USING TIGHTLY COUPLED ELECTRICAL/THERMAL MODEL AND A NOVEL POWER CONDITIONING AND DISTRIBUTION UNIT TO MANAGE THE ONBOARD POWER

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1 ABSTRACT

Using models to develop mission planning can be helpful and relevant for satellite and balloon missions. Simulating parameters such as temperatures at critical thermal nodes, at solar arrays and by using batteries that handle large temperature ranges it is possible to take advantage of excess thermal and electrical energy to reduce thermal management needs during eclipse.

Strateole-2 missions use pressurized spherical balloon drifting for up to 3 months at altitudes between 18 and 20km. This environment is cold and the day-night cycle requires energy production and storage onboard.

Heating is required to maintain the gondola functions in the cold. During the day sun power provides heat and electrical energy for systems, excess power is stored in batteries. Heaters are dimensioned to electrically heat the internals above normal temperature when the battery is full. Then run for as long as possible without heating at night using the thermal mass and lowering the temperature that trigger heating. At sunrise, power is used to re-heat internals to a normal value.

The simulation demonstrated the validity of the process, leading to an implementation with sufficient thermal and electrical margins. During mission, observations on all balloons were made that validated the simulation.

2 THE STRATEOLE-2 MISSION

On November 11th 2019 the first balloon of the Strateole2 campaign was released from Mahé airport in the Seychelle archipelago. Over the next month 7 other balloons were released with a wide variety of scientific instruments hanging from it, their purposes are: water vapour analysis, chemical analysis of aerosols, cloud detection using a nadir LIDAR, ozone and CO2 measurements, air temperature measurement via GPS radio-occultation, measurement of upwards infrared flux, as well as atmospheric temperature sounding on a 2km high column using a fiberoptic thermometer unspooled below the gondola.

Each balloon's mission was set to last up to 3 months and fly in the lower stratosphere, circumnavigating the planet all around the equator in the intertropical zone.

The eight balloons of the first mission accumulated 680 days in the air. With an average of 85 days each and a maximum flight duration of 107 consecutive days. Flights were terminated by separation of the balloons from the gondolas over safe areas (deserts and oceans). Their recorded tracks are shown on Figure 1.

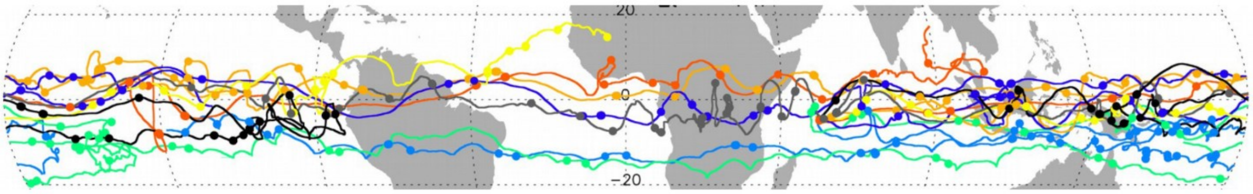

Figure 1: Flight trajectories for the 2019-2020 campaign [1].

In 2021, between October and December, a second mission of this type was sent from Mahé with this time a set of 17 balloons released

The third and last part of the Strateole-2 mission will happen in 2024, between 20 and 25 balloons should also be deployed.

Strateole-2 data will help improve the understanding of the global climate.

Once released, balloons quickly ascend at 6m/s into the lower equatorial stratosphere where they will harvest scientific data for up to 3 months. Chemical analysis of gases, temperature and pressure records as well as the position of the balloon is used to study certain climatic phenomena with the participation of many meteorology institutes from the USA and France. Wind measurement was extrapolated from the displacement of the balloon in the atmosphere. These windspeed measurement were also used during the calibration campaign of ESA's ADM Aeolus satellite used to record wind speeds.

Bringing a payload this high in the atmosphere brings its fair share of challenges. At altitude, the temperature of the air is between -86°C and -60°C, this may cool any exposed equipment therefore the gondolas are mostly made out of polystyrene for its isolation characteristics. Temperature reference points recordings during the mission demonstrated that the internal equipment only varied between -30°C and +45°C, never reaching any critically dangerous temperatures thanks to heating and thermal isolation.

Handling an unmanned aircraft above civil aviation flight altitudes also brings a few constraints. During takeoff, then altitude gain and finally the descent, the aircrafts are in controlled airspace. FL600 or 60000ft/18.2km ASL is a typical ceiling for civil aviation airspace. Entering into controlled airspace requires the activation of safety systems such as radar transponder (mode-S) and position lighting.

