DEVELOPMENT OF SOLAR ARRAY FOR A WIDEBAND INTERNETWORKING ENGINEERING TEST AND DEMONSTRATION SATELLITE: SYSTEM DESIGN

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Abstract

JAXA(Japan Aerospace Exploration Agency) is conducting the development of Wideband InterNetworking engineering test and Demonstration Satellite(WINDS), which aims at developing and verifying the main technologies for future ultra high speed satellite communications. WINDS has two solar array paddles laid down approximately 8,500 triple junction solar cells. From the point of view of certain and reliable development, ground based ESD test was carried out on 3 solar array coupons for WINDS. Although the power degradation caused by trigger arc was observed in all coupons, there was no sustained arc in any coupon. According to the test result, the power degradation by trigger arcs is estimated 1.4% for lifespan of 5 years

Outline

Table 1 and Figure 1 show major characteristics and overviews of WINDS respectively.

Table 1. WINDS Major Characteristics

Item	Characteristics
Orbit	Geostationary Earth Orbit(GEO)
Mass	2,700kg at the beginning of mission life
Size	2m×3m×8m (tip to tip 21.5m including Solar Array Paddle), refer to Figure 1
Designated Lifespan	5 years (targeted life)
Attitude Control	3-axis-stabillized (zero-momentum)
Electricity	More than 5,200W
Launch	2005 fiscal year by H-IIA Launch Vehicle at Tanegashima Space Center)

Objectives of WINDS

WINDS has the following development objectives:

(1) Ultra fast communications
WINDS satellite communication system aims for a maximum speed of 155Mbps(receiving) / 6Mbps (transmitting) for home using 45-centimeter aperture antennas, which are as small as existing Communications Satellite antennas, and an ultra fast 1.2Gbps for office use.

(2) Broader communication area coverage
The technology for the Ka-band multi-beam antenna with a high-powered multi-port amplifier can achieve fixed ultra fast communications all over Japan and in major Asian cities, such as Seoul, Beijing, and Singapore. At the same time, flexible power distribution to each communication area can cope with the regional communication demand and the rain attenuation.

In addition, the Ka-band active phased array antenna technology makes it possible to control the antennas communications direction rapidly and electronically, thus communication can be carried out quickly to specific area with demand.

WINDS Solar Array Design

WINDS solar arrays, which adapt to DET (Direct Energy Transfer)/Shunt with 50V regulated Bus voltage, employ the following cell and cover glass:

- 3J GaAs/Ge solar cell(NASDA-QTS-2130/501)
  Thickness: 0.15mm / Size: 37mm X 76mm
- CMG-100-AR without conducting coating
  Thickness: 0.1mm

WINDS has two solar array paddles where 292 parallel strings of solar cells are mounted. Each string is made by the series connection of 30 triple-junction cells. Those parallel strings are divided into 2 charge-arrays for battery charging, and 6 main-arrays and 2 half-arrays for main power generation. The grouping of the solar array strings is the following;

- 20 strings for each charge-array, 1 charge array on each paddle.
- 36 strings for each main-array, 3 main-arrays on each paddle
- 18 strings for each half-array, 1 half-array on each paddle

Figure 2 shows the basic layout of the solar array strings. Although each string produces approximately 80V for open circuit, the spacecraft shunt regulator limits the string voltage to approximately 55V for non-shunted string and 0V for shunted string. The negative terminal of each string is arranged at center on the solar panel, while the positive one is arranged at the edge side.

