar cells in one string and capacitance between cells and substrate. The roles of the diodes and the capacitances are discussed in Ref.8.

When an arc occurs, the energy is supplied by electrostatic energy accumulated on insulator surface such as Silver-Teflon or white paint over the diode board. The coupon size is too small to account for all the insulator surface of solar paddle that can contribute to an arc. We put a spherical probe of 30mm diameter as shown in Fig.4. The direct distance to the coupon surface from the probe is 120mm. The probe is connected to a high voltage power supply and a capacitance. Once an arc occurs and develops as surface flashover, the arc plasma reaches the probe producing conductive path between the coupon surface and the probe. Then, the energy stored in the external circuit, Cext, is discharged to the arc plasma. The inductance and resistance connected to the capacitance is to limit and slow down the current from the probe by considering the fact that the energy is released by surface flashover that propagates with a finite velocity. We use R=4W and L=270μH based on previous works[9].

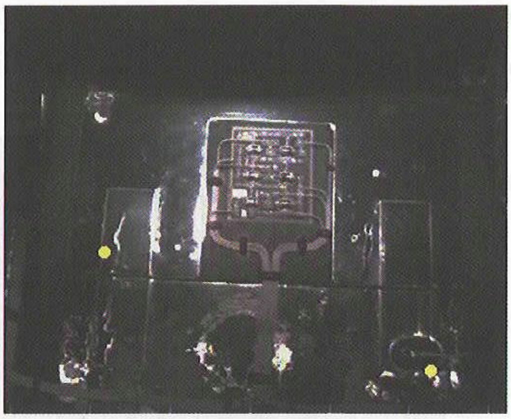


Figure 6. Positions of arcs observed at 3keV electron beam energy.

In the experiment, the current measured at Cp7, which is the total current inside the external circuit, triggers oscilloscopes. The current probes, Cp_1,Cp_2,Cp_3 and Cp_4 can measure current from DC to 10MHz. The current probes, Cp_5,

Cp_6 and Cp_7 can measure between 1kHz and 120MHz. The voltage probes, Vp_1, Vp_2 and Vp_3 are 50x differential probes. The voltage probes, Vp_4, is a Trek probe that monitors the floating heat sink potential. A cable connected to the heat sink is extracted outside the vacuum chamber through a high voltage feed-through and connected to a copper plate. The Trek probe measures the potential of the copper plate outside the vacuum chamber. The voltage probes, Vp_5, is a 2000x high voltage probe. The voltage probes, Vp_6 and Vp_7, are 1000x and 100x high voltage probes. During experiment, we take video of the coupon surface. After each experiment, the video image is analyzed via a computer to extract arc positions by detecting optical flash associated with each arc. Because both the oscilloscopes and the video image keep time record, we can match position of each arc and its waveform. Before and after each experiment, we scan the entire coupon surface by an optical microscope with 60x magnification.

3.2. Experimental Results

Figure 6 shows position of arc that occurred during threshold measurement. In this case, the electron beam energy is 3keV and the insulator surface is charged to as low as –1.5kV. The insulator surface is charged to a negative value of the electron beam energy minus 1.5kV. When the beam energy is low, arcs appear as single flashes originated from individual points. Arcs occur mostly at the edge of Silver-Teflon insulator. As the beam energy is increased to 8keV, we observe surface flashover that covers entire coupon surface. The surface