During the whole mission, controllers in Toulouse (France) can use 2 actuators to pilot the aircraft: ballast (composed of 1mm-wide steel balls) can be released and valves can help reduce the pressure of helium in the balloon's envelope.

Each flying ensemble is composed of 2 to 3 main elements:

- The balloon is a pressurized sphere filled with helium. Its diameter ranges from 11 to 13m depending on the mission and load.
- The EUROS housekeeping gondola is developed by CNES and holds mission and safety critical elements such as radar transponder, position lights, pyrotechnic controller, satellite navigation system and satellite communications, as well as renewable energy production. The criticality of these functions means that redundancy is necessary and a reliable power system is required. EUROS also hosts environment sensors for temperature and pressure onboard. This gondola weights about 13kg.
- The ZEPHYR gondola is a payload that holds scientific equipment such as spectroscopes, atmospheric sounding equipment and other environment sensors. It weights 22kg. Both gondolas are independent, this means that ZEPHYR has its own means of communication and power system. For simplicity, the power system is based on EUROS' MC2 and have the same solar cell and battery technologies, reducing development costs, testing and expertise.

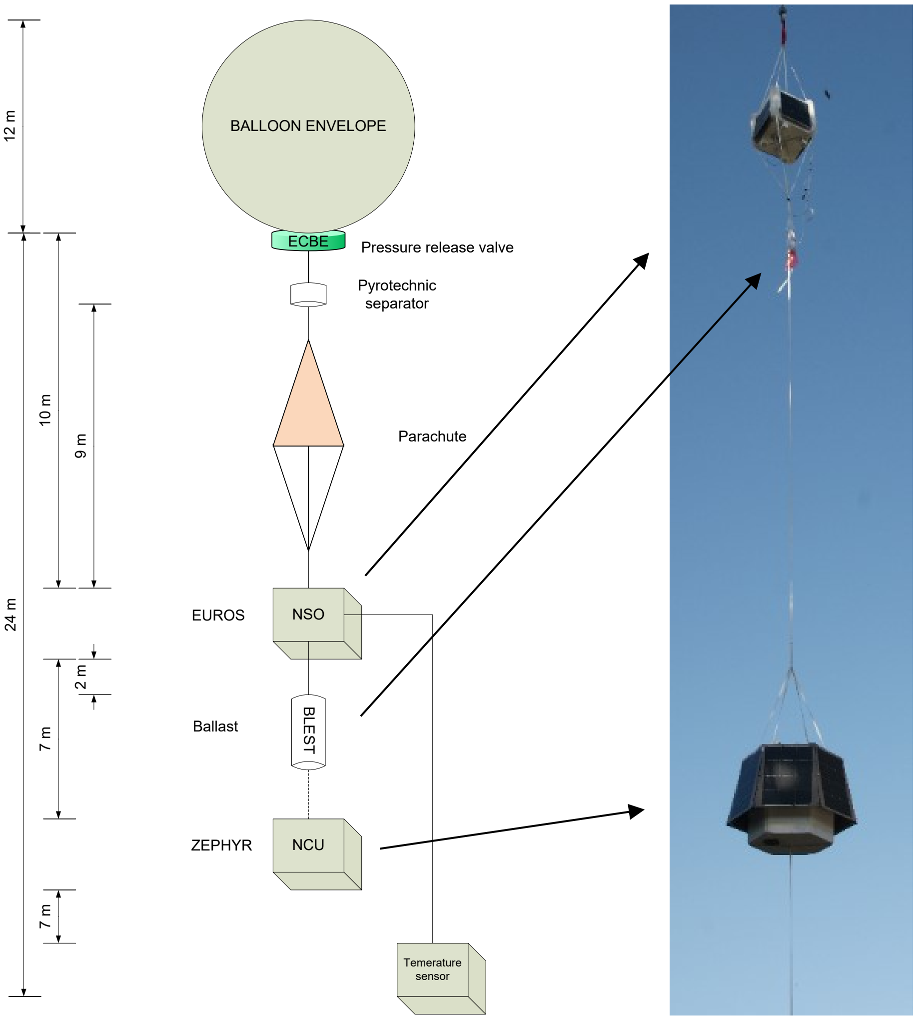

Figure 2: Overview of the full aircraft and photograph of the gondolas (EUROS on top and ZEPHYR at the bottom)

