

POWER SYSTEM DESIGN AND PERFORMANCE ON THE WORLD'S MOST ADVANCED IN-ORBIT NANOSATELLITE

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ABSTRACT

In June of 2000, the world's most advanced nanosatellite was launched into a 700km Low Earth Orbit onboard a Cosmos rocket from Plesetsk. The spacecraft was developed, manufactured and launched as a technology demonstration mission in the amazingly short timescale of 12 months.

This paper will describe the design and in orbit performance of the power system, highlighting the decisions taken in order to meet the mission requirements within the 12 month, concept-to-launch program.

The design and construction techniques used in the production of the power system for the nanosatellite, backed up by the success of the mission and the impressive in-orbit performance of the power system, clearly demonstrates how commercial-off-the-shelf technologies can be applied successfully to meet space mission objectives.

1. Introduction

For over two decades, Surrey Satellite Technology Ltd. has lead the world in microsatellite design at the same time pioneering the use of commercial-off-the-shelf (COTS) electronics in space. Surrey's novel spacecraft engineering techniques have been proven time and again, through eighteen 50kg microsatellite missions, one 350kg minisatellite mission and more recently Surrey's first nanosatellite mission.

By applying Surrey's rapid, low-cost method of spacecraft engineering, SNAP-1 (Surrey Nanosatellite Applications Platform – 1) was designed, built and launched within a 12-month period. At the time of writing this paper, SNAP-1 has completed over 1.5 years in orbit and is the worlds most advanced in-orbit nanosatellite.

The spacecraft incorporates subsystems and payloads such as; advanced micro-miniature GPS navigation, on-board computing, cold gas propulsion, a decentralised telemetry and telecommand system, bus receiver and transmitter, a machine vision system with 4 cameras and the ability to inspect other spacecraft in

orbit, an inter-satellite link receiver and an attitude control system which uses magnetorquer rods, a magnetometer and momentum wheel to maintain 3 axis stabilisation. The most astounding thing about the spacecraft is that it weighs in at less than 6.5kg.

In its first year of operation, the spacecraft has accomplished a remarkable number of 'world firsts', including:

- First fully 3-axis attitude stabilised 'nanosatellite'
- First nanosatellite with on-board propulsion demonstrating orbit control
- First in-orbit images of another spacecraft from a nanosatellite
- First successful use of GPS on-board a nanosatellite - used for orbit manoeuvring

As with the rest of the spacecraft, the power system was required to be miniature in both mass and volume, but still provide the same functionality as a power system 10 times its size.

In order to meet the tight schedule imposed on the mission by the already agreed launch date, the power system design is based on the highly successful SSTL microsatellite and minisatellite power systems, but in miniature scale. Commercial electronic, surface mount components are used throughout the power system. Another interesting feature of the power system is that there is virtually no redundancy, a design philosophy almost unheard of in the spacecraft industry.

The SNAP-1 power system has already successfully exceeded its target design life of 1 year and is expected to continue operation beyond June of 2002, two years after the spacecraft's launch.

2. Spacecraft Description

Although this paper focuses primarily on the power system, it is interesting to note the complexity of the spacecraft by briefly looking at the spacecraft subsystems and payloads.

The command and data handling system on board SNAP-1 consists of:

- VHF uplink Receiver (9.6 kbps FSK)
- S-Band downlink Transmitter (38.4 kbps)
- SA-1100 32-Bit RISC OBC (220Mhz)

The Guidance Navigation and Control (GNC) System is perhaps the most impressive feature of SNAP-1 and is responsible for many of the world firsts achieved by the spacecraft. The GNC consists of the following systems:

- 12-Channel GPS Receiver
- 3-Axis Fluxgate Magnetometer
- 3-Axis Magnetorquer Rods
- Single Pitch-Axis Momentum Wheel
- 30 mN, 3 m/s DV Butane Cold-Gas Thruster [1]

SNAP-1 is three axis stabilised and capable of orbit control [2].

The payloads on SNAP-1 are as follows:

- 4 CMOS Video Camera-Based Vision System (Machine Vision System or MVS)
- VHF Spread Spectrum Transmitter
- UHF Inter-Satellite Link Receiver

The MVS is the product of a student project at the Surrey Space Centre and was design to be activated during the separation of the spacecraft from the launch vehicle. The MVS then captured images the launch vehicle (the Russian satellite Nadezhda) and captured the separation of Surrey's other satellite (which was also a payload on the Cosmos rocket). These images are shown in Fig 1.

