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In Orbit Irradiation Effects Evaluation of the Alsat-1 Solar Panels

Mohammed Bekhti*

Centre for Satellites Development, Ibn Rochd, USTO, Oran, Algeria

Abstract

In order that photovoltaic solar cells may be used more effectively to provide electrical power for spacecraft, it is desirable to refine the engineering design of solar cells and power systems, based on a better understanding of the space radiation environment and of radiation damage effects on semiconductor components. The objective of this paper is to provide the reader with some of the useful ideas and test data which can be applied in designing radiation resistant power systems. It is found that the most serious obstacle which prevents accurate prediction of solar cell degradation for earth satellites is our inadequate knowledge of the fluxes and energy spectra of electrons and protons in the magnetosphere. When the space environment can be better defined, it will be possible to predict more accurately the degradation of present day types of silicon and GaAs solar cells, for which the radiation damage characteristics have been quite well determined by laboratory research. As improved types of solar cells and materials become available, it will be necessary to make laboratory measurements of their radiation resistance to protons and electrons in order to predict their performance in space. The advances in technology are nowadays allowing the production of solar cells in different sizes and more importantly with increased efficiencies exceeding 30%. However, these semiconductors can suffer a great deal of degradation in performance when hit by high energy electrons and protons. The paper will attempt to identify areas where an improved understanding of defects behavior is necessary to produce further improvements in performance. From, the results in this paper, all the compiled telemetry data and the predefined assumptions show that Alsat-1 solar panels did not suffer a high level of degradation and that the real degradation never reached those assumptions made during mission analysis and design phases [1][2][3][4][5].

Keywords

Space Degradation, GaAs Solar Cells, Aluminum Honeycomb, Ultrasonic Welding, Insulation Layer, Irradiation Effects, Design Procedures, Electron and Protons

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1. Introduction

Alsat-1 was designed to image the earth with 32 m resolution multi spectral cameras across a 600km swath width. The three spectral bands are equivalent to Landsat-7's bands 2, 3 and 4 covering green red and infra red wavelengths (0.5-0.6µm, 0.6-0.7µm, 0.7-0.8µm). The imaging system, consisting of two cameras per spectral band, will allow a maximum swath width of 600km.

The Algerian satellite is one of SSTL's new generation microsatellites in the sense that it carries a push broom sensor. This type of sensors could previously only be found in larger commercial satellites. Because of the advances in electronics and semiconductor integration on a single chip, nowadays these sensors are being implemented by SSTL on micro satellites.

Alsat-1 used 2*10 000 pixels Kodak sensors digitized to 8 bits radiometric resolution (256 levels). The camera system

* Corresponding author
E-mail address: m_bekhti@yahoo.fr

can gather images continuously along the flight track. This represents a huge quantity of data for the electronics on board (processors, Solid State Data Recorders, fast clocks) to deal with. The images are stored on board the micro satellite in a Solid State Data Recorder (SSDR) comprising 2*512 Mbytes solid state memory for later transmission to the ground via digital packet error controlled links at 8 Mbps in S-band.

Flexibility was included on the satellite by an option to "window" the images. By using this technique, we can take images of 80*80 km^2 and thus extend the track range and target coverage. Table 1 summarizes Alsat-1's orbit data [8][9].

Table 1. Orbit data for the Alsat-1 mission

Inclination	98,3°
Altitude	686 km BOL, 660 km EOL (de orbiting phase)
Orbit period	98 minutes (average)
Eclipse period	< 33 minutes

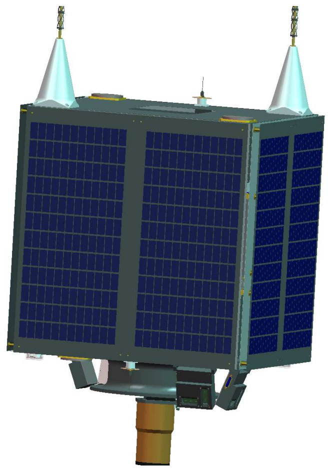

Figure 1. artistic view of Alsat-1.

