Design and Qualification Tests of the Alsat-1 High Efficiency Solar Panels

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Abstract-Since the commissioning of the manufacture facility and qualification of the processes in 2001, Alsat-1 solar panels were the first ones ever to be made and tested in house by SSTL. The solar panels used lightweight solar panel substrates of aluminium honeycomb with aluminium face skins. The front face skin has a polyimide insulation layer ready for the electrical lay down of the solar cells. The panel cell interconnections, bus barring and wiring are fully welded for high reliability. All stages of manufacture are routinely checked for quality assurance. Final acceptance performance testing was performed in Farnborough. SSTL used an ultrasonic welding technique for the connection of gold coated interconnects to the front bus bar of the cell. The cells are then glassed using space qualified glass, followed by retesting and grouping in the appropriate current class. This paper describes the design procedures for the Alsat-1 body mounted solar panels manufactured, for the first time, by SSTL. Because of the power requirements both for the payload and the bus, the solar panels were equipped with high efficiency single junction GaAs solar cells mounted on aluminium substrates for a more efficient radiation shielding for the payload.

Keywords-Single Junction, high efficiency GaAs Cells, aluminium substrates, radiation shielding, design procedures.

1. Introduction

Alsat-1 is the new generation of SSTL enhanced micro satellite weighing 100kg. The satellite is powered by four body mounted GaAs solar panels, with a total power rating of 60 watts. [4]

The solar panels are the primary source of power to the satellite. Twenty two 4Ah Nickel Cadmium cells will be used to power the satellite during eclipse. [3]

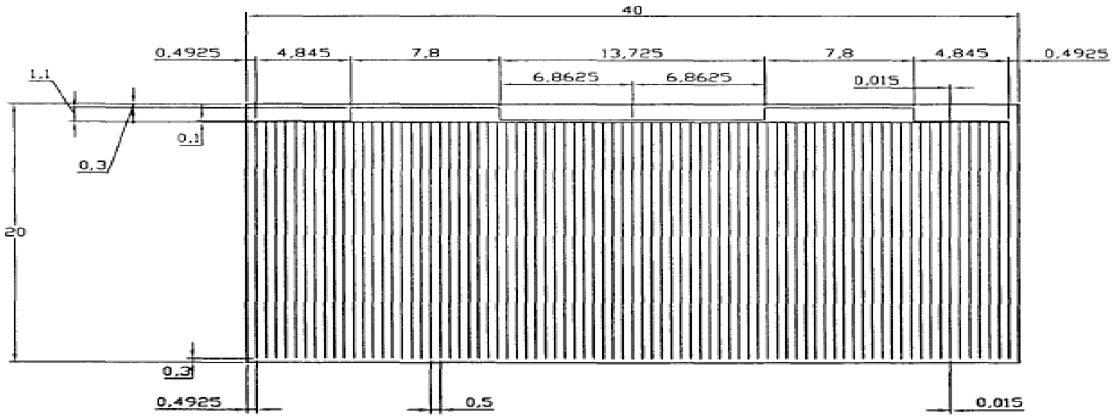
2. Solar Panel Realization

The solar cells used in the frame of the Alsat-1 project were manufactured from ENE (Belgium) in the size 2cmx4cm using the MOCVD process (Aix 2400) and fully evaporated metals (fig. 1).

The solar cells were single junction GaAs/Ge cells, mounted on an aluminium face sheet and an aluminium honeycomb substrate. The cells provide on average 19 % conversion efficiency at ambient temperature.

The solar panels were configured as follows: The panel substrates were made of a 20mm aluminium core honeycomb with 0.5mm aluminium face skins front and rear. The front of the panels has an insulating layer of 75µm kapton. The cell lay down design of the four panels was identical consisting of 6 strings of 48 cells in series (288 solar cells per panel).

The cells were arranged on the panel in 12 columns of 24 cells. This convenient arrangement allowed the entire terminal wiring (redundant positive and negative) for each string to be done at one end of the panel. The 2cmx4cm GaAs/Ge solar cells were glassed and welded into solar cell assemblies (SCAs).



Cell Surface (mm2)	800	
Mask surface (mm2)	42.5595	
Collectors and Bus bar surface	20.8740	% of mask surface : 49.05
Fingers surface	21.6855	% of mask surface : 50.95
Shadowing	5.32 %	

Fig. 1. Mechanical drawing of a 2cm x 4cm ENE solar cell.