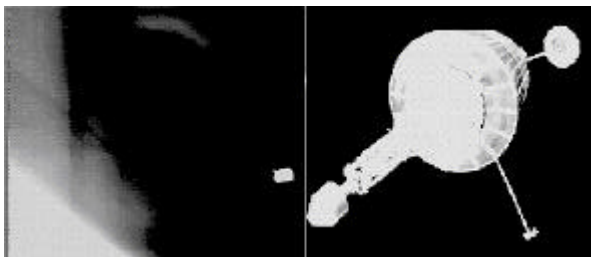


Fig. 1: (Right) Image of Nadezhda (2 seconds after separation)

(Left) Image of Tsinghua-1 and the Limb of the Earth (10 seconds after separation) [3]

3. Power System Description

Primary power to the satellite is supplied via 4 solar panels. The power from each of the four solar panels feed into a dedicated Battery Charge Regulator (BCR) (i.e. one BCR per solar panel). The output of the BCRs is connected to a 6 cell, 1.4Ah 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. See Fig 2 for the power system block diagram.

By isolating the solar arrays from the bus using a BCR per panel suits the low earth orbit environment and the nature of the SNAP design for several reasons:

- Allows the use of differing solar cell technologies and string lengths on each panel.
- The Maximum Power Point (MPP) of an individual panel can be tracked over the changing thermal conditions whilst in sunlight.
- The battery is charged for the majority of the sunlight period resulting in little impact on the overall sunlight efficiency of the power system.
- The direct connection between the battery and the bus provides maximum efficiency during eclipse.

The power system uses only a single string of systems, resulting in no redundancy. Although, a failure of a BCR can result in a graceful degradation of orbit average solar array power, a failure in the PCM, PDM or Battery will result in the loss of the spacecraft. This same redundancy philosophy has been used for all of the SNAP subsystems.

The available power from the solar panels depends on the spacecraft orientation (spin, inertial, nadir or sun pointing). A spacecraft pointing constraint, based on the solar aspect angle, is observed in operations where the spacecraft -z-axis (the nadir face) is maintained at an angle greater than 30° from the sun-vector for any period longer than a small fraction of the orbit period. The solar arrays could be reconfigured on a mission-by-mission basis to tailor the power profile or enhance the power capability.

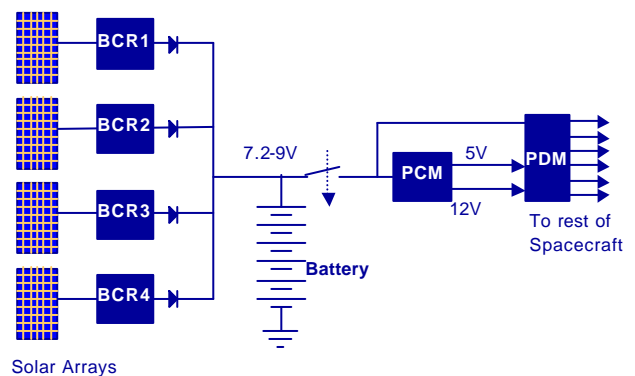


Fig. 2: Power System Block Diagram

3.1 Solar Panels

The four body mounted solar arrays used on the SNAP-1 mission were EEV type single junction GaAs cells. The solar cells are mounted on aluminium face

sheet aluminium honeycomb substrate. The cells provide approximately 19% conversion efficiency. The solar panels were configured as follows:

- 2 panels with 2 strings GaAs/GaAs 4 x 2cm.
- 1 panel with 2 strings of GaAs/Ge 4 x 2cm.
- 1 panel with 1 string of GaAs/Ge 4 x 4cm.

All four solar panels used 16 cells in series to provide a nominal solar panel voltage at MPP of approximately 14.5V and a power level of 6.5W per panel (at AM0 and 25°C). The peak power is around 10W from all panels combined.

The SNAP-1 solar panels are the last panels to be produced at EEV (UK) Ltd (now known as Marconi Applied Technologies). Surrey Satellite Technology Ltd has since acquired the intellectual property rights and relevant equipment from Marconi Applied Technologies and now produces solar panels in-house.

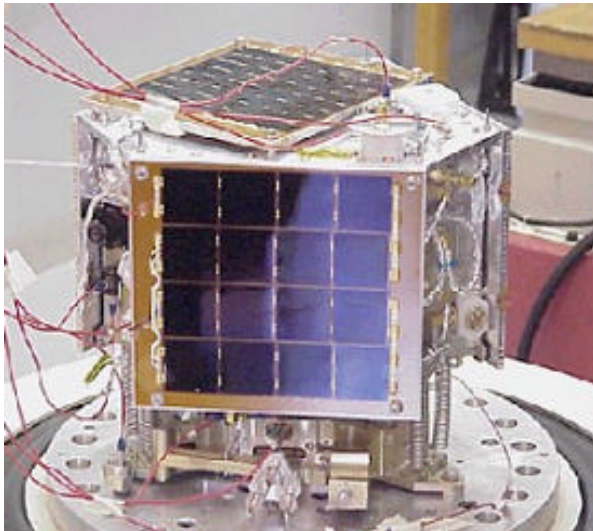


Fig. 3: SNAP-1 at vibration testing. EEV 4x4cm GaAs cell 6.5W solar array in foreground.