2. Alsat-1 Solar Panel Design

Alsat-1 satellite was based on SSTL enhanced microsatellites platform. It is a body mounted solar panels satellite and cubical in shape with 600mm*600mm*600mm in dimensions. The solar panels are all identical and the power supplied to the subsystems by each solar panel was 60 watts at AM0 and sun normal to the panel. Fig. 1 represents an artistic view of Alsat-1 [8] [9].

2.1. Design Considerations

The ambient temperature was assumed to be 25°C and Air Mass zero AM0 light intensity. To complete the design of the panels the following loss factors have been assumed [7][9]:

Isc 1.5 % cell mismatch

1.5 % calibration error

9 % radiation degradation

Voc 2 % due to wiring

5 % radiation degradation

2 % to allow for higher temperature

V drop to diodes.

2.2. Solar Panel Substrate

Alsat-1 four solar panels used aluminum honeycomb as substrate with a thickness of 20 mm and 0.5 mm thick aluminum face skins for the front and rear of the panel. An insulating Kapton layer of 75 mm is placed on the front of the panel for an electrical isolation of the solar cells. The rear of the solar panel is left for wiring of the solar cells assemblies (strings) and the mounting of the thermistor for the maximum power point tracking and the temperature sensing of the panel for telemetry measurements, see fig. 2a and 2b. The cells lay down design of the four panels was identical consisting of 6 strings of 48 cells each in series [7][8][9].

Figure 2a. Alsat-1 rear panel.

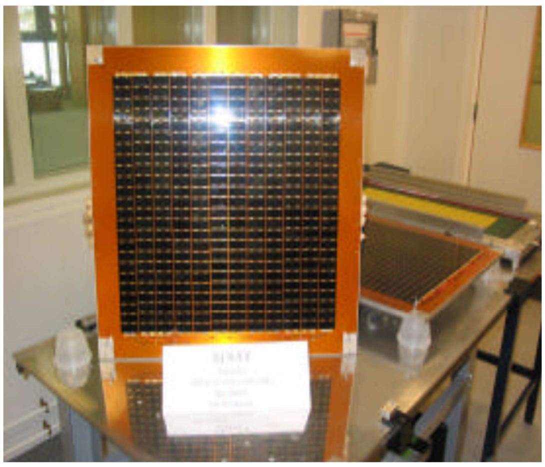

Figure 2b. Alsat-1 front panel.

2.3. Solar Cells

The solar cells selected by SSTL for the Alsat-1 project were the single junction PN Gallium Arsenide (GaAs) cells made by ENE (Belgium) using the MOCVD process. The cells were manufactured on 114.7 mm in diameter wafers. Eight cells 20mm*40mm were diced from each wafer. The cells provided an average conversion efficiency of 19 % at ambient temperature. Fig. 3 shows the wafer size and the cell mask [7][11].

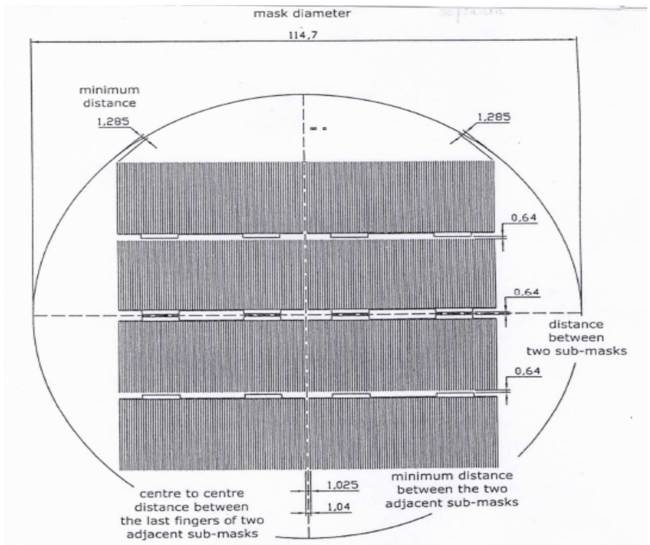

Figure 3. wafer size and cell mask

After completion of the solar cells inspections (visual and microscope) looking for cracks and manufacture defects, the cells were ultrasonically welded to produce 12 strings of 24 cells.