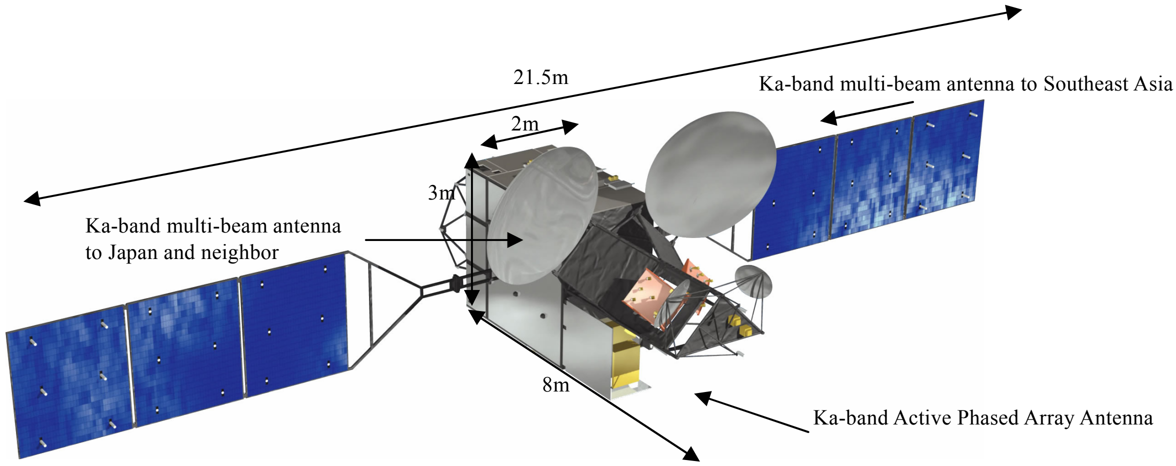


Figure 1. Overviews of WINDS on Orbit

Therefore a potential difference between adjacent strings is 0V, except 55V between the shunted string and non-shunted string. The gap between adjacent cells is potted with nonconductive adhesive, RTV, as same as previous JAXA's solar array design [1]. Also, because WINDS dose not carry ion thruster, there is no need to coat the bus bar with RTV to avoid the current leakage to the high density plasma generated by the backflow from the ion thruster plume [2].

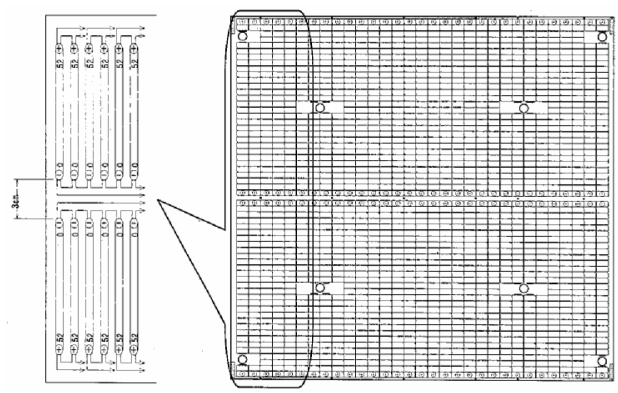


Figure 2. WINDS String Layout

ESD Test

The ground ESD test was performed by Kyushu Institute of Technology. The purposes of the test are the following.

- Confirm that the solar array suffers no sustained arc
- Study how the amount of RTV coating applied to the cell edge affects the power degradation due to trigger arcs
- Determine the flight design of solar array

The Outline of the test condition and result are described in this section. The detail explanation is presented in Ref. [3].

Test Condition and Test Configuration

Three test coupons were used for the ground ESD test. Photograph of a coupon is shown in Figure 3. The cross-sectional view of solar array coupon is shown in Figure 4 and 5. The summary of difference among the coupons are listed in Table 2. A coupon consists of 15 cells. Five cells are connected in series making three parallel strings. Each string was named as R, B and G string. All the three coupons has the same thickness of RTV layer between cells and Kapton sheet, approximately 100 μ m. The gap between strings are grouted by RTV. The coating of RTV at the cell edges of the coupon 1 is much thicker than the coupon 2 and 3. The bus bars of the coupon 3 is not coated with RTV to confirm whether the bus bars act as lighting rods where a trigger arc occurs before it occurs at more dangerous points such as the string-gaps or the cell edges.