3.2 Battery

SNAP uses a single battery that consists of six SANYO KR-1400AE cells in series and has a nominal voltage of 7.2 to 9 V (depending on state of charge). The KR-1400AE is an "A" size cell from the SANYO Cadnica 'Extra' series of cells. These commercial cells were subject to a comprehensive set of mechanical and electrical tests and match to produce the flight battery [4].

Each KR-1400AE has a mass of approximately 31g, this coupled with an estimated carrier mass of 40g, results in a complete battery mass of approximately 225g. The energy to mass ratio is therefore 45Whr/kg.

The battery is designed such that it is capable of being used if a future SNAP requires to be launched from the shuttle payload bay.

3.3 Battery Charge Regulators

The SNAP BCR is based upon the microsatellite BCR, but has been downsized to a rating of 10W. The BCR is a low power BUCK topology DC-DC converter. There are four BCRs in total, one dedicated to each solar array, stepping down the 14 V from the solar arrays to the 7.2 V unregulated bus. The BCRs are housed in the same module box as the battery for ease of connection.

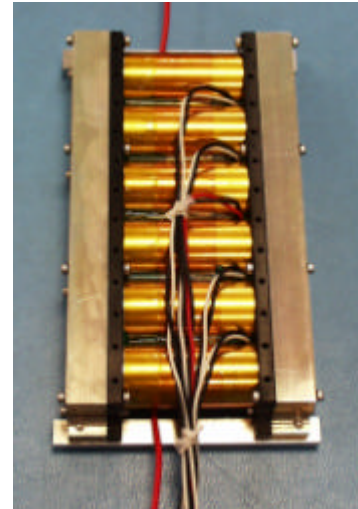


Fig. 4: SNAP-1 Nickel Cadmium Battery

Each BCR is self-sustaining and does not rely on the battery to power their operating circuits. This is a safety feature to prevent a complete discharge of the battery killing the mission.

The BCRs operating frequencies are not synchronised together but are instead separated by 15 kHz to prevent beat frequencies interfering with sensitive RF systems such as the receiver. The nominal switching frequency of the BCR is 200kHz.

The BCR makes use of low profile EFD20 inductor cores, a low RDS(on) surface mount power MOSFET (IRF5305S) and CTC21E solid tantalum capacitors to reduce the footprint and increase the system performance.

An estimate of the solar array 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-life characteristics of the arrays are supplied by the array manufacturer.

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 watchdog 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. The efficiency of the BCR varies from 73% to 88% depending on the Input Power. The BCR has a maximum output current of 1.5A.

The BCR was also designed to accommodate a Li-ion battery without the need for modifications to the electronics.

3.4 Power Conditioning Module

The Power Conditioning Module is a BUCK DC-DC converter and provides a regulated 5V supply, and a semi-regulated 12V from the raw battery voltage. The switching frequency of the PCM is 270kHz and the maximum output current is 3A.

The PCM provides deep discharge protection to the battery by shutting OFF when the battery voltage falls below approximately 6.2V and permitting the system to come back up again once the battery has recovered to a voltage of 7V. This safety feature is used as a fail-safe in the event that the safety task running on the On-board Computer fails.

As with the BCRs, the PCM makes use of low profile EFD25 inductor cores, a low RDS(on) surface mount power MOSFET (IRF5305S) and CTC21E solid tantalum capacitors.

The PCM has a maximum efficiency in excess of 90%.



Fig. 5: The SNAP-1 Power System under test.

3.5 Power Distribution Module

The power distribution module consists mainly of MOSFET based power switches. These are of a

similar design to the FET switch design as used on current microsatellites. The switch design is based on a previous microsatellite power switch and has been miniaturised using surface mount technology. The same switch design is used for regulated 5V, unregulated 12V and raw battery power distribution. By using P-channel MOSFETs with a very low RDS(on) of about 20m Ω (IRF4905S), the switch provides a highly efficient and proven interface to subsystems and can easily be configured to 'trip' at the required current level.

Essential systems such as the receiver are connected via a fuse during ground tests and then hardwired prior to launch.