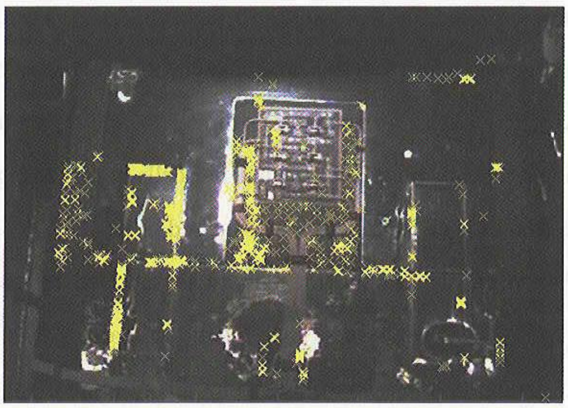


Figure 7. Arc positions observed for electron

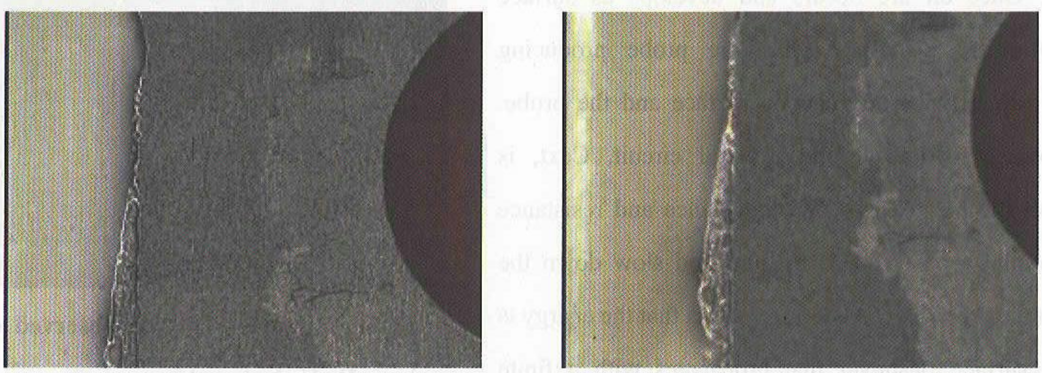
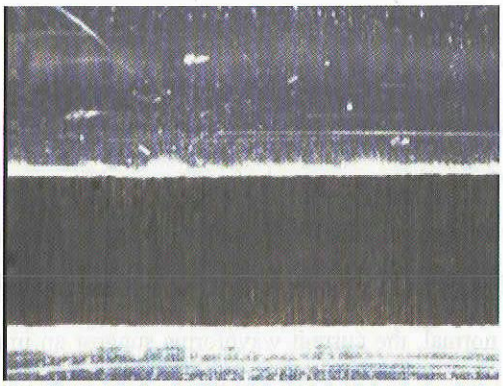
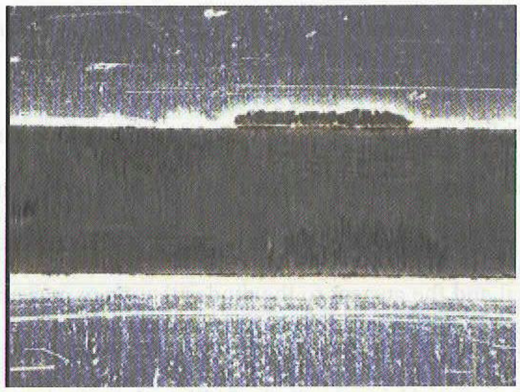


Figure 9. Photographs of diode board edge before experiment (left) and after experiment (right)





flashover accompanies much brighter flashes than those arcs at low electron beam energy of 3keV and often ends at the edge of Silver-Teflon or electrical wires on the surface. From these measurements, we have concluded that arc threshold is –1.5kV for a small arc and –7kV for surface flashover.

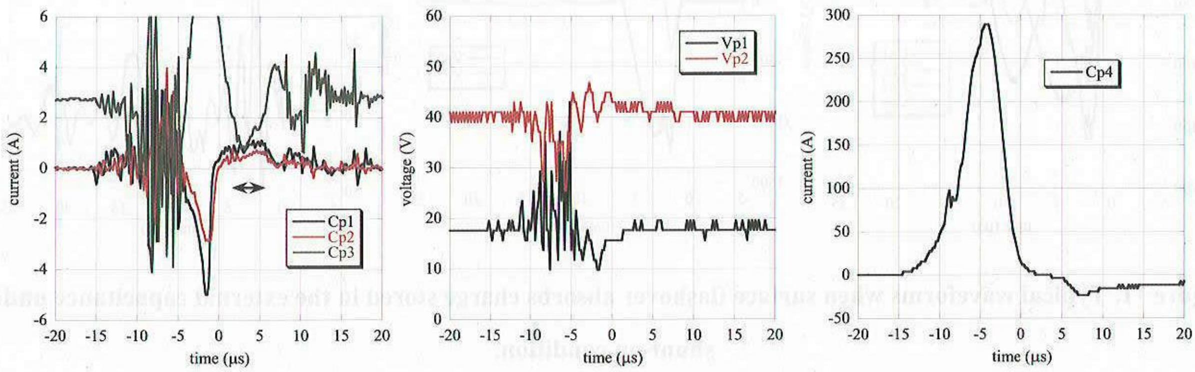


Figure 10. Typical waveforms when surface flashover absorbs charge stored in the external capacitance under the shunt-off condition. The arrow in the left figure indicates an imperfect secondary arc.