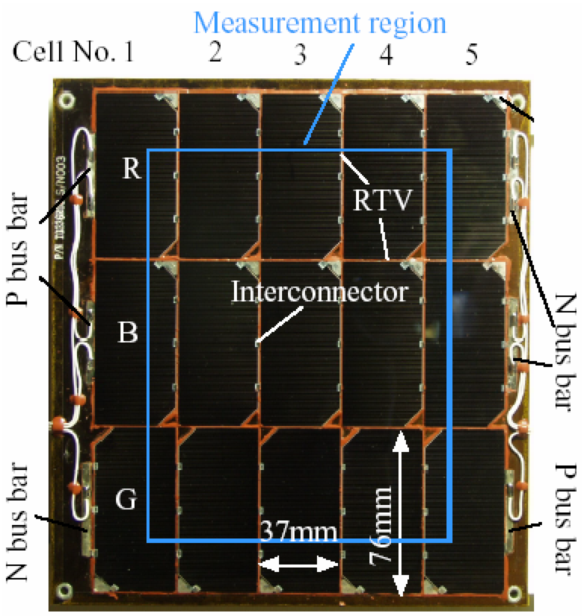


Figure 3. Photograph of a test coupon

Table 2. Difference of test coupons

Coupon No.	Amount of RTV	Bass bar coating
1	Large	Yes
2	Normal	Yes
3	Normal	No

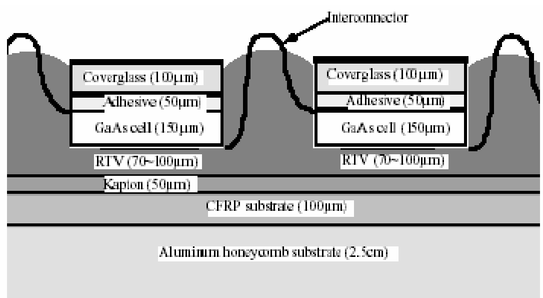


Figure 4. Cross-Sectional view of coupon 1

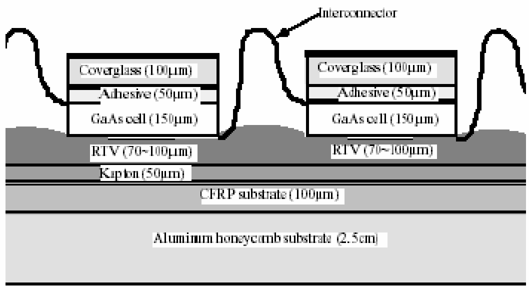


Figure 5. Cross-sectional view of coupons 2 and 3

Figure 6 shows the set-up configuration of ESD test. A coupon panel was placed in a vacuum chamber. In the ESD test, the coupon panel was charged by the electron beam gun.

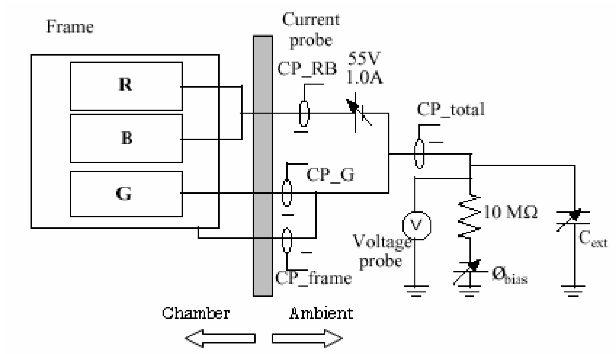


Figure 6. ESD test circuit

WINDS test condition is defined as shown in Table 3. The bias voltage (ϕ_{bias}) and the emitted time (t_{exp}) were decided on NASCAP worst case analysis in next section. The coupons 1 and 2 were tested for 20 hours and the coupon 3 for 65 hours. From the case 1 to case 3, the beam center was aligned to the center of the coupons. For the cases 10 and 11, the beam center was set to the No.1 cell of the B string, because the test purpose was to see the trigger arcs at the bus bars.

At every 10 hours, the coupons were removed from the chamber. After the photographs of the cell edges were taken by the 60× optical microscope, they were measured the output power. Each coupon was taken out form the vacuum chamber after the case 2, 3, 5, 6, 8, 9 and 11, it means every 10 hours emission. Once a coupon was put in the chamber, it was kept in vacuum for approximately three days. Every time the coupons were exposed to atmosphere, they were baked for 2 hours at 70℃ before the ESD test.