3.6 Telemetry and Telecommand Interface

CAN (Controller Area Network) microcontrollers on every module provide a serial bus interface through which system telemetry data can be monitored and telecommands can be issued. Due to the high number of telemetry channels on the power module, there is a need to interface the signals to the CAN microcontroller via an analogue multiplexer. The telemetry channels on the power system include:

- Solar Array Voltage (one channel per solar array)
- Solar Array Current (one channel per solar array)
- Solar Array Temperature (one channel per solar array)
- Battery Voltage
- Battery Current
- Battery Temperature
- PCM Input current
- Subsystem current monitor (one per power switch + VHF Receiver 'fused' line = 15)

There are a total of 32 telemetry channels on the power system.

As mentioned previously, telecommands are issued via the CAN serial bus through CAN microcontrollers in each module. The telecommands on the power system are as follows:

- PDM Power Switch ON/OFF Commands (One per power switch or power switch pair [i.e. each module is provided with 7.2 V and 5 V]).
- BCR Computer Control Enable

There are a total of 8 telecommand channels on the power system.

4. Power System Packaging

During the mission definition, the power system was allocated two 170mm by 122mm module boxes, each with a depth of 20mm, to accommodate both the power system electronics and battery.

Having designed a method of retaining the nickel cadmium battery with a minimum of extra mass and volume, the amount of area available for the PCB could then be determined. This resulted in a half module sized board in the module box that housed the battery and a full sized board in the remaining box. The two PCBs are linked together using flexi-PCB technology. This is shown in figure 6.

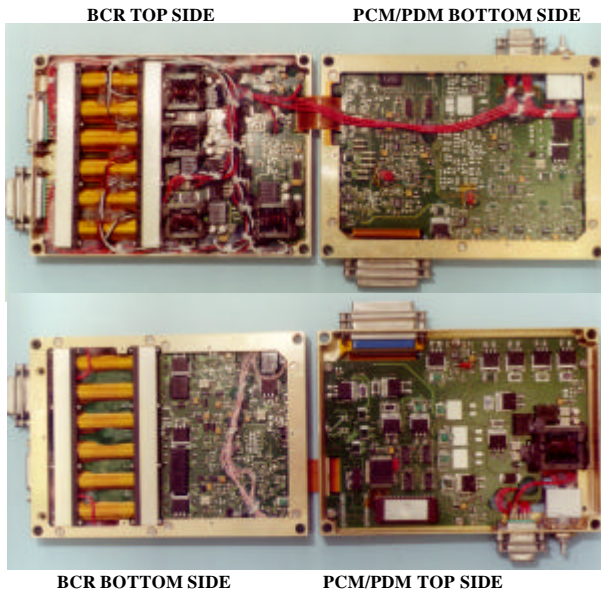


Fig. 6: Front and Rear views of the SNAP-1 Power System.

At this stage, the interfaces to the power system module were also defined. These included the solar array connections (two 15way D-types on the left hand side of the box), connections to the SNAP subsystems and payloads (44 way D-type connector close to the centre section of the module) and the 9-way D-type safe-arm and environmentally sealed activation switch (shown on the right hand side of the picture).

It made sense to house the BCRs and battery telemetry electronics on the half PCB due to this being closest to the battery and solar array connections. The four EFD20 inductors of the BCRs can be seen on the 'top side' picture and the surface mount MOSFET and capacitors on the bottom side. It was necessary to fully use both top and bottom sides of the PCB to fit the circuits in such a small area, highlighting the packing density advantages of using surface mount technology.

The larger PCB was used to house the PCM, all of the power switches and the CAN microcontroller. The PCM accommodates the right hand side of the PCB as shown in the picture (note the EFD25 inductor on the top side and MOSFET on the bottom). The CAN microcontroller sits in the bottom left corner of the PCB (note the aluminium tape covering the EPROM). The MOSFETs for the power distribution switches can be seen covering the remainder of the PCB surface. As

with the BCRs, it was necessary to use both sides of the PCB.

Once fully assembled, the PCM/PDM box is folded over on top of the BCR/battery box and secured into position. This results in a single power box housing all of the power system electronics (including the telemetry and telecommand interface) and power storage. The fully assembled box weighs less than 1kg and is shown figure 7.



Fig. 7: Fully assembled SNAP-1 Power System in final configuration.

5. In-Orbit Performance

Since its launch in June 2000, SNAP-1 has completed approximately 8000 orbits and therefore, in the region of 8000 charge discharge cycles of the battery. Considering that the cells used in the battery have never flown in space previously, nor had there been time to perform sufficient life cycle testing, the SNAP-1 nickel cadmium has performed admirably. The depth of discharge of the battery often exceeds 25%, and is subjected to operating temperatures that are not pertinent to maximising the expected life time of the battery.