The cells were then individually measured (at 0.86V) to arrange the cells into their respective current classes. The cell performance was selected so that the +Y and -Y panels had a better performance than the +X and -X panels (table 1). [5]

Table 1. Flight model solar cells classes.

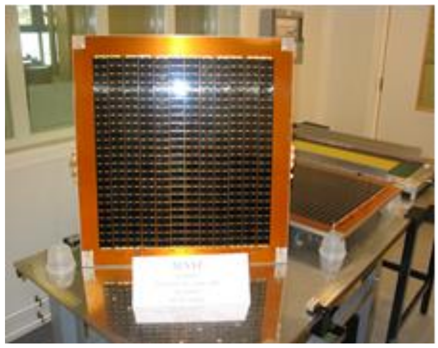
Solar cells classes
234 – 237 mA at 0.86V
238 – 241 mA at 0.86V
242 – 245 mA at 0.86V
246 – 249 mA at 0.86V

Alsat-1 solar array models philosophy comprises one engineering panel (test coupon of 20 cells) and four flight panels (fig. 2) to be submitted to qualification and acceptance tests at DERA - Farnborough - United Kingdom. [2, 4,5]

2.1. Cells Selection

From a mission analysis point of view, it quickly became apparent that silicon cells were not an option, for Alsat-1, due to the available panel area, only enough power could be generated to power up the platform and probably none of the payloads. This is why, single junction GaAs/Ge cells were chosen as a high performance method of primary power generation. Alsat-1 four solar panels will be populated using GaAs cells. The following parameters were assumed as the baseline performance for the cells in the design: [2-5]

- Isc (short circuit current) 254.6 mA
- Voc (open circuit voltage) 1.022 V
- Vpmax (max power point voltage) 0.9 V
- Ipmax (max power point current) 238 mA
- Pmax (max power) 214.2 W
- FF (fill factor) 0.82
- Eff (solar cell efficiency) 18.5%



(a)

(b)

Fig. 2. Alsat-1 flight model panel (a) front (b) rear.

2.2. Cells Interconnections

The interconnectors used on Alsat-1 are of gold plated molybdenum foil construction. An advantage of the gold plated molybdenum material is the complete resistance to atomic oxygen attack, which means that these are suitable for all space environments without additional protection. Molybdenum also provides mechanical strength and a good thermal expansion match to GaAs and the plating gives a ready to weld surface.

After interconnector welding, the 150 µm cover glasses are attached using DC 93-500. After an in house inspection and electrical testing, the bare cells are turned into solar cells assemblies using ultra sonic welding. The solar cells strings are then integrated onto the solar panel substrate using screen printed CV - 2566 adhesive. [4]

2.3. Design Assumptions

The operating temperature was assumed to be 25°C and AM0 light intensity. To complete the design of the panels the following loss factors have been assumed: [5]

Isc : (1% cell mismatch, 1% radiation degradation)
Voc: (2% due to wiring, 1% radiation degradation)

2.4. Panel Layout

The 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 layout, for the solar panels, was dependent upon the range of efficiencies obtained during testing: [4] [5]

- +X and -X panels populated with lower efficiency cells. [4] [5]
- +Y and -Y panels populated with higher efficiency cells. [4] [5]

2.5. Estimated Power

Based on the cell layouts, the baseline cell parameters and the assumptions above, the solar panels have shown the following beginning of life BOL design power parameters (power and efficiencies) (table 2): [4]

Table 2. BOL design power parameters.

Panel	Power (W)	Efficiency (%)
+X	56.54	18.95
-X	56.97	19.15
+Y	58.04	19.47
-Y	57.30	19.22

3. Manufacture

3.1. Cell Types

Each panel comprises 12 half strings and each half string comprises 24 GaAs solar cells. The solar cells used for Alsat-1 were manufactured in the size 2cmx4cm, using the MOCVD process and fully evaporated metals. The grids on the cells's front side are obtained by evaporation through a nickel evaporation mask.

- both the front and rear contacts are made by a silver layer at least 5 m thick on top of which an additional 200nm gold layer was evaporated for improved welding on gold plated Molybdenum interconnects.
- distance between the welding pads and the cell edge is 0.3mm.
- contact length is 7.8mm
- separation between the contacts is 13.725mm.

3.2. Cell Production

About 1400 cells were subjected to the routine type approval testing such as humidity storage contact, tape peel test. 1260 cells were selected according to the procurement specification (fig. 3). The cells showing defects, cracks and poor electrical performances represented less than 10% of the whole production. This was considered acceptable. The efficiencies of all cells are in the range 18.5-20.5%. The average efficiency is 19% at (AM0).