Table 3. WINDS test conditions

Case	Coupon	ϕ_{bias} -kV	C_{ext} nF	V_e kV	t_{exp} hour
1	1	3	400	2.8～4.0	6
2	1	4	200	3.0～4.0	4
3	1	6	100	3.0～6.0	10
4	2	3	400	2.8～4.0	6
5	2	4	200	3.0～4.0	4
6	2	6	100	3.0～6.0	10
7	3	3	400	2.8～4.0	6
8	3	4	400	3.0～4.0	4
9	3	6	100	3.0～6.0	10
10	3	3	400	2.8～4.0	6
11	3	4	200	3.0～4.0	4
12	3	3	400	3.0-4.0	35

Test Results

The number of arcs observed is listed in table 4. During the tests of 20 hours, the number of arcs is 288, 392 and 266, respectively for the coupons 1, 2 and 3. The coupon 2 had arcs more than the other two coupons. The cases 10 and 11 had 260 arcs in 10 hours. The cases with higher arc rates had higher chamber pressures. There is no significant difference for number of arcs depending on each coupon, according to this point. There was no sustained arc with so many trigger arcs, whether bass bar was coated or not. It was confirmed that the solar array design is very effective at suppressing the sustained arc occurrence.

Table 4.　Number of arcs

Coupon	Difference of Coupon		N_{arc}	T_{exp}, h	Power Degradation	Failure Cell
	RTV	Bas bar				
1	Large	Coating	288	20	18%	2～3
2	Normal	Coating	392	20	32%	3
3	Normal	Non-Coating	266+260+84	20+10+35	36%	3～4*

*: T_{exp} =30h

The output power of each coupon was measured after the test. The ratio of degraded power to the initial power is plotted in figure 7. The horizontal axis denotes the test time. The R and B strings were connected in parallel at the back side of the coupon, and were not separated as the output power was measured.

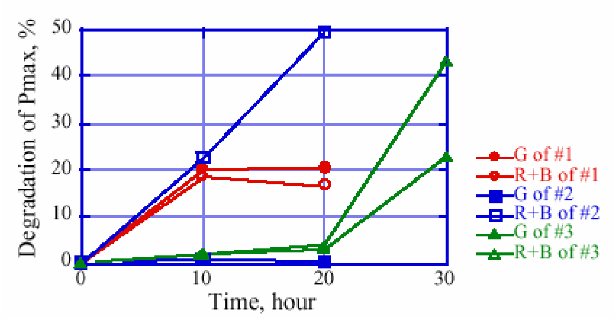


Figure 7. Degradation of solar array output power

NASCAP Analysis

NASCAP Model

The WINDS NASCAP model is shown in Figure 8. The major features are the following material.

- Body: mostly covered with conducting thermal blankets and Optical Solar Reflector (OSR) with ITO (Indium-Tin- Oxide).
- Solar Array: surface cover glass and backs of which are covered with a black conducting polymer.

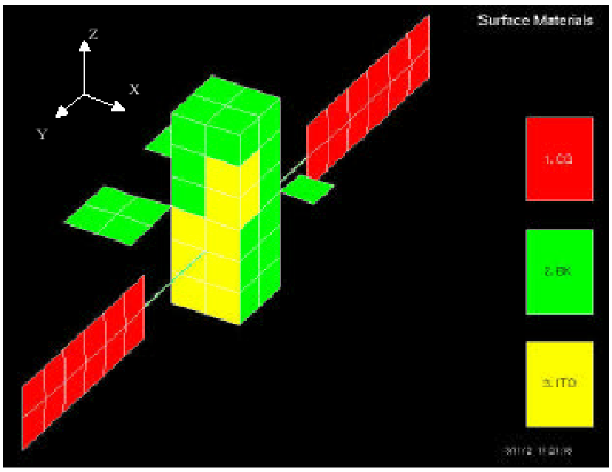


Figure 8. NASCAP model of the WINDS

Worst Case Analysis

Spacecraft charging analysis was carried out in order to clarify the spacecraft charging expected on the WINDS solar panel. The analysis defines bias voltage which simulated a relative voltage between cover glass and spacecraft ground for measurement of the threshold voltage for the trigger arc inception [4].

The calculation was performed under the condition of the charging environment as shown in Table 5 [5][6].

Table 5. Charging Environment

	Electrons Density	Electrons Temp.	Ions Density	Ions Temp.
Population 1	1.2 (/cm^3)	27.5 (keV)	1.3 (/cm^3)	28.0 (keV)
Population 2	0.2 (/cm^3)	0.4 (keV)	0.6 (/cm^3)	0.2 (keV)

It was already known that the SEE (Second Electron Emission) coefficient of CMG-100-AR coated MgF2 is as Figure 9 [7][8].