3 AVIONICS AND ELECTRICAL ARCHITECTURE OF THE PILOT GONDOLA

The rest of this paper will focus on the EUROS gondola as it drove requirements for safety and reliability of the whole system. Elements of EUROS are used on ZEPHYR, the scientific gondola but will not be described as much here. However, the close proximity of needs between the two systems (approximate mass / power consumption / identical environment) meant that a global approach was simpler.
Because of its duration, the mission requires the use of renewable energy thus a new power system was designed and used. It is composed of 4 subsystems that can be tailored to suit mission requirements between EUROS, ZEPHYR and potential later missions. The solar panels can be of various sizes (9-cells and 12-cells configurations have been flown depending on the power needs of the gondola). The MC2 is also compatible with 4-panel gondolas (EUROS type) and 6-panel gondolas (ZEPHYR-type). These will translate into a peak power extracted from the solar array of 65W for EUROS (4-panel gondola with 9-cells each). For ZEPHYR, the theoretical power available is about 120W (6-panel gondola with 12-cells each).
The battery capacity can also be dialed between 200W.h (EUROS-type) and 450W.h (ZEPHYR-type). Both have been flown using cells suitable for extreme temperatures.
At last, the “Communicating Conditioning Module” (MC2) is tying the whole power system by doing Maximum Power Point Tracking (MPPT) on up to 6 different solar panels, Li-Ion battery management and autonomous thermal control of the battery. This module can then safely distribute the power to subsystems as its outputs are protected by independent programmable Latch Current Limiters.

MC2 controls the Li-Ion battery safe charge through PWM regulators with current and voltage limiter. The battery active thermal control is autonomously handled by MC2.
Because MC2 is not redounded, a set of electrochemical cells is also added. They ensure mission critical systems have guaranteed power for at least as long is necessary for a safe separation and descend back to earth (using pyrotechnic separator, radar transponder and position light).

The main design drivers of the MC2 module are mass, costs and efficiency. A CAN Bus between MC2 and the OnBoard-Computer allows to have commandability and observability of MC2. The overall avionic gondola is designed to be Single-Point-Failure free by using two segregated chains to be compatible with safety rules. This overall architecture allows both chains to be designed without SPF free constrains.

The main innovation with MC2 is the way the converter is used: the MPPT algorithm is run at the output of the converter. This MPPT extracts maximum power of both solar panel and power converter. The power converter efficiency and solar array characteristics are taken into account by this Maximum Power Point Tracker. The main advantage is that this MPPT uses only one sensor (output current of boost converters) instead of using current and voltage sensor of solar panels. Safeties are added to avoid damaging the battery. Overcurrent protections at the battery input and charge current regulation are derived from the addition of all currents produced by the boost converters. There are other protections on the battery and PCDU against thermal overload, overvoltage and low temperatures depending on the time of day.
Because the gondola is in a cube shape with 4 solar panels on its 4 sides, no two opposite sides may see the sun at one time. It is therefore not necessary to use 4 separate converters. It was decided to design a multiplexer that allows to select between two opposite panels and feed their current into only two converters. Once every 60s the MPPT switches this multiplexer to try and see if a more optimal power point can be found on the opposite side.
The MPPT itself is finding the best power point on one panel by scanning the whole duty-cycle state space and saving the value giving the best current output to the converter to fulfill the current need of the system.

When the maximum power point is found the MPPT algorithm raises a flag signaling that it is locked for the next 30 seconds on that converter duty cycle.

From the current output of the converters and the status of the MPPT algorithm, the MC2 is capable of estimating a "time of day" status. It will be used to manage the rules for battery charge regulation and the rules for heating the battery as well as the content of the gondola.
In the "Day" mode, the converter is trying to regulate the current going to the battery to charge it the fastest.
In the "Night" mode the converters is scanning all solar panels to try and find the one that will deliver any electrical power sufficient to go into "Day mode".
In the "End of day" mode the converters stop to regulate the converter output current but rather regulates the battery voltage to converge on the full charge voltage. This mode also starts the battery heater to extract excess power available.

"Day" is the default mode, the PCDU goes into "Night" mode whenever the total produced power at converter output is below a threshold, and goes out of "Night" mode when this power goes up.
To go into "End of day" mode, the PCDU have to detect that the battery is charged above a threshold and will go out if the battery voltage goes down.