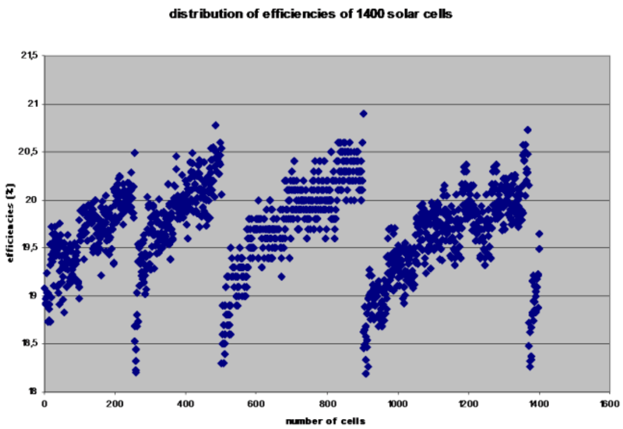


Fig. 3: Alsat-1 solar cells efficiencies distribution.

3.3. Cell Interconnection and Panel Laydown

For Alsat-1, only one structural qualification model (SQM) (fig. 4) and four flight panels were made. The SQM panel allowed us to check the strength of the structure during vibration testing. During this test, the cells laid in the middle of the panel did not show any damage.

In accordance with the electrical design and considering the panel area available, each panel consists of 12 half strings of 24 cells connected in series for the flight model panels.

The electrical characteristics of the solar array at AM0, 25°C are as follows (table 3): [4] [5]

Table 3. Electrical characteristics of the solar arrays.

Panel +X	Panel -X	Panel +Y	Panel -Y
Isc=1560.5 mA	Isc=1543.8 mA	Isc=1559.6 mA	Isc=1547.4 mA
Voc=49.3 V	Voc=49.27 V	Voc=49.2 V	Voc=49.1V
Pm= 59.06 W	Pm= 59.68W	Pm= 60.69 W	Pm= 59.9 W
P@28V =56.5W	P@28V =56.9W	P@28V =58 W	P@28V =57 W

4. Qualification and Acceptance Testing

In order to demonstrate the suitability of the solar panels for use on Alsat-1, a range of tests were carried out at various levels of integration from cell to panel level. These tests were aimed at showing that the cells and panels will survive the launch and space environment constraints for at least the mission lifetime. These tests were carried out at Astrium (Portsmouth-UK) at the following levels: bare cell (visual inspection), solar cell assembly (air bubbles, cracks), coupon, engineering panel and finally flight panel. [2] [4] [5]

4.1. Cells

Cells were tested with calibrated mechanical jigs.

a) Weight: average 0.819g/cell.

b) Visual inspection: successfully performed on all cells.

c) Marking: each cell is marked on the rear with a two digit code identifying the front contact manufacture lot.

4.2. Coupon

SSTL manufactured a small test coupon consisting of two strings of 24 (2cmx4cm) cells on an aluminum panel substrate. This coupon was then subjected to 1000 cycles of 12 minutes duration each between +80 and -40°C. The coupon was also visually inspected and electrically measured before and after the test, no change in performance was found and no damage occurred. [4, 5]

4.3. Panel Substrate

The panel substrate is made of an aluminum honeycomb core with a 0.5mm aluminum front and rear skins along with a bonded kapton insulation layer on the front face. The honeycomb thickness was 20mm. As Alsat-1 panels have reached newer dimensions (60cmx60cm) compared to SSTL old generation micros, they were subject to qualification tests (vibration and thermal testing). Due to the tight mass budget of Alsat-1, the primary consideration in the choice of the substrate material was mass with the retention of strength. High stiffness and low mass (2 kg per panel) was obtained using aluminum honeycomb core. The resulting low thermal expansion of aluminum was a further advantage in that it reduces thermal stresses caused by the excessive temperatures the panels will be subjected to. [5]

4.4. Engineering Panel

Two strings of 24 cells each using (2cmx4cm) cells type were laid down across the middle of the SQM panel. This panel was then subjected to vibration and thermal vacuum testing at Astrium. The strings of cells were then visually inspected and electrically tested. Low level sine sweeps were performed before and after the random vibration which showed that resonance peaks were also unaffected, indicating that no significant internal damage had been done to the panel. [5]

