Temperature effects on satellite power systems performance

M. Bekhti, M. N. Sweeting,

Abstract - Alsat-1 is the first small satellite for the Centre of Space Techniques (CTS) – Algeria. It was designed, built, assembled and tested at Surrey Satellite Technology Limited (SSTL) at the University of Surrey, with the participation of 11 Algerian engineers covering all aspects of micro satellite engineering within a technology transfer programme between SSTL and the CTS. Alsat-1 is an enhanced micro satellite weighing 100kg (launch mass). The satellite measures 60 by 60 by 62.5 cm, and is powered by four body mounted GaAs solar panels, with a total power rating of 60 watts. The solar panels are the primary source of power to the satellite. Twenty two 4Ah Nickel Cadmium cells are used to power the satellite during eclipse.[9]

The power system on Alsat-1 has met or exceeded prelaunch predictions excepting for the NiCd battery pack which started showing signs of defects in August 2005. [8][10]

This paper shows how, from August 2005 until now, teams from SSTL and CTS have been working together to monitor battery health and performance in particular with regard to its charging cycles. The key points affecting the battery thermal condition including power consumption during eclipse, heat generated by the battery itself and the depth of discharge of the battery are discussed. Some recommendations and ideas regarding thermal design and battery protection are presented.

Keywords - micro satellite, system performance, degradation, depth of discharge, temperature, thermal conditions.

I. Introduction

Small satellites have already been launched with considerable success by many institutions in the developing countries. Their attraction lays in the promise of low cost and short development timescales made possible by the use of proven standard equipment and off the shelf components and techniques. Coupled with realistic and focussed goals, such satellites make it possible for a country with even a small research budget to participate in their development, launch and operation.

Small satellites thus present an ideal opportunity for training students and engineers in different disciplines, including engineering, software development for on board and ground computers.

The Algerian engineers were trained at Surrey through the AlSat-1 project with specializations in the following disciplines: System Engineering, ADCS, Power, RF, OBDH, Mechanical and Launch Interface, Earth Observation Payload, GPS, Operation, TTC and Propulsion. [8]

Manuscript received July 20, 2010. This work is part of a research project on power systems on board small satellites.
M. Bekhti, Centre des Techniques Spatiales, BP 13, Arzew 31200, Algérie. Tel: +213 41 47 38 26 - Fax: +213 41 47 36 65, Email: m_bekhti@yahoo.fr
M. N. Sweeting, Surrey Satellite Technology Limited,Tycho House, 20 Stephenson Road , Surrey Research Park , Guildford GU2 7YE , United Kingdom, Tel: +44 (0)1483 803803 - Fax: +44 (0)1483 803804, Email: m.sweeting@sstl.co.uk.

II. Alsat-1 platform architecture:

The spacecraft is cubical in shape with four body-mounted panels, with the remaining sides including the spacecraft launch adaptor, sensors, payload apertures and antennas (figure 1). The structure is based on aluminium and aluminium honeycomb panels and was been designed to be compatible with a range of launchers. The stack of trays carries an optical platform and between the stack and the panels, the battery pack, the wheels and the propulsion system are carried. A propulsion system is required in order for the spacecraft to carry out initial launcher injection corrections, spacecraft separation into the final orbital slot, altitude maintenance and finally an end-of-life manoeuvre to remove the spacecraft from the operational system. [9]

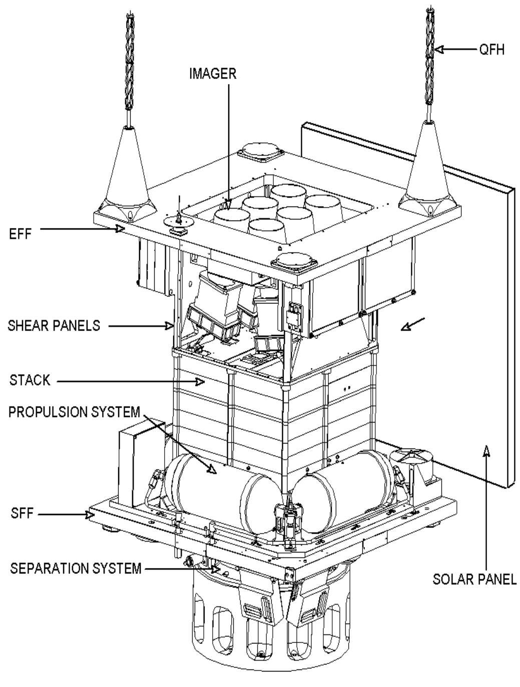

Fig 1 Alsat-1 platform architecture.