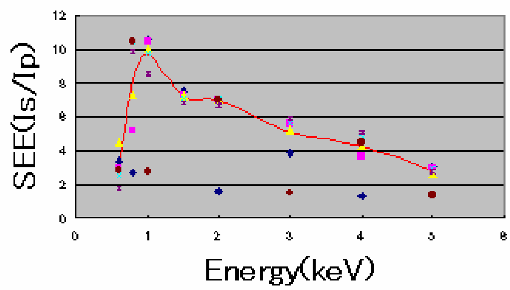


Figure 9. SEE coefficient of CMG-100AR

The analytical result that was reflected the above -mentioned SEE coefficient is shown in Table 6, Figure 10 and Figure 11. The NASCAP calculation shows that maximum differential voltage observed at exit of eclipse, which reaches approximately 5.2kV.

Table 6. Charging Analytical Result Summary

Case	Ground (V)	CG1 (V)	CG3 (V)	MaxDiff. (V)
Sun; +X	-1310	-893	-703	604
Sun; -Z	-1450	-1080	-798	652
Eclipse	-11300	-7810	-6110	5190

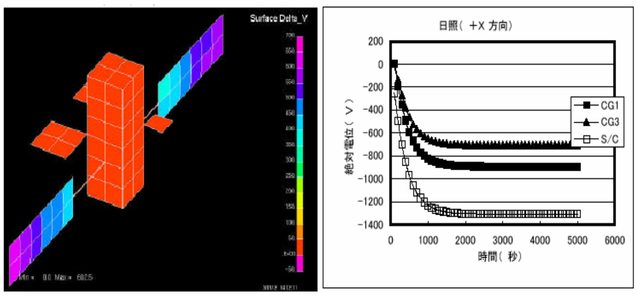


Figure 10. Sun direction +X case

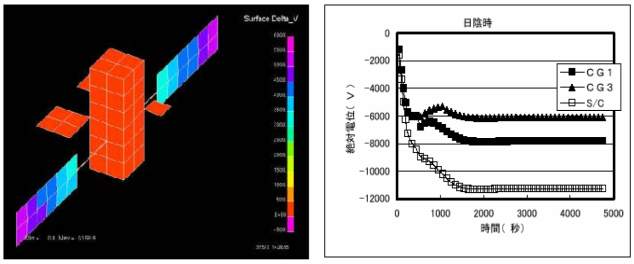


Figure 11. Eclipse case

Static Analysis

Here, it should be considered that what is necessary to evaluate the result of ground ESD test. Namely the problems are following points.

(1) How many duration the satellite has critical charging in the orbit (exceeding 400V inverted potential gradient)?
(2) How many times the satellite has trigger arcs?

Therefore, the charging analysis was carried out based on statistics data.

Procedure:

(1) The $7.5*10^6$ GEO plasma environment data (equivalent to 21 years 5 month; 1993/03/15 ~ 2003/09/24) of LANL (Los Alamos National Laboratory) satellite were collected.

(2) The combination of parameters (Ne, Ni, Te, Ti) were divided to 556 cases and calculate the probability of each case at every 3 hours of local satellite time (LST) that the data point falls in a given box of parameters as shown Figure 12. Figure 13 shows accumulated probabilities of electron temperature distribution and ion temperature distribution.

(3) NASCAP/GEO simulation was carried out based on the Spacecraft Charging Analysis (mentioned-above 5.1) for all the combinations of plasma parameters and local time, and calculated the total duration when the differential charging between cover-glass and the satellite ground exceeds 400V. Total simulation cases are 5004 (=(eclipse 8LST zone)556 plasma parameters cases), but NASCAP/GEO cannot model the oblique solar incidence (e.g. LST=3, 9, 15, 21). Therefore NASCAP/GEO simulation was run for the 2780 cases identified.

