ESA’s fleet of four Cluster satellites was launched in 2000 to investigate the magnetic interaction between the Sun and Earth. Designed to last 3 years, the mission has now been extended to the end of 2009. But the batteries of the satellites are well beyond their design lives and are starting to fail – the power situation first became critical during the long eclipses in September 2006. The battery aboard one could not power the heaters or computer, so new options had to be developed to avoid dangerous low temperatures and to regain control after each eclipse.

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The batteries that power the satellites during eclipses are clearly the most critical units. It was evident they would fail before the end of the extended mission and that Cluster would have to find ways to survive eclipses without electrical power. The satellites would be without onboard amplifier and propellant pipes could cool too far and the computer would require recovery after each eclipse. With 4 years’ operational experience, the Flight Control Team in ESOC was confident that the satellites could be operated during eclipses using only a fraction of the power supplied by the Spacecraft User Manual. However, there was the concern that, under certain circumstances, the command decoder might not restart correctly after power-generating solar cells. Each year, there are short eclipses of 15–40 minutes around the orbit’s perigee in March and long eclipses around apogee in September. The three or four long eclipses each last about 3 hours.

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Preparations

The Flight Control Team held regular discussions with industry and ESTEC experts to come up with new approaches, and in 2004 a strategy to prolong the battery lives was in action. Meanwhile, the team concentrated on adapting the power, thermal and data-handling operations. Individual treatment of the 20 batteries, warming the satellites, recovery from all low-power situations, and rules to allow fast decisions when necessary. Months before the eclipses, a ground station plan was prepared to enable real-time contact with the satellites at the start and end of each eclipse. Extra ground stations – Kourou (French Guiana) and the deep space antenna in New Norcia (Australia) – were prepared for Cluster.

Working with Aged Batteries

During eclipses, each satellite is powered by five silver-cadmium batteries. In the early 1990’s, when Cluster was designed, these were the only non-magnetic batteries available (as Cluster’s instruments were intended to measure magnetic fields, the internal fields had to be minimized). Their short lifetime of typically 2.5 years is limited by the amount of cadmium, which is gradually dissolved by the aggressive electrolyte. The lives are also limited by mismatch between the individual cells of a battery building up over time. On Cluster, the Battery Realignement Facility reduces this mismatch by discharging each cell individually. Monitoring by the computer also checks the batteries, preventing over-charging/discharging, which can generate gas. Since 2004 two strategies have been used to extend the batteries’ lives: the satellite temperature has been lowered, slowing the rate that cadmium is dissolving, and all the batteries have been completely discharged and left unused for months at a time. The associated risks were accepted because these measures dramatically reduce the rate of deterioration. By April 2006, 16 of the 20 batteries were still operational but their capacity had halved. Three had cracked cells and leaking gas and electrolyte had caused small orbit changes. To minimise the risk of further cracking, the performance of all the batteries was being monitored individually. To decide on the approach for each satellite it was important to forecast battery behaviour: how much energy could each store and provide? The measurements taken in April after the short eclipses could not be relied on months later for such aged batteries. Measurements taken when the batteries were brought out of empty storage in September would have been too late. Procedures for all the possible cases had to be prepared in advance.

New Power Scenarios

The main problem was with Spacecraft 1: three of its five batteries had been declared ‘non-operational’. Two had cracked and one had a suspected ‘failed cell’. The energy drawn by the satellite’s units that cannot be switched off was more than could be stored in the remaining batteries. Tests on the three non-operational batteries, looked for any way to bring them back to life. The results were positive: two could be used with some constraints. Even with these results, the situation for this satellite remained critical: one battery non-operational, two requiring precautions, one showing a large internal electrical leakage and the only ‘healthy’ battery had low capacity. Altogether, the capacity was around 12 Ah (4 A for 3 hours). This equated to 45 W available for the subsystems, whereas 92 W would normally be required during an eclipse, even with the payload, transmitter and all other non-essential units switched off.

The problem was clear: either find ways to reduce the consumption to a level the batteries could handle, or they would run flat and the satellite would shut down, and possibly die. Operating the satellite with critical systems switched off had never been considered before and it was not covered by either the Spacecraft User Manual or Operating Procedures. It was time to think ‘outside the box’. The first step was to switch off the data recorder and to disable all heaters, leaving only the computer powered. This reduced the average consumption to 75 W – still too high. The only other load that could be switched off is the computer. The others are permanently connected to the power bus. These ‘non-switchable’ loads are the main and redundant receivers and decoders that handle commands from ESOC, and the power unit, which conditions, controls and distributes the power. With the computer off, the power needed was finally around the target value of 45 W.

If it turned out before an eclipse that the available power would be less than 45 W, then only one option remained: disable ‘battery discharge’ after the eclipse began, instantly shutting down the entire satellite. This ‘power-down’ strategy would protect the batteries from cracking and reserve their energy for use during the restart after leaving eclipse.