III. Alsat-1 power system description

The primary power to the satellite is supplied via 4 solar panels (figure 2). The power from each of the four solar panels is fed into a dedicated Battery Charge Regulator (BCR), i.e. one BCR per solar panel. The output of the BCRs is connected to a 22 cell, 4Ah NiCd battery, the Power Distribution Module (PDM) input and the Power Conditioning Module (PCM) input. The solar arrays and BCR outputs are isolated from each other using one blocking diode per BCR. By isolating the earth orbit environment and the nature of the Alsat-1 design for several reasons:

1. the maximum power point (MPP of an individual panel can be tracked over the changing thermal conditions whilst in sunlight.
2. the battery is charged for the majority of the sunlight period efficiency of the power system.
3. the direct connection between the battery and the bus ensures maximum efficiency.

The function of the PCM is to convert the raw battery voltage into a regulated 5V line and a –5V line. The dual redundant PCMs (1 and 2) are virtually identical.

PCM 1 has a battery under-voltage lockout system incorporated into its design, providing further protection to the power system. When the PCM input (battery) voltage goes below 20V, the PCM switches off completely.

This removes the 5V bus from the spacecraft, switching OFF the power system CAN microcontrollers and with it all of the power switches in the power system. The PCM will re-start once the battery voltage has recovered to approximately 22.7V.

Only PCM 1 has this safety feature, so by selecting PCM 2 this feature will be disabled. PCM 2 will operate down to a battery voltage of about 11.5V. At voltages lower than this value, the PCM can no longer regulate the output voltage to 5V, and the voltage goes to zero.[4][5][6]

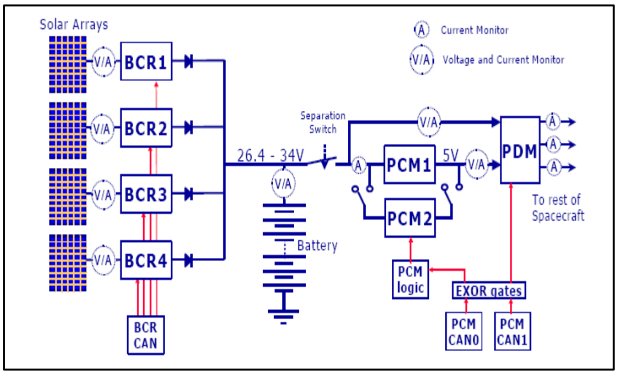

Fig 2 Alsat-1 power system block diagram.

A. Solar Panels

The solar cells used on Alsat-1 were single junction GaAs/Ge cells, mounted on aluminium face sheet and aluminium honeycomb substrate. The cells provide on average 19.52 % conversion efficiency at ambient temperature.

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

solar arrays from the bus using a BCR per panel suits the low

wiring (redundant positive and negative) for each string to be done at one end of the panel. 20mm x 40mm GaAs/Ge solar cells were glassed and welded into solar cell assemblies (SCAs).

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.

The panels were busbarred and wired completely after. The panels were then rear wired (thermistor, temperature sensor, and 15 pins D type connector added). Large Area Pulsed Solar Simulator (LAPSS) measurements of the panel powers pre-environment tests (EVT) were performed at QinetiQ in Farnborough on 29/5/02, (figure 3). Panel powers were again measured on 19/7/02 post – EVT, see table 1.[2][4][5][6][7]

Fig 3 Alsat-1 flight model panel.

Test conditions: Air Mass Zero (1366.1W/m^2) at 25°C. [10]

+X Panel	**Pmax**	**Ptest**
Pre test	59.06W	56.5W
Post test	58.63W	56.5W
+Y Panel	**Pmax**	**Ptest**
Pre test	60.70W	58.04W
Post test	60.00W	57.60W
-X Panel	**Pmax**	**Ptest**
Pre test	59.68W	56.97W
Post test	58.85W	56.25W
-Y Panel	**Pmax**	**Ptest**
Pre test	59.92W	57.30W
Post test	58.85W	56.51W

Table1: Pre and Post EVT power measurements.