Figure 7 shows arc positions observed for one coupon. More than 2000 arcs were recorded for this coupon with the beam energy of 8keV. The most negative insulator surface potential is approximately –7kV. Arcs occurred at the edge of Silver-Teflon insulator, diode board and electrical wire, where insulator forms triple junction with nearby conductor. In Figs.8 and 9, we show arc spots observed at edge of Silver-Teflon and the diode board. Because silver layer of Silver-Teflon is not grounded, once Teflon surface is charged to a negative value, the silver layer also has a negative value almost half the potential of Teflon surface. The side edge of Silver-Teflon is occasionally shielded by RTV adhesive that displace from the bottom of Silver-Teflon. But, unless we intentionally shield the side by RTV adhesive, that is the case for the experimental coupon, the side edge has exposed silver layer. The silver layer is adjacent to CFRP that is grounded and distance is only 100μm or so. Therefore, once Silver layer acquires a negative potential close to

−1kV, a small arc occurs between the silver layer and CFRP. If the charging potential is large, the small arc may evolve to surface flashover that absorbs charge of one or more patches of Silver-Teflon.

Figure 10 shows waveform observed when the surface flashover absorbed charge stored in the external circuit. The external capacitance provided current as much as 300A into the solar array circuit for 15μsec. The arc plasma momentarily short-circuited the power supply V_2. The current from the power supplies V_1 and V_2, that was measured by Cp_3, decreased and the current to the diodes that were measured by Cp_2 and Cp_3 increased. Although the voltage of the solar array simulators measured by Vp_1 and Vp_2 were relatively normal, the current waveforms suggest an imperfect secondary arc occurred between diodes. Although we had nearly 1000 arcs with the Shunt-OFF configuration, we had no sustained arc. Only imperfect (less than 10μs) secondary arcs similar to the ones shown here were observed.

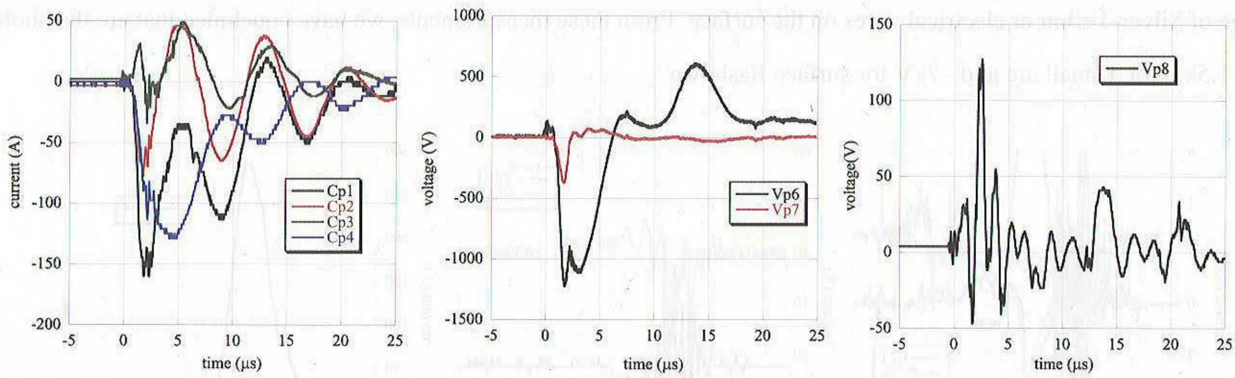


Figure 11. Typical waveforms when surface flashover absorbs charge stored in the external capacitance under shunt-on condition.

When a large arc that absorbs charge stored in the external circuit occurs near CFRP substrate under the shunt-on condition, the voltage drop across the ground resistance produces substantial surge voltage inside the array string circuit. The array string circuit and the paddle ground are coupled through capacitance of adhesive and polyimide sheet below solar cells. Nine solar panels of ALOS are grounded to the satellite body via ground wires. The equivalent resistance and inductance of the ground wire between the outermost panel and the satellite body are 0.8W and 11μH, respectively. In the ground experiment, we have simulated the resistance and inductance by inserting AWG22 wire of 11m in the external circuit. Figure 11 shows the waveforms measured in various points in the circuit. The charge stored in the external capacitance, C_{ext}(=160nF), is discharged in less than 10μs. A part of the charge is discharged directly to the chamber wall and the rest is discharged through the power circuit to the ground. The current measured at the common ground, Cp_1, has a peak value of 150A, of which 120A flows the ground wire, Cp_4. The current flowing the ground wire produces a significant voltage drop across the impedance, Vp_6. Then, a voltage as large as 1000V appears as Vp_6-Vp_7 across the capacitance that produces surge voltages in the power circuit. Between the hot and return ends of the bypath diodes, the surge voltage, Vp_8, is between +120V and –40V and oscillates with a few MHz. Among more than 100 measured waveforms, the maximum value of the surge voltage was +180V/-140V. Because voltage between the hot and return ends is divided by the six diodes connected in series, each diode can withstand the surge voltage. We need to study, however, influence of the surge voltage on other power devices such as shunt transistors.