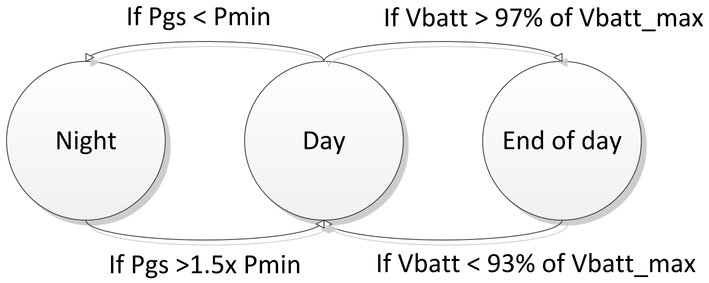

Figure 3: Mode diagram for heater and battery regulation management

The battery was selected for its extended temperature range. Saft's MP176065 XC (Figure 4) limits are that no charging is allowed below -30°C and discharge is impossible below -50°C. This means that as long as the temperature is above -30°C the system can charge and discharge itself correctly only with a heightened Equivalent Series Resistance on the battery causing some performance losses at low temperatures. Between -30°C and -50°C it is impossible to safely charge the battery. However the system may use its own power to heat itself up to at least -30°C to start recharging. And at last, if the battery goes below -50°C, the system is safe as backup electrochemical cells are used to terminate the flight in a regular manner.

Figure 4: Saft's MP 176065 XC rechargeable Li-Ion cell for extremely cold environment

4 USE OF THERMO-ELECTRICAL COUPLED SIMULATION FOR MISSION PLANNING

During mission's preparation period, a thermal model was devised that would couple the thermal representation along with the electrical model of the system using Simulink.
At first a typical thermal model was done using 3D modeling. It took into account the typical altitude temperature's worst-case, the infrared flux coming from the ground and the flux comping from space and sun. The model was also completed with a simulation of the electrical system and heaters inside. Simulating the systems means that the heat produced when powering the transponder or discharging the battery will increase the temperature inside the enclosure as it would do in the real system. Simulating the smart heaters inside also means that excess solar energy that may not charge the already full battery may be used to run the heaters and increase the inside temperature.
Figure 5 is one of the output of this simulation, the temperature at the node of the battery during a full day – night cycle. At the start of the day (1), the sun on the horizon is providing maximum power to the solar cells and heating the surface of the gondola. Because the temperature is too low for day-use the heaters are active and the temperature sharply rises up to (2). At that point the thermal regulation stops heating for a short while and regulates the temperature between -25°C and -20°C.
After (2) the battery is close to full charge, systems are used for telemetry and the infrared flux (from sun and albedo) is sufficient to keep the system in the correct temperature range. At (3) the solar time reaches 12:00, the sun is high up in the sky. Sun at zenith is the worst case as solar cells are oriented toward the sides of the gondola. After that, as the sun get closer to the horizon and MC2 have had time to charge the battery, the system goes into "End of day" mode and bushes the heating up to raise the temperature as much as possible.
At (4) the night starts and the gondola stop heating and temperature goes down as the night progress. Because it is nighttime the regulation thresholds for temperature are lower and heating kick-back on only when temperature reaches point (5). Some of the battery energy is used to regulate temperature between (5) and (6), at least until the sun rises again and it goes back to (1).

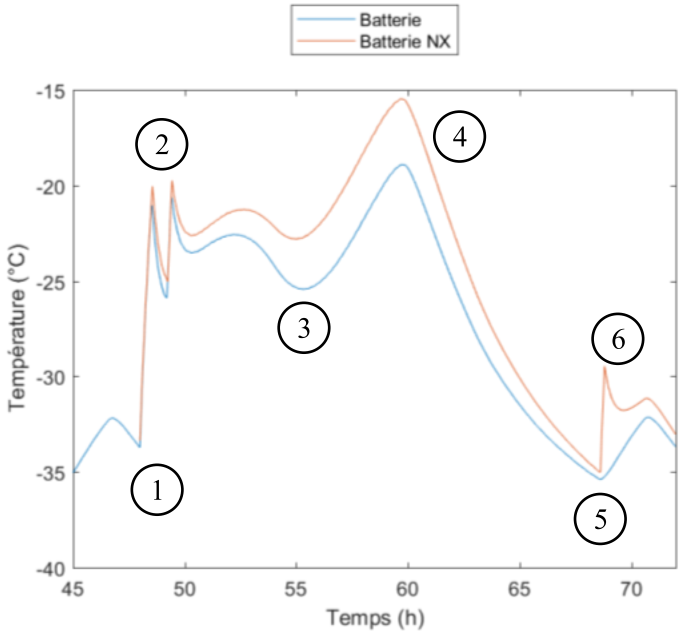

Figure 5: Simulation of the battery temperature during a 24h cycle

The inflight observations revealed later that conditions were much more favorable than those simulated, with temperatures ranging from -30°C and +45°C rather than -35°C and -15°C.