B. Battery Pack

Alsat-1 uses a single battery pack (figure 4) that consists of 22 Sanyo N4000 DRL cells in series and has a nominal voltage of 26 to 34 volts (depending on the charge). The cells used are fast charging cells and have undergone a set of mechanical and electrical matching tests to produce the flight battery pack.

There is an under voltage protection for the battery provided by the PCM/PDM module. This protection will stop the battery voltage dropping below 26 volts and therefore stop any of the cells from being damaged by over discharge. The battery pack has 37 Telemetry lines that provide all temperature and voltage data to the PCM/PDM and BCR Modules. The PCM/PDM Module provides some of the house

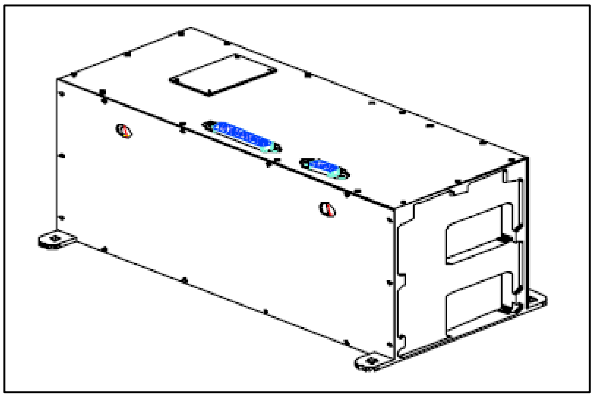

Fig 4 Alsat-1 flight model battery pack.

keeping data processing for the Battery, including the individual cell voltage telemetry and the battery pack temperature. The BCR Module provides battery current and battery voltage telemetry and interfaces with the 4 thermistors mounted in the battery for temperature compensated control of the BCR. Fast charging of the battery requires careful tracking of the maximum power point (MPP) of the solar panel. The MPP for Alsat-1 panels is roughly 40 volts, a value which is carefully monitored by a microcontroller associated with the BCR, varying the voltage of the panel to allow the optimal production of power.[1][3][10]

C. Battery Level Tests

Once the battery has been assembled, it undergoes battery level tests that include conditioning cycles, battery capacity measurements and thermistor / temperature sensor tests. The battery was subjected to three full charge/discharge cycles at 22.5°C. The charge current was 400mA for approximately 15hrs and the discharge tests consisted of discharge rates of C/5 (800mA). The capacity of the battery is calculated from the third and last discharge. The discharge current of 800mA takes just over 5 hours to fully discharge the battery, giving a capacity of 4.25Ah. It should be noted that it is possible for the battery voltage to increase to a voltage of approximately 33.4V if charged at 0°C, and can reach over 31.6V when charged at room temperature.[5]

D. Battery Charge Regulator

The BCR used on Alsat-1 is a low power buck topology DC-DC converter. In total, we have 4 BCRs, one dedicated to each solar array stepping down the 40 volts from the solar arrays to the 28 volts unregulated bus. The BCRs operating frequencies are not all identical but separated from each other by 15 KHz to prevent beat frequencies interfering with sensitive radio frequency systems such as the receiver. The chosen nominal frequency of a BCR is 200 KHz. An estimate of the solar array maximum power point (MPP) is made by sensing the array substrate temperature using thermistors. The array voltage is set to the end of life MPP in hardware. The end of charge (EoC) voltage of the NiCd battery is set in hardware and uses a thermistor for temperature compensation. Once the battery voltage reaches the EoC set point, it is held at this value as the charge current naturally tapers off to a trickle charge level, thus the battery is never overcharged. 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. The BCR efficiency has been calculated from tests performed at room temperature and varies from 70% to 80% depending on the input power.[10]

E. Power Conditioning Module

The Power Conditioning Module (PCM) is a buck DC-DC converter and provides a regulated 5 volts supply and a semi regulated 15 volts from the raw battery voltage. The output current is 3A.