The housekeeping Whole Orbit Data-file (WOD) from July 2000 (figure 8) shows that the battery is in good health. The BCRs charge the battery following the spacecraft's exit from eclipse. Once the end of charge voltage is reached, the BCRs clamp the voltage at this level and the battery charge current naturally decreases to a trickle charge level of 150mA. It can also be seen that the battery voltage set point of the BCR (which is temperature compensated) varies as the battery temperature increases over the sunlight period.

Figure 9 shows a more recent WOD taken from December of 2001. The battery temperature has increased significantly over the six-month period,

mainly due to the spacecraft orientation (i.e. the battery side of the spacecraft is now sun pointing). It is suspected that the elevated temperatures are taking their toll on the battery, resulting in a decrease in the available capacity. The battery, however, still maintains a voltage of 7.2V or more at the end of the eclipse period, indicating that the cell voltages also stay above their nominal level of 1.2V per cell. It is expected that the SNAP battery will provide a further 6+ months of operation for SNAP-1, doubling the spacecraft's original life expectancy.

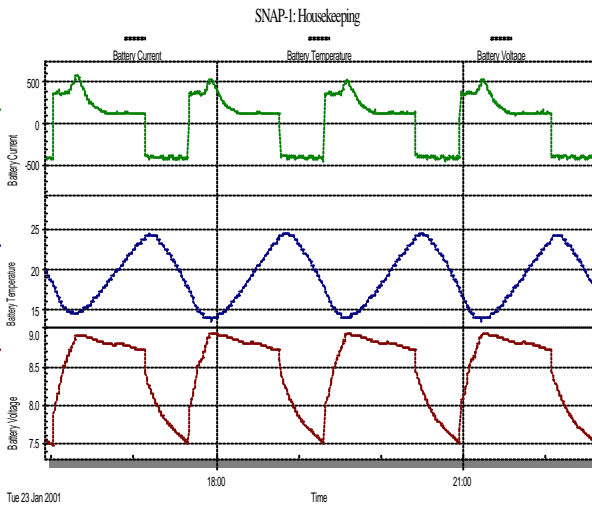


Fig. 8: Battery Telemetry from January 2001

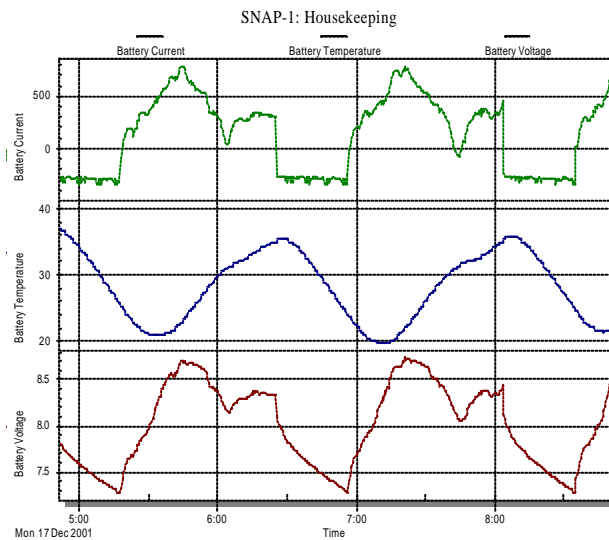


Fig. 9: Battery Telemetry from December 2001

It should also be remembered that the power system has no redundancy, and has encountered no problems or failures to date. This is also the case with the solar arrays, which have shown little degradation in performance over the spacecraft's 1.5 years of operation.

6. Conclusion

In producing a spacecraft power system from concept to launch in the space of 12 months, Surrey Satellite Technology Ltd. has demonstrated what is possible when working in small teams of highly motivated, experienced engineers.

SNAP-1 has also taken Surrey's use of commercial off-the-shelf components, for the first time flying a wholly plastic component spacecraft. Not content with using all COTS, Surrey also decided at an early stage in the programme not to build any redundancy into the spacecraft. Surrey's faith in commercial technology in space is born of over 100 orbit years of heritage using plastic components, and it was no surprise to the engineers at Surrey when SNAP-1 performed so exceptionally well.

The space industry in general has doubted for many years the usefulness of micro and nano sized spacecraft. The success of the SNAP-1 mission in particular has changed the attitude of many in the space industry surprised the space industry in general, and there are now many more SNAP based mission planned over the coming years. SNAP subsystems, including the power system, have already contributed to success at the USAF Academy in Colorado Springs and will form the bus systems for their planned Falconsat-2 mission in 2003.

7. REFERENCES

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