This arrangement allowed the entire terminal wiring (redundant positive and negative) for each string to be done at one end of the panel. The 20mm*40mm GaAs/Ge solar cells manufactured by *énergies nouvelles et environnement* (ENE) were later individually measured (at 0.86V) to arrange the cells into their respective current classes [10][11]. Table 2 summarises the solar cells classes.

Table 2. Alsat-1 solar cells classes

Classes of string (mA at 0.86V)
234 – 237
238 - 241
242 – 245
246 - 249

2.3.1. Solar Cells Assemblies

The solar cells supplied to SSTL in the frame of the Alsat-1 project were as bare GaAs/Ge cells and it is SSTL in house that produced the solar cells assemblies (SCAs). The interconnectors that have been developed at “Thin Film Products-France” are of gold plated molybdenum foil construction and are produced in house.

These interconnects were welded using ultrasonic techniques to the cell front gold contact. An advantage of molybdenum is the complete resistance to atomic oxygen attack, which is a good thing for space environments applications. Molybdenum also provides a mechanical strength and a good thermal expansion match to GaAs and the plating gives a ready to weld surface.

After interconnector welding, the 150 μ m cover glasses are attached using DC 93-500 silicone adhesive. Screen printed CV-2566 adhesive was used to integrate solar cells assemblies onto the solar panel substrate.

2.3.2. Cells Production

Four (04) lots of solar cells, respectively of 2*400 and 2*300 making a total of 1400 cells were produced by CISE and subjected to the approval testing such as humidity storage contact, tape peel test, etc.

1260 cells were selected according to the procurement specification. The cells showing defects, cracks and pour electrical performances represented less than 10% of the whole lot. Fig. 4 shows the distribution of Alsat-1 solar cells Vs efficiency.

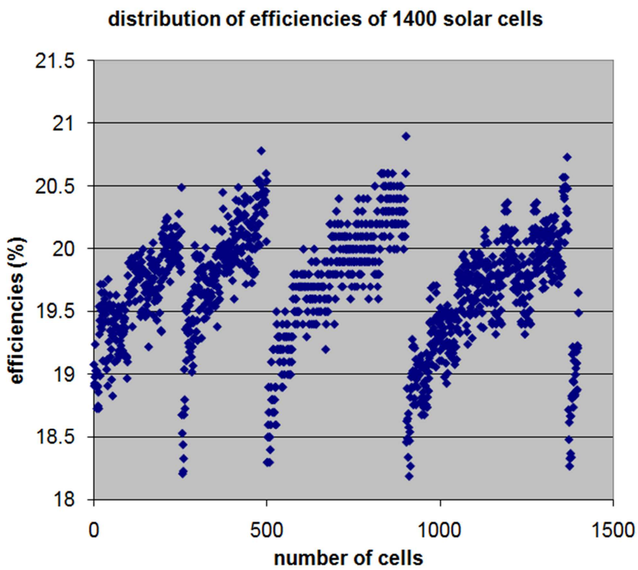

Figure 4. Alsat-1 solar cells distribution Vs efficiency

2.3.3. Average Electrical Performances

Table 3 includes the degradation of the load current I_L after the screening in reverse bias and the voltage Vb at -250 mA. All these electrical measurements were performed using a pulsed solar cell tester equipped with a high pressure Xe lamp at AM0, 25°C.

Table 3. Alsat-1 average electrical performance data from manufacturer

Isc (mA)	254.6
Voc (V)	1.022
Pm (mW)	214.2
Im (mA)	238.0
Vm (V)	0.900
I_L @ 0.86 V (mA)	244.9
Fill factor	0.82
Eff. %	19.8
ΔI_L % after reverse bias	-0.25
Vb (V)	-9.13

Alsat-1 power system operates at a constant 28 V which given the above assumptions requires a minimum string length of 35 cells in order that we are at the maximum power point at the end of life EOL. However this is not the maximum possible power as it is the current at 28 V which determines the useable end of life power. The maximum power occurs when I approximates to Isc, i.e., if the string length is considerably longer than 35 cells. The final design of the solar panels was dependent upon the range of efficiencies obtained during cell testing:

- +X and –X panels populated with lower efficiency cells.
- +Y and –Y panels populated with higher efficiency cells.