The PCM provides deep discharge protection to the battery by shutting OFF when the battery voltage falls below approximately 26 volts and permitting the system to come back up again once the battery has recovered to a voltage of 28 volts.[10]

F. Power Distribution Module

The power distribution module (PDM) consists mainly of MOSFET based power switches. The same switch design is used for regulated 5 volts and 15 volts and raw battery power distribution. By using P channel MOSFETS with a very low RDS (On) of about 20 mΩ (IRF 4905S), the switch provides a highly efficient interface to subsystems and can easily be configured to trip at the required current level. The PDM consists of around 100 P channel MOSFET, which act like programmable circuit breakers. They can be switched On and Off, allowing the control of power to the satellite subsystems and payloads. This switching is controlled by a microcontroller which switches power to a subsystem when requested via the CAN. Radiation is, however, still enough of a factor to determine the choice of MOSFET in the PDM. A P channel device has been chosen over an N-Channel because it lasts far longer in conditions of higher radiation.[10]

IV. Telemetry data processing and battery data analysis

Since its launch on the 28th November 2002, Alsat-1 has so far completed 28 000 orbits and thus 28 000 charge/discharge cycles for the battery.

The software implemented in the ground station has basic statistical tools. It can also allow variable telemetry data

ISBN: 978-960-474-250-9

comparison and calculation, for example, the power generated by the solar cells using voltage and current data.
The analysis of the telemetry data files related to the solar arrays temperature shows for most of the times that it fluctuates between -35°C when in eclipse and +35°C in sunlight.

Fig 5-a Cell 19 healthy 30/08/2005.
A more detailed analysis of the telemetry data over the period 2003-2008 gave the results on table 2: [4][5][6]

Solar array configuration	Min temperature	Max temperature	period
-X	-30°C to -10°C	+10°C to +20°C	2003-2008
+X	-35°C to -5°C	+5°C to +30°C	2003-2008
-Y	-35°C to -30°C	+10°C to +35°C	2003-2008
+Y	-30°C to 0°C	+5°C to +20°C	2003-2008

Table 2: Alsat-1 solar arrays telemetry data

The battery environment in orbit (temperature, voltage and current) was carefully checked all the time using this tool. Since the battery pack cells are charged during sunshine and discharged in the shadow, therefore their respective voltage increases and decreases periodically. As an example, figure 5-a shows the voltage for cell 19 in its healthy state. The telemetry data was taken from the 30th August 2005 file and clearly shows that the cell was charging and discharging properly. The voltage was increasing from 1.2 volts (nominal) to 1.45 volts (max).

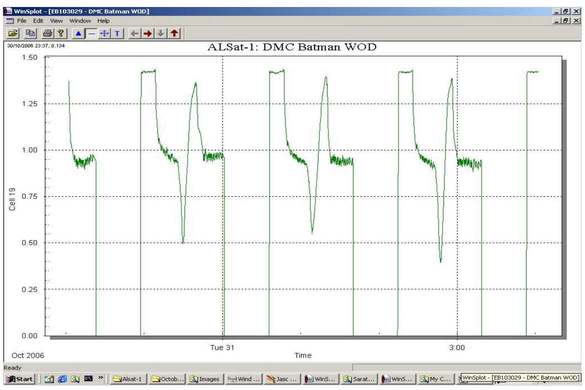

Fig 5-b Cell 19 acting as a resistor30/10/2006.

Figure 5-b shows, a year later and for cell 19, a sign of defect. In fact, cell 19 started acting as a resistor from 30th October 2006. The discharge cell voltage was hitting a lower value well below the nominal value.
A close monitoring of cell 19 data showed later that it was deteriorating slowly and finally it went to the short circuit state on the 22nd March 2008 with a voltage of 0 volt, see figure 5-c.