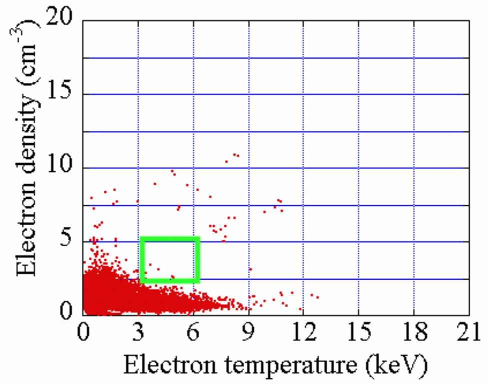


Figure 12. Sample of parameters matrix box

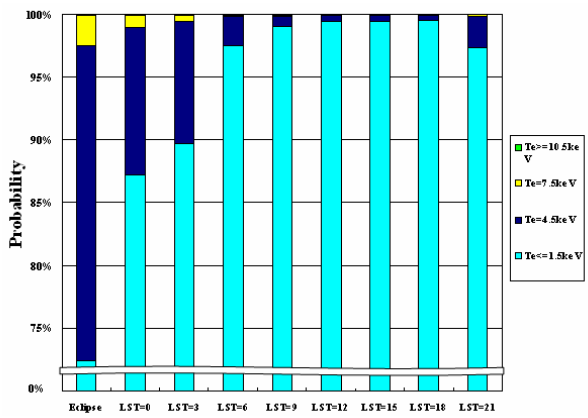


Figure 13. Accumulated Probabilities (Electron temperature distribution)

Total Duration of Critical Charging:

The cases of exceeding 400V inverted potential gradient[8] was identified and the total critical charging duration was calculated. Table 7 shows sample of Maximum differential voltage (ΔV). Table 8 shows summary of critical charging duration in 1 year. The critical charging duration was estimated through multiplying by each combination of the parameters and each LST zone total hours or total eclipse hours a year. (e.g. one LST zone hours are 1095 hours a year.).

Table 7. Sample of Maximum ΔV

Te (keV)	Ne (cm-3)	Ti (keV)	Ni (cm-3)	LST=0 eclipse	LST=0 sunlit	LST=6	LST=12	LST=18
4.5	10	5	0.25	6418	931	871	917	934
4.5	10	5	1	4324	883	827.8	870	888
4.5	10	10	0.25	6501	925	864	907	928
4.5	10	10	1	4270	856	800.2	844.9	860
4.5	15	5	0.25	7069	1290	1232	1275	1294
4.5	15	5	1	4927	1243	1188	1225	1246
4.5	15	10	0.25	7189	1286	1226	1265	1288
4.5	25	5	0.25	7901	1802	1752	1787	1810
4.5	25	10	0.25	8051	1802	1749	1787	1806
7.5	5	5	0.25	9480	1141	1064	1117	1145
7.5	5	5	1	6217	1084	1010	1059	1087
7.5	5	10	0.25	9760	1133	1056	1109	1136
7.5	5	10	1	6321	1054	980	1030	1057
7.5	10	5	0.25	11240	2015	1942	1987	2022
7.5	10	5	1	7831	1951	1882	1924	1957
7.5	10	10	0.25	11630	2012	1935	1976	2017
7.5	10	10	1	8070	1931	1857	1898	1937
7.5	15	10	1	9080	2549	2480	2521	2556
7.5	25	5	0.25	13660	3515	3450	3488	3524
10.5	5	0.2	0.25	8900	1712	1624	1677	1717
10.5	5	0.2	1	5367	1606	1535	1583	1616
10.5	5	5	0.25	13280	1723	1636	1685	1731

Table 8. Total duration of ΔV >400V in a year

	LST=0 eclipse	LST=0 sunlit	LST=6	LST=12	LST=18
Total duration in 1 year(hour)	22.3	0.8	1.7	2.7	0.7

NASCAP/GEO cannot model the oblique solar- incidence, therefore it was estimated that total critical charging duration in sunlit as follow.

(0.8+1.7+2.7+0.7) * 2 = 11.8 hours/year

A possibility that sustained arc will occur is among sunlit. As a result, about 60 hours in mission life, the WINDS solar array generates the power under the inverted potential gradient. Figure 14 shows Te dependency of charging duration of each LST.