Summary

As charging hazard on the solar paddle carried by ALOS is pointed out, laboratory experiments have been carried out to investigate charging and arcing phenomena on back surface of the solar paddle. As ALOS passes the aurora zone near the North Pole, insulator at the backside of the solar paddle can be charged to a highly negative potential because ionospheric ions cannot neutralize negative charge accumulated by aurora electrons because of plasma wake developed behind the solar paddle. ALOS stay as long as 1200s inside the aurora zone. Because the satellite body is kept to plasma potential, so-called normal potential gradient occurs on the back surface, where insulator surface is more negative than nearby conductor.

We have tested three coupon panels that represent design of back surface of solar paddle in a vacuum chamber and irradiated the coupons by an electron beam. At the backside of the solar paddle, there are bypath diode boards that have exposed conductor connected to the solar array string circuit. A small arc is observed once the insulator surface potential becomes –1500V, though its current is too small to cause any effect on the power circuit except minor electromagnetic interference. As the surface potential becomes –7000V, we have observed extensive surface flashover whose optical flash covers entire coupon panel.

When the surface flashover occurs the voltage across the diodes fluctuates indicating inception of imperfect secondary arc that momentarily short-circuit the hot and return ends of the power circuit. So far, we have tested three coupon panels and the total number of surface flashover arcs accumulated for the three coupons exceeds 3700, though this number includes both shunt-on and off cases. We have observed no sustained arc so far. Therefore, the diode board has the minimum insulation strength against sustained arc. This conclusion should be verified by more tests that expose the diode boards to the surface flashover.

When the surface flashover occurs toward the CFRP surface, that is the panel ground, surge voltage of more than ±100V has been observed between the hot and return ends. The surge voltage is developed by capacitance coupling between the ground wire line and solar array string circuit. As a large current flows the ground wire, the voltage drop across the wire impedance, especially inductance, produces a large voltage across capacitance made of polyimide insulator and adhesive between the solar paddle ground and solar cells. Because the surge voltage is divided by six diodes, probably it may not pose any threat to the diode board. Influences on other parts in the power circuit, such as a shunt transistor, should be considered carefully.

In the present paper, we have focused on charging and arcing on the backside of solar paddle in the aurora zone near the North Pole. Near the South Pole, the solar paddle front surface, where solar cells are attached, faces the wake direction. Therefore, we should also consider charging and arcing on the solar paddle front surface under the normal potential gradient.

Not only the wake side, but also the ram side can have arcs once the aurora electron flux increases extremely high and the plasma density is very low so that the satellite body potential drops to a negative value. The body potential does not have to drop to a kV level to have arcs on the ram side. On the ram side, the insulator is charged by ionospheric ions. This is the inverted potential gradient case under LEO plasma environment and threshold voltage for arc inception is only one or two hundred volts. Therefore, once the satellite body potential drops by 40V from the nominal value, -60V, arcs may occur on the ram side. Near the North Pole, the ram side is front surface and arcs occur around solar cells. Near the South Pole, the ram side is the back surface and arcs occur on diode boards and CFRP surface. Possibility of sustained arc should be investigated to prepare for such situation. Laboratory test results for the cases of front surface in the North- and South-poles and back surface near the South Pole will be presented in near future.

Although the laboratory tests carried out so far have shown the paddle's immunity against sustained arc and endurance against accumulated trigger arcs, they have suggested that the arcing of the paddle back surface might induce surge voltage on other power devices and the satellite ground. Therefore, we have decided to test several design changes to the solar paddle to improve robustness of the paddle and the power systems against the surface flashover on the back surface. Effectiveness of each mitigation method is being tested in laboratory experiment. The result and final design of ALOS solar paddle will be presented in near future.

Acknowledgments

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