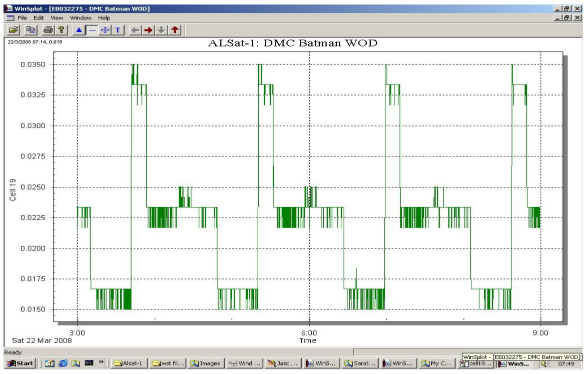

Fig 5-c Cell 19 short circuit 22/03/2008.

A. Depth of discharge of the battery

Following the start of breakdown of the Alsat-1 battery pack, a close watch of the temperature effect on the battery characteristics was daily measured. The depth of discharge of the pack was also kept under control to make sure it does not contribute to the damage of the battery. Table 3 gives an insight of the range of depth of discharge being experienced on Alsat-1:[4][5][6]

year	Battery temperature	Depth of discharge
2003	16 to 20°C	15 to 25%
2004	21 to 28°C	16 to 25%
2005	25 to 39°C	16 to 22%

Table 3 monitoring of the depth of discharge.

It can be seen from table 3 that the depth of discharge is kept within the required range for the lower values, i.e., 15%. The higher value can for some situation be considered good as well as long as it does not exceed 25%. The most noticeable data figure is the temperature which has exceeded for the years 2004 and 2005 the optimum value. The battery pack has an operational temperature limit of 0°C to 40°C but it should be kept within the range 15 to 20°C for good performance.

B. Temperature and voltage monitoring and control

To protect the battery pack, several plots of voltage/current against temperature were used to monitor the thermal working environment according to the variable working modes of the spacecraft. Figure 6 shows the battery temperature over the spacecraft lifetime. This shows a steady rise until the introduction of the software charge control in early 2005. The

ISBN: 978-960-474-250-9

most significant drop in early 2006 is due to the spacecraft being yawed by 180° when not imaging.

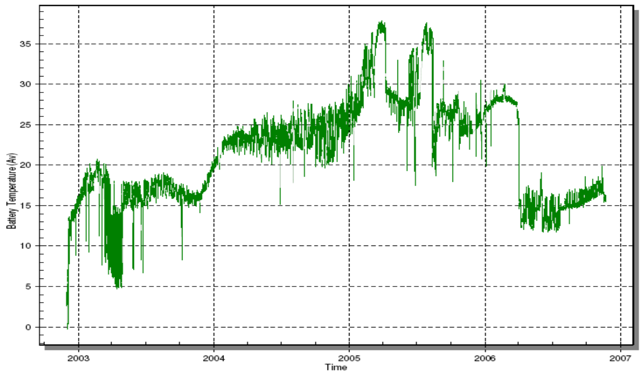

Fig 6 Battery temperature.

C. Cell Voltages

Figure 7 shows the individual cell voltages as of the 24th of November 2006. Cell 19 has effectively failed and is acting as a resistor. This can be seen from its behaviour with the changes in current during charging. Effective battery management and a reduction in battery temperature have greatly improved the performance of cells 3 and 12 which have shown signs of defects lately also.

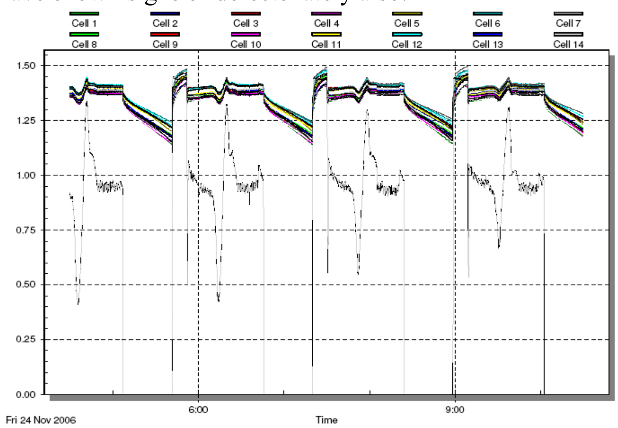

Fig 7 Cells voltages.