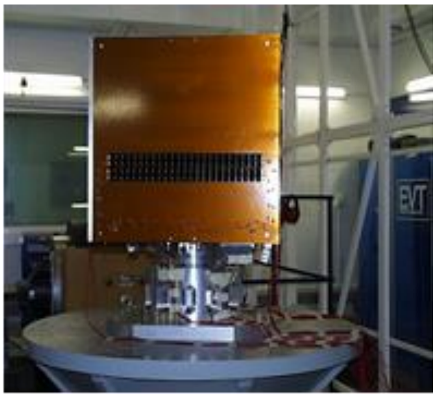


Fig. 4. Alsat-1 structural qualification model panel.

4.5. Flight Panels

The mechanical structure of each panel comprises a 20mm thick aluminum honeycomb substrate with 0.5mm thick Aluminum skins; the active face sheet is covered with a 50 µm thick dielectric insulating (kapton) material.

Each panel includes the holes dedicated to the panel fixing to the satellite, the protection cover fixing and the wiring feed through. The panel dimensions are: 4 panels: 60cmx60cm. The Alsat-1 panels have undergone a thermal vacuum soak test to outgas them. They also have been subjected to the flight acceptance vibration level before final acceptance (fig. 5).

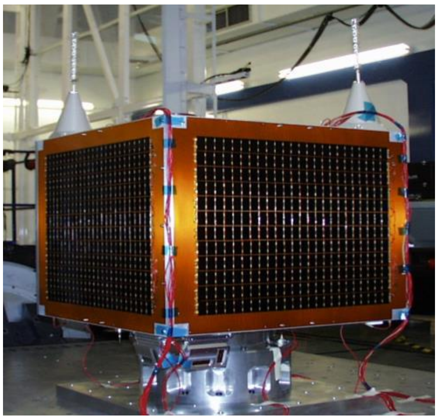


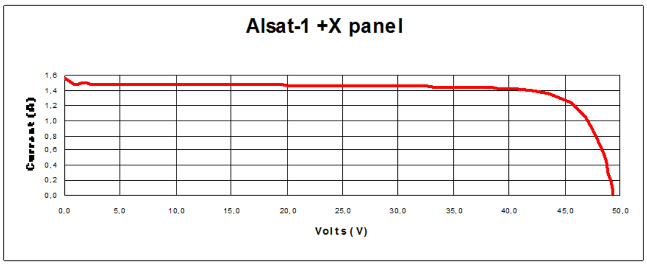
Fig. 5. Acceptance vibration test for Alsat-1 solar panels.

The following tests were performed at Astrium-UK, on the 4 panels attached to the spacecraft:

- mechanical vibration (sinus and random).
- shock separation.

A shock test was carried out to verify the mechanical integrity of Alsat-1 under the pyros separation shock.

Electrical measurements were performed on the Alsat-1 solar panels before and after the tests at DERA in Farnborough-UK using the flash simulator. A comparison study between the two measurements highlights that no electrical damage or degradation of the panels performance has occurred. In figures 6 a, b, c, d… below, the IV characteristics of the four panels are reported. [4] [5]



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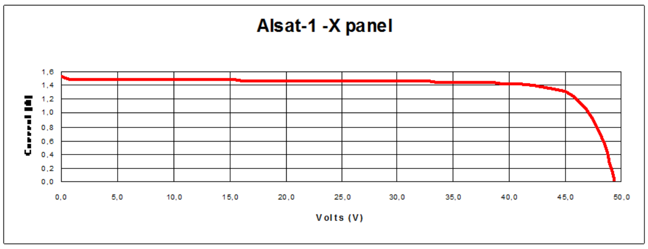

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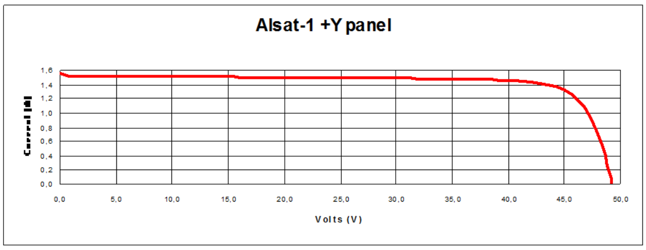

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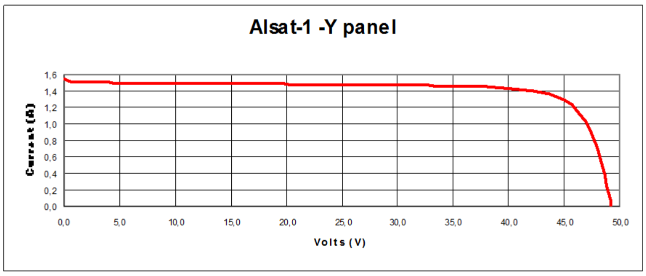

(d)

Fig. 6. Measured I-V characteristics.