Keeping the Satellite Warm

Given that the power shortage had serious thermal implications and considering the increasing battery mismatch between the satellites, Markus Pietras began studying the problems for his Masters Thesis at Darmstadt University. The effects of different heating strategies were studied using an existing computer thermal model, updated with flight data, and a new model developed for this Thesis.

As the satellite cools down during eclipse, the most critical items are the transmitters’ High Power Amplifier (HPA) and the propellant pipes. The HPA might be damaged if it drops below –30°C and the oxidiser might freeze if the pipes drop below –12°C.

In sunlight, the solar array generates more electrical power than needed for the instruments and subsystems, so the excess is used to regulate the temperature of the Main Equipment Platform (MEP). Enough power to maintain the MEP at about 15°C is directed into a network of heaters. During eclipse seasons, more power can be made available for heating only by switching off other units. During eclipses, the HPA and propellant pipes are protected from getting too cold by three heaters that turn on when the temperatures drop below set values. The 80 W drawn by these heaters is a large burden on the weakened batteries, so in previous years their activation was delayed by pre-heating the spacecraft to 20°C before each eclipse. The extra power was made available by switching off the HPA and propellant pipes. In 2006, with the batteries of Spacecraft 1 even weaker, these heaters could not be used. To prevent the satellite from getting too cold it needed to be pre-heated to more than 22°C.

The orbital period of 57 hours allows 24 hours between eclipses to charge the batteries and to warm the satellite. The solar arrays do not provide enough power for simultaneous heating and charging, so the MEP temperature was allowed to drop below set values. The 80 W drawn by these heaters was a large burden on the weakened batteries, so in previous years their activation was delayed by pre-heating the spacecraft to 20°C before each eclipse. The extra power was made available by switching off the HPA and propellant pipes. In 2006, with the batteries of Spacecraft 1 even weaker, these heaters could not be used. To prevent the satellite from getting too cold it needed to be pre-heated to more than 22°C.

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The orbital period of 57 hours allows 24 hours between eclipses to charge the batteries and to warm the satellite. The solar arrays do not provide enough power for simultaneous heating and charging, so a ‘cold reserve’ of batteries were charged for the first 30 hours after eclipse, leaving the rest for the heaters to warm the spacecraft.

By September 2006 several batteries on spacecraft 1 showed such large differences that these could not be used; a large part of the energy in the batteries would leak away while the MEP was being heated. Conversely, if the satellite were heated during the first 24 hours, it would then have 30 hours to cool while the batteries were charging. Another solution was needed.

Propellant Tanks as Thermal Capacitors

Whereas there was no way of storing enough electrical energy, perhaps it
In the new pre-heating strategy, heat stored in the propellant tanks frees the time for the batteries to be charged close to the eclipse.

Critical operations in the Cluster control room

The priority strategy is calculated with conservative margins. The strategy is as follows:

1. Maintain power to the decoders. All other units would be powered down in preference to losing power to the whole satellite during an eclipse and thereby risking loss of command from the decoder.
2. Protect the batteries. New monitoring schemes were introduced to ensure that batteries were neither over-charged nor over-discharged.
3. Turn off the computer. The computer could not be monitored, so battery predictions should always be calculated with conservative margins.

These priorities and Flight Rules superseded those previously laid down in the Spacecraft User Manual and Flight Operation Plan. They were approved by the Cluster Project Management shortly before the start of the eclipse season.

The uncertainty in the capacity predictions and the need to be prepared for the worst case meant that new procedures had to be ready for all three power options (heaters-off, decoder-only and power-down) on all four satellites. As the new procedures took shape, they were approved by experts and industrial partners before being tested on the Cluster Simulator. The new procedures worked well and there was a growing optimism that they would bring the satellites safely through the eclipses. But the true test was still to come.
could be done for thermal energy. Previously, pre-heating concentrated on warming the MEP, but perhaps heating other ‘thermal masses’ could be a more effective way of keeping critical units warm.

Each Cluster houses six propellant tanks, weighing 6 kg each and currently containing a total of 50 kg of oxidizer and fuel. The tanks are well insulated and have 40 W of heaters. The thermal models suggested that any heat stored in the tanks could buffer the temperature of the rest of the satellite.

Tests on the flying satellites were encouraging: the tanks could be heated from 16°C to 35°C in 24 hours and the insulation was just right to store the heat and release it slowly into the rest of the satellite during the eclipse. This would be enough to slow the temperature drop of the HPA and propellant pipes, keeping them above their critical temperatures.