D. Battery Voltage

Figure 8 shows the battery voltage over the lifetime of the Spacecraft. The battery voltage has been steadily decreasing over the in orbit period, showing signs of recovery around mid 2005 when the charge control software was implemented and even better performance since early 2006 when the spacecraft was yawed by 180°, the battery temperature decreased and cell capacity improved. Battery voltage is averaging about 23.5V at the present time.

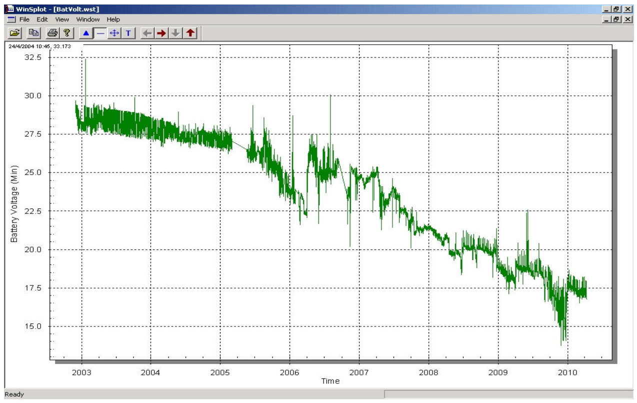

Fig 8 Battery voltage.

Conclusion

The present state of the battery on the spacecraft and the main factors which led to the damage of a few battery cells in the pack for Alsat-1 has been discussed.

At present the battery voltage is above the reset voltage but it is expected that this will fall with age and increased spacecraft utilisation.

For the time being Alsat-1 is still operating with a close watch of the battery parameters as to avoid further damage for other cells.

It is clear on the graphs shown in this paper that temperature is one factor contributing to the battery damage and here we could point the fact that for future missions, the battery position within the spacecraft must be studied carefully.

This is confirmed as being a temperature related problem because when the satellite was yawed 180°, ie, the battery pack changed place in the satellite reference frame, the temperature went down to normal and the cells performance had gone up noticeably regarding charge/discharge schemes.

References:

[1] C.S. Clark, A.D. Hill, M. Day, Commercial nickel cadmium batteries for space use: a proven alternative for LEO satellite power storage, Proceedings of the Fifth European Space Power Conference, Tarragona, Spain, 21–25 September, (1998), pp. 715–720.

[2] M. D'Errico, M. Pastena, Solar Array Design and Performance Evaluation for the Smart Microsatellite, 49th Congress of the International Astronautical Federation, Sept. 28 – Oct. 2, (1998), Melbourne, Australia.

[3] M. Pastena, M. Grassi, Design and Performance Analysis of the Electronic Power Subsystem of a multi Mission Microsatellite, Acta Astronautica, vol. 44, n°1, (1999), pp. 31-40.

[4] Clark, C.S., Alsat-1 Power System TVT Test Procedure. Surrey Satellite Technology Limited, November (2002), pp. 1-17.

[5] Clark, C.S., Alsat-1 Battery Conditioning, Operation and Handling Procedure. Surrey Satellite Technology Limited, November (2002), pp. 1-7.

[6] Clark, C.S., Alsat-1 AIT Power System Test Report. Surrey Satellite Technology Limited, November (2002), pp. 1-11.

[7] R, Kimber, Alsat-1 solar array interface control document. Surrey Satellite Technology Limited, December (2002), pp. 1-8.

[8] M. Bekhti, J.R. Cooksley, Alsat-1 in orbit performance results, in: Third Disaster Monitoring Constellation Consortium Meeting, Abuja, 3–4 April, (2003).

[9] M. Bekhti, M. Benmohamed, M.N. Sweeting, The role of small spacecraft in the developing countries: the Algerian experience, in: Small Satellite and Services Symposium, La Rochelle, France, 20–24 September, (2004).

[10] M. Bekhti,M.N. Sweeting, power system design and in orbit performance of Algeria's first micro satellite Alsat-1. Electric power systems research 78, (2008), pp 1175-1180.

Biography:

Mohammed Bekhti received his first degree in electronics from the University of Science and Technology of Oran, Algeria, a master degree in power electronics from the University of Nottingham, UK and a Mastère in space telecommunication from a High School of Engineering (SUPAERO) in France. His fields of interests are microstrip technology applied to filter design and power electronics for micro satellites power systems design.