Table 4 shows measured data especially for Vmp and Imp for all the panels, ie, -X, +X, -Y and +Y.

Table 4. Solar panels measured data.

Designation	Vmp (V)	Imp (mA)	Pmp (W)	Ptest (W)	Meas. Eff %
+ X panel	43.126	1369.4	59.056	56.54	19
- X panel	43.429	1374.3	59.684	56.97	19.15
+ Y panel	43.247	1403.5	60.698	58.04	19.47
- Y panel	43.227	1386.3	59.923	57.30	19.22

5. Solar Array Design: [6-8]

The BCR used on Alsat-1 is a low power buck topology DC-DC converter. In total, we have four BCRs, one dedicated to each solar array, stepping down the 40V from the solar arrays to the 28V unregulated bus.

An estimate of the solar array maximum power point is made by sensing the array substrate temperature using thermistors. The array voltage is set to the end of life MPP in hardware.

Each BCR also has the ability to be controlled by software, enabling more accurate tracking of the MPP of the solar array. The software has a watchdog timer that protects the power system from a software crash. If the software times out, the BCR will automatically revert to hardware control. The software control is managed within the power system which has its own microcontroller.

Vmp varies from 0.86 V to 0.935 V (on average Vmp=0.9 V). For most solar cells dVmp/dT = -1.9 mV/°C.

Voc varies from 0.99 V to 1.033 V (on average Voc taken to be 1.02 V).

On all 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). [9] [10] [12]

Take worst case cell voltage which 0.86 V*48 cells in series = 41.28 volts.

If we assume 1% radiation degradation over 5 years in low earth orbit and 2% losses in interconnects and cabling which is 3% in total. This will induce a voltage loss of around 41.28 volts *3%= 1.2384 volts.

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.

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.

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.

The values found here coincide perfectly with the values found from the graph.

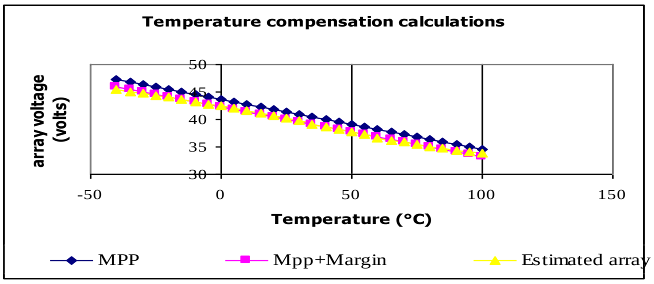

Fig. 7. Alsat-1 array voltage Vs temperature.

Table 5. Data comparison (orbit and estimated panels voltages)

T (°C)	-20	-10	10	30	40
Estimated panel voltage (V)	44.15	43.24	41.42	39.59	38.68
Telemetry data (V)	43.79	42.87	41.78	39.19	38.26

Table 5 shows a data comparison study for the period 7 to 19 July 2007 for the orbit and estimated panel voltages.

Table 6. Data comparison (orbit and estimated panels voltages) for a different period

T (°C)	-40	-20	-10	10	20	40
Estimated panel voltage (V)	45.9	44.1	43.2	41.4	40.5	38.6
T (°C) in orbit	-42	-25	-10.	13	22	42
Telemetry data (V)	46.1	43.1	42.2	41.7	38.6	36.2

For comparison, we have chosen a period during 2010, where the satellite's attitude compared well with previous ones. From table 6, one can see in details how the Alsat-1 solar panels are behaving in orbit beyond the defined lifetime.

6. Conclusion

Our participation, within the frame of the CTS/SSTL know how transfer, has given us deep knowledge of the whole process from solar cell selection to the lay down process. The learning process was concluded by a full participation in the electrical and thermal testing.

Figure 7 illustrates well our expectations for the panels against the whole range of temperatures between -40°C and +60°C. It must be noted that the satellite's panels worked perfectly over the whole lifetime period and beyond. The telemetry data which we received all over the lifetime of the satellite shows the panels worked within design exact limits.

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