Based on the cell layouts, the baseline cell parameters and assumptions above, the solar panels have shown the following beginning of life BOL design powers as shown on table 4.

Table 4. Test performance on panels +X, -X, +Y, -Y (AM0, 25°C) Solar panels measured data

Solar panels characteristics	Panel +X	Panel -X	Panel +Y	Panel -Y
Isc (mA)	1560.50	1543.80	1559.60	1547.40
Voc (V)	49.30	49.27	49.20	49.10
Imp (mA)	1369.40	1374.30	1403.50	1386.30
Vmp (V)	43.126	43.429	43.247	43.227
Pmp (W)	59.06	59.69	60.69	59.92
Fill Factor	0.767	0.785	0.791	0.788
Efficiency %	18.94	19.15	19.47	19.22

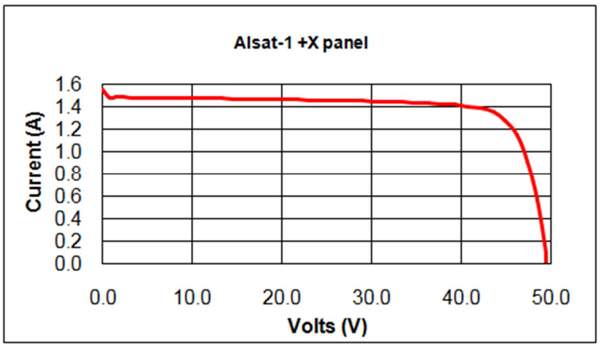

Figure 5. I-V characteristics for +X Alsat-1 panel.

2.3.4. Design Layout

The solar cells used for the Alsat-1 microsatellite are the single junction GaAs/Ge type, manufactured from CESI (Italy). The selected dimensions of the solar cells are 20mm*40mm, thus providing an active area of 0.2304 m^2. Table 5 summarizes the solar cells characteristics.

Table 5. single junction GaAs solar cells electric performance (AM0, 25°C)

Solar cells technology	Single JunctionGaAs/Ge
Js (mA/cm^2)	32.35
Voc (V)	1.025
Jmp (mA/cm^2)	28.82
Vmp (V)	0.9
Pmp (mW/cm2)	25.94
dIsc/dT (A/cm^2/°C)	20*10^{-6}
dVmp/dT (mV/°C)	-1.9
dVoc/dT (mV/°C)	-1.8

Each solar panel has 6 strings in parallel and each string has 48 solar cells in series making up a total of 288 solar cells per panel. The solar cells assemblies are then mounted on isolated honeycomb substrates using a Kapton layer.

Table 6. power performance prediction for panel +X

Solar panel characteristics	AM0 (25°C)	BOL +50°C	EOL @+50°C 5 years	EOL @+50°C 7.5 years
Isc (mA)	1560.5	1566.7	1535.41	1519.75
Voc (V)	49.30	47.08	46.61	46.37
Imp (mA)	1369.4	1374.8	1347.38	1333.63
Vmp (V)	43.126	41.08	40.67	40.46
Pmp (W)	59.06	56.48	54.79	53.96

The power generated from each solar panel is used to power up the satellite's subsystems and charge the on board battery. A power prediction of the solar arrays during their lifetime was simulated using an excel spreadsheet [6]. The programme generates the I-V curve of the solar arrays, see fig.5, based on the data provided by the manufacturer, see table 3.

Table 6 reports data of the simulations for panel +X for end of life (5 years) and beyond (7.5 years). The degradation factors used for the simulations are summarized in the next section.

3. Results and Discussions

To estimate in a more precise manner the power loss encountered by the solar panels, the following end of life design degradations were assumed [1][2][3][4][5]:

- Ultraviolet (0.98)
- Micrometeoroid (0.99)
- Thermal cycling (0.99)

- Contamination (0.99)
- 1MeV electron equivalent fluence

With Alsat-1 being a low earth orbit microsatellite evolving in a polar inclination orbit means that the environment for the solar cells and solar panels should be taken into account during the design phase for the solar cells. The low energy trapped electrons and protons get absorbed by the 150µm cover glass and adhesive but there are chances that the low energy electrons pass through the cell.