Operating Without a Computer

It was clear that Cluster’s 1’s battery situation required the decoder-only configuration. However, given the fragile state of the batteries, the Flight Control Team had to be ready to switch to the power-down option at short notice. Even if power-down was not used in 2006, it will be needed some time after the eclipse season. The return of power also triggers the System Reconnection Logic (SRL), automatically turning on the computer, activating the batteries and turning on thermostatic heaters. As the satellite is cold, the heaters may try to draw more power than is available, causing the voltage to collapse and triggering a restart of the computer. This might repeat several times until enough power is available.

The decoder problem is considered unlikely, but its consequences would be far more serious than the other potential problems. Whenever possible, the decoder-only option should be used, even if this means operating the batteries without monitoring. Unlike power-down, the SRL would not trigger, allowing the Team to choose when and how to turn on the computer after the eclipse.

Flight Rules and Procedures

In addition to preparing for all the possible operating scenarios, the Flight Control Team also needed a set of rules to decide which to choose for each eclipse. The priorities for maintaining the health of the satellites were defined:

**Priority 1**: maintain power to the decoders. All other units would be powered down in preference to losing power to the whole satellite during an eclipse and thereby risking loss of commands from the decoder.

**Priority 2**: protect the batteries. New monitoring schemes were introduced to ensure that batteries were neither over-charged nor over-discharged. With the computer off, the batteries could not be monitored, so battery predictions should always be calculated with conservative margins.

**Priority 3**: maintain critical units within thermal limits. Pre-heating the MEP and propellant tanks should follow the thermal-model predictions. Any additional power requires powering down the payload and other non-essential units.

These priorities and Flight Rules were used to establish Flight Operations.

**Eclipse Operations**

Before each eclipse, the batteries’ latest parameters were compared against requirements and the rules were invoked to decide which option should be followed. In all cases, the batteries were stronger than expected. Spacecraft 2, 3 and 4 adopted standard strategies for all the eclipses. For Spacecraft 1, the decoder-only option was used, avoiding the feared command lock-out.

The satellites are separated by 10 000 km so did not all experience eclipses on the same days. Fifteen eclipses were spread across 12 days. The first orbit saw an eclipse only for Spacecraft 2, the coldest but with the strongest batteries. The second orbit had eclipses for 12/23/4. The only day when all four were eclipsed was 15 September, beginning with #1. The Team was still refining and testing procedures on the Simulator right up to this day.

Then, while part of the Team took care of the others, a Tiger Team prepared #1 for its first eclipse. Some 30 minutes before it began, they used high-level commands processed by the computer to switch off all the satellite systems one by one, until only the transmitter and the computer remained.

As the computer is required to process high-level commands, the System Reconnection Logic (SRL) was not enabled. Once the computer was switched on, the decoder-only option was used, avoiding the feared command lock-out.

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the commands to turn off the transmitter, it was left until last. By then, of course, the transmitter was off and all signals from the satellite had ceased. Then, although it contradicts accepted practice, the low-level commands to turn off the computer were sent in the blind, with no way of confirming that the commands had been executed. These commands were distributed directly to the power switches and did not need to be processed by the computer. Spacecraft 1 was now in ‘sleep mode’, ready to enter the Earth’s shadow a few minutes later.

After 2.5 hours, as Spacecraft 1 exited the eclipse, it was time to switch on the computer and recover the satellite. The low-level commands to turn on the computer were sent, again in the blind. Allowing time for the computer to boot, the high-level commands were sent a minute later to turn on the transmitter. A few more nail-biting seconds and an alarm sounded on the control system – a signal from the satellite, woken from its hibernation!

But there was no time to relax. The team had only 2 hours’ contact time to restore the satellite to its normal configuration and load the commands to prepare for the next eclipse. Some 50 hours later, the operation was repeated for the second eclipse and then again for the third, until finally the most critical and stressful operations since Cluster’s launch were completed!

Although the focus was on Spacecraft 1, the team also managed the eclipses for the other three. Fortunately, they behaved as predicted and there was no need to resort to the special strategies.

**Conclusion**

With the pre-heating, none of the satellites’ units reached critical temperatures. In fact, the effect of using the tanks as heat stores was greater than expected: the temperatures at eclipse exit were above expectation.

The groundwork was also laid for future eclipse operations:
- a new strategy for heating the satellites was developed and validated;
- the decoder-only configuration was validated;
- the procedures for the power-down scenario are ready for use if they are ever needed.

One major uncertainty remains with the command decoders – will they function after a power-down eclipse? The answer will come in September 2007 when the worsening situation will demand that approach.

**Acknowledgements**

The authors thank the experts who contributed to the discussions and the development of new strategies, drawing on their knowledge from the Cluster design, integration and test phases: G. Lautenschläger and H. Sondermann (Astrium), and T. Aielli (AAS-I Laben). The time-critical operations during the intensive eclipse season would not have been successful without the excellent support provided by the ESTRACK operations teams at ESOC and the ground stations and the dedication of the entire Cluster Flight Control Team.