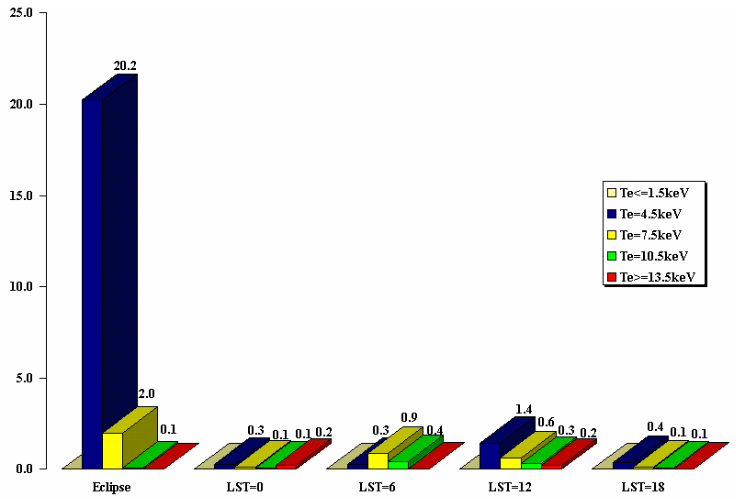


Figure 14. Te dependency of Charging duration

Total Number of Trigger Arcs:

The time (Tesd) to reach 400V differential voltage by NASCAP/GEO for the 2780 cases identified were calculated to estimate the total number of trigger arcs based on the charging duration result. Figure 15 shows calculation concept.

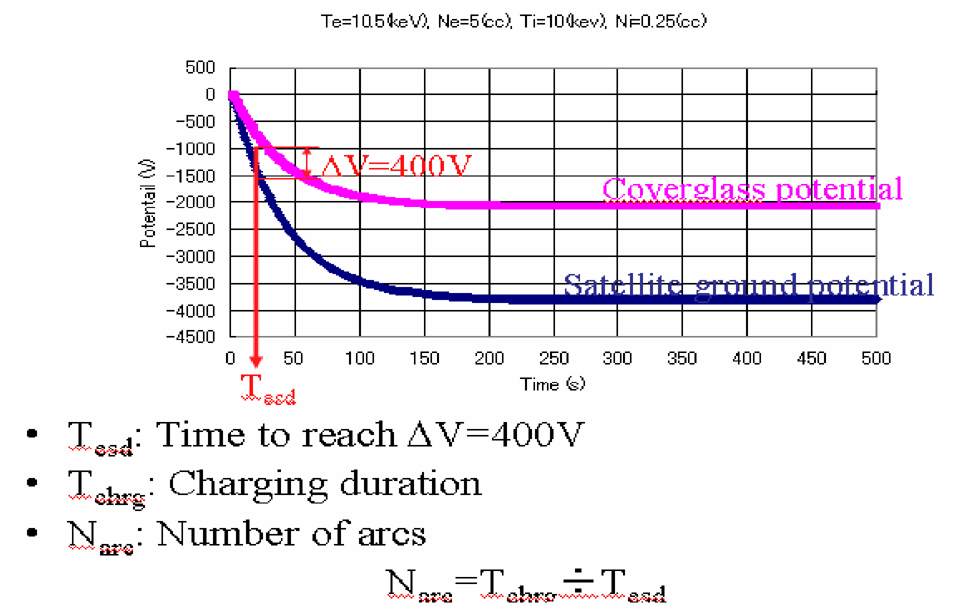


Figure 15. Trigger arc frequency analysis concept

Table 9 shows total number of trigger arcs in 1 year.

Table 9. Total number of trigger arcs in a year

	LST=0	LST=0	LST=6	LST=12	LST=18
	eclipse	sunlit			
Total numbur of trigger arcs in 1 year	**556**	**151**	**478**	**487**	**95**

As a result, WINDS solar array has about 12170 trigger arcs in sunlit of mission life, and it has about 14950 trigger arcs in total 5 years of lifespan. Figure 16shows Te dependency of charging duration of each LST.