In addition a 1% annual degradation consisting of 0.5% for ultraviolet radiation darkening the cover glass adhesive and 0.5% for micrometeoroid and manmade debris impacting on the cover glass is assumed. Using the following formulas:

$$L_d = (1 - degradation/year)^{sat\ life} \quad (1)$$

$$P_{EOL} = P_{BOL} * L_d \quad (2)$$

$$I_{pmax} * V_{pmax} * UltraV * Micromet \quad (3)$$

Formula (3) represents the total loss of power over the lifetime of the satellite in orbit. The life degradation coefficient was computed from (1). An end of life (EOL=5 years) power loss of approximately 4.62% is found in theory when we compute the above mentioned data using formula (3) [6].

Because of the fact that Alsat-1 survived this environment for a longer period than its predefined mission lifetime, ie, 7.5 years, we expressed using the same data as before to compute a power loss of 6.75% over the 7.5 years [6].

Table 7. Manufacturer's Data for Solar Cells Distribution

Cell class/Name	Isc (mA)	Voc (V)	Pm (mW)	Im (mA)	Vm (V)
1/027	252.6	1.047	198.1	224.0	0.884
1/133	247.1	1.029	198.3	224.6	0.883
1/136	252.5	1.011	200.4	229.1	0.874
1/021	246.7	1.049	201.5	225.6	0.893
1/006	242.6	1.024	204.4	224.2	0.912
1/050	243.0	1.010	202.8	227.4	0.892
2/022	253.7	1.052	205.0	230.4	0890
2/002	246.3	1.014	206.4	231.0	0.894
2/028	260.7	1.017	203.8	233.4	0.873
2/072	251.8	1.037	203.7	229.3	0.888
2/071	249.4	1.019	203.9	232.1	0.879
2/104	253.0	1.016	202.3	234.7	0.862
3/014	245.7	1.017	211.1	232.7	0.907
3/018	252.1	1.024	209.4	233.2	0.898
3/026	253.2	1.014	207.8	235.3	0.883
3/028	247.6	1.015	208.1	232.7	0.895
3/032	247.9	1.014	208.6	232.3	0.898
3/002	249.8	1.032	209.2	230.3	0.908
4/000	250.9	1.014	213.0	237.6	0.896
4/001	255.7	1.042	209.0	237.0	0.882
4/003	248.4	1.014	212.5	233.6	0.910
4/007	250.3	1.017	213.7	236.7	0.903
4/008	255.7	1.022	214.3	236.1	0.907
4/010	251.6	1.016	214.5	238.6	0.899

Table 7, which represents a sample of data only, summarises the electrical parameters of the GaAs solar cells used in the frame of the Alsat-1 projects. The reader should be aware that the list is very long and that lot n° 1 consists of 400 solar cells.

The line up of these values on table 7 coincides with the solar classes as shown on table 2.

3.1. In Orbit Solar Panels Performance

The compilation of lot n°1 data shows that Vmp varies from 0.86 V to 0.935 V (on average was taken Vmp = 0.9 V). For most solar cells dVmp/dT = -1.9 mV/°C. Also, Voc varies from 0.99 V to 1.033 V (on average Voc was taken to be 1.02 V).

For our solar cells, we assumed 4.5 E+12 e/cm^2 at 1 MeV, equivalent energy gives 1% degradation at End of Life (EOL). Take worst case cell voltage which 0.86 V*48 cells in series = 41.28 volts [11].

Assuming 1% radiation degradation in low earth orbit and 2% losses in interconnects and cabling which is 3% in total. This will yield to a voltage loss of around 41.28 volts *3%= 1.2384 volts [11].

The array voltage at 25°C is then equal to 41.28 volts - 1.23 volts = 40.05 volts.

Due to the coefficient temperature of the solar cells, the 48 solar cells connected in series give a drop of voltage equal to: -1.9mV/°C *48= -91.2 mV/°C [11].

Finally at low temperatures (-30°C), we expect to reach a voltage drop of: (-30°C-25°C)*(-91.2mV/°C) = 5.02 volts. This will give then a voltage at -30°C reaching 40.05 volts+ 5.02 volts = 45.07 volts [11].

We can complete our reasoning by supposing now a panel at a higher temperature of 50°C. Therefore, if we calculate the array voltage at ambient temperature (+25°C) minus the voltage at +50°C (an increase of 25°C), we get: 40.05 volts- (-91.2 mV/°C)*25 = 37.77 volts [11].

3.2. In Orbit Data Analysis

The telemetry (TM) data in our possession concerns all four panels but for the comparison we analyzed data from panel +X as this the panel to be illuminated first when Alsat-1 leaves an eclipse period and the monitored current has always been the maximum to start feeding the battery and subsystems. The +Y and –X are then illuminated in turn as the satellite rotates.

Table 8 summarizes for comparison telemetry data and estimated +X panel voltages using manufacturer's data. From this table, it can easily be seen that for the chosen period (7 – 19 July 2010), both estimated panel voltages and those measured in orbit do not differ much. As an illustration, ΔV was expressed and seems to give a clear idea on the overall behavior of the +X solar panel independently of temperature. Also, one can see that 7.5 years after launch, Alsat-1 solar panels are not showing signs of defects in orbit.

Table 8. orbit TM DATA and estimated +X panel voltage

T (°C)	-40	-20	-10	10	20	30	40
Estim panel voltage (V)	45.9	44.1	43.2	41.7	40.5	39.6	38.6
Orbit T (°C)	-42	-25	-9.8	13	22	28	42
TM data (V)	46.3	43.7	42.8	41.4	40.1	39.19	38.2
ΔV (V)	+0.4	-0.36	-0.3	-0.3	-0.3	-0.4	-0.4

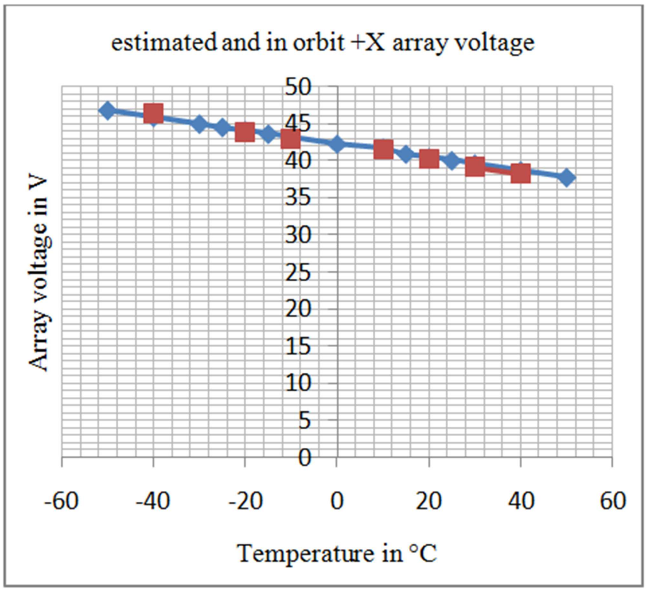

Figure 6. Alsat-1 estimated and in orbit array voltage

Fig. 6 shows a plot of telemetry data and estimated +X solar array output voltage over the 5 year lifetime in orbit. The graph reports clearly the values for comparison and it must be noted that the difference between two voltages at the same temperature is not exceeding 0.4 V. Also, it should be said that over this long period, the +X solar panel had gone beyond 30 000 thermal cycles.

From a design point of view, the satellite's power generation system (solar panels) worked perfectly over the lifetime (5 years) and did as well beyond that period (7.5 years). The compilation of telemetry data both for the solar panels voltages and currents and temperature shows that the panels worked within design exact limits and did not in any case exceed a power loss of 3% compared to the assumption made during the design phase of 4.6%.

4. Conclusions

The realization, for the first time, of the Alsat-1 solar array demonstrated the significative production capability level achieved by SSTL especially to satisfy any power demand for micro and mini satellites.

The solar cells made by ENE (Belgium) for the Alsat-1 project have shown a good in orbit behavior over the entire mission and beyond.

In summary no great degradation was noticed and the solar panels were a key component for the success of the Alsat-1 mission.

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