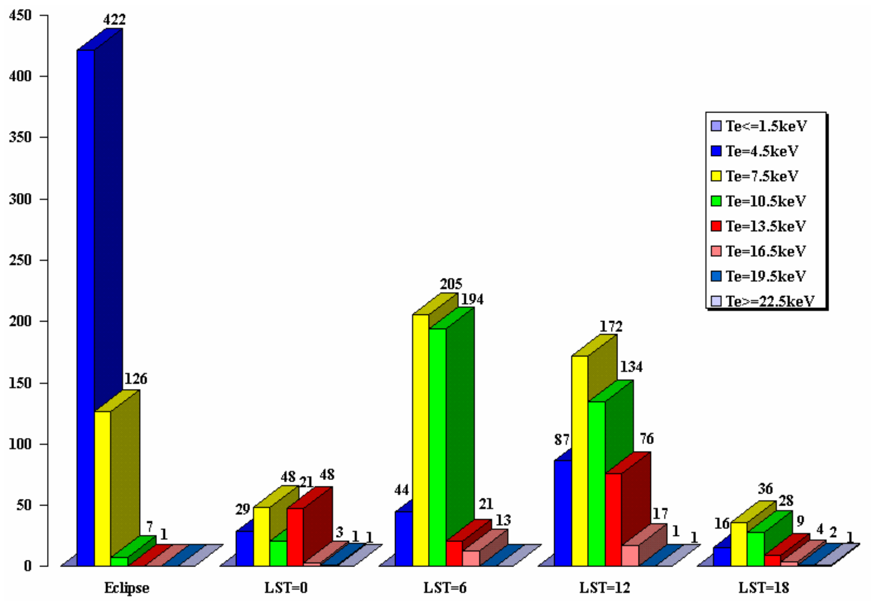
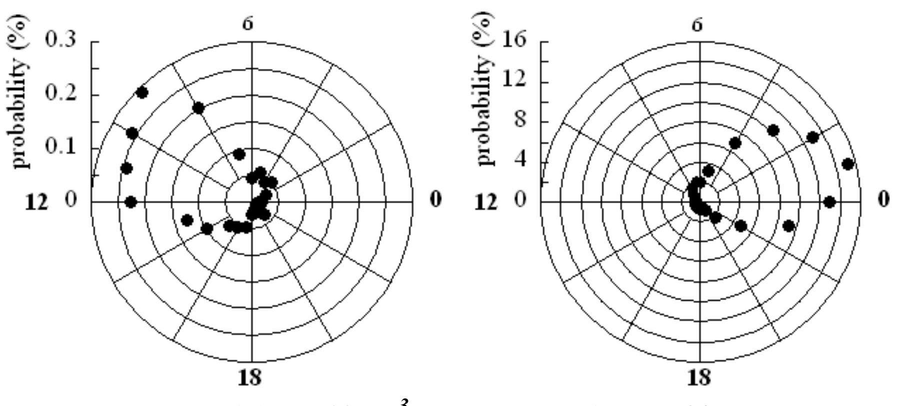


Figure 16.　Te dependency of trigger arcs

It had been comprehended that a critical time zone on the spacecraft charging is from end of eclipse to LST=12. According to the static analysis, however, it is shown that also LST=12 should been considered as a part of critical time zone for the spacecraft charging. This interpretation is supported by Figure 17. This figure shows that there is higher probability of occurrence for n_e (>10cm^{-3}) around LST=12.



(a) ***n_e>10cm^{-3}***　　**(b)** ***T_e>3keV***

Figure 17.　Probability of occurrence for n_e>10cm^{-3} and T_e>3keV observed on LANL satellite

Conclusions

The ground ESD test and the NASCAP analysis were carried out for WINDS. There was no sustained arc in any coupons during the total 105 hours of the test. The extreme power degradation of 10 solar cells was observed in all the coupons by the total 1206 trigger arcs. It means that coating the cell edge with RTV was not perfect solution for trigger arc. On the other hand, the total number of trigger arcs was 14950 for 5 years, according to NASCAP static analysis. Therefore 124 solar cells were estimated for power degradation with trigger arcs for WINDS lifespan. It is necessary to consider the approximately 100 solar cells additionally for power degradation in WINDS solar array design. Also it was confirmed that exposing the bus bars to space without RTV coating did not show any-side effect. Therefore, to reduce the satellite mass and the risk of arcs at the cell edge, it determined not to coat the bus bars with RTV.

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