During the first campaign, testing was done to verify the validity of this methodology. 3 Balloons with similar flight profile (same area, local temperature and IR flux) were selected for a real time comparison. By using telecommands to patch the "End of day" heating threshold, one balloon was set at a low temperature and the others at a high temperature for comparison.
On Figure 6, balloon 1 in red is set at an "End of day" temperature threshold of +20°C. Balloons 2 and 3 (green and yellow) are set at a threshold temperature of +30°C.
The difference in temperature is visible at the end of the day. At about 12:00 (global time), the nights starts and no more heating is done to avoid draining the battery. Because the power system switches to "Night" mode it will only activate the heaters if the temperatures dips below -35°C.
All gondolas starts to cool down, but those that started at a higher temperature are kept a bit warmer. Theoretical models predicts that for a 10°C difference when starting, after 12h there will be a 3°C difference. On the real measurements, after 12h we can see a difference that is close to 2°C.

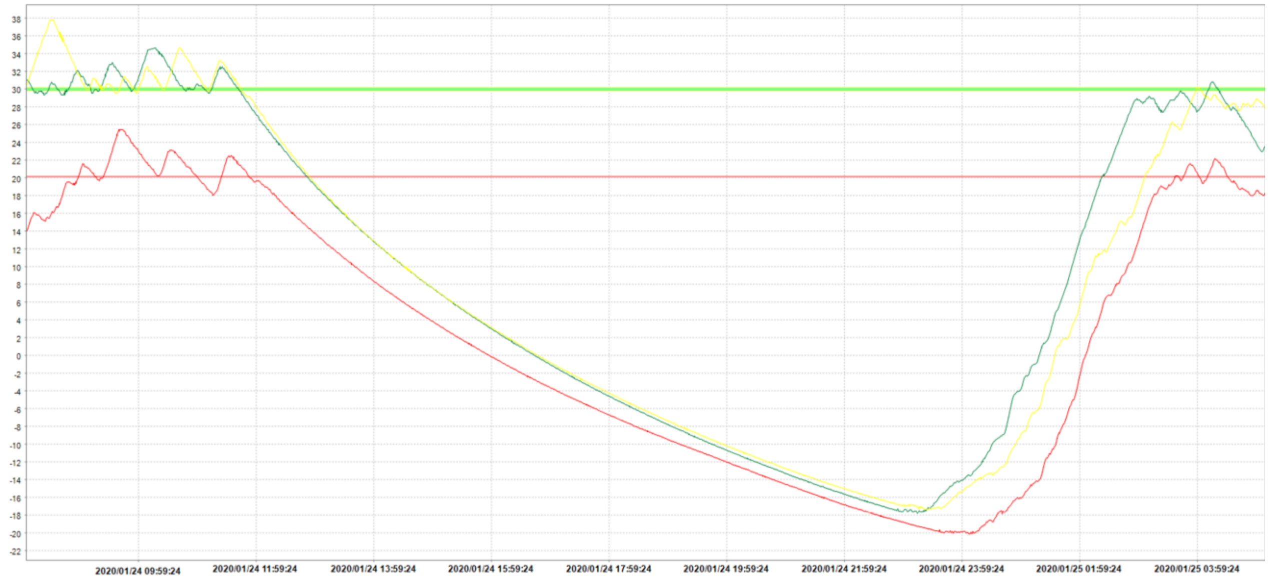

Figure 6: Comparison of the effect of "End of day" heating on battery temperature

5 INFLIGHT OBSERVATIONS

Thanks to the quantity of balloons released, a large dataset is available to judge the reliability of the renewable energy system onboard. The data was downloaded daily using satellite datalink on each balloon. Onboard data recording is done at a 1 sample/second resolution. While it is possible to download a telemetry dataset at that resolution for debugging and analysis, the satellite link does not have a sufficient bandwidth and the regular telemetry is only downloaded with a resolution of 1 sample/minute for all variables.

During flight the command center have automated reporting of balloon health metrics. In the case of the onboard renewable energy, the most important factors are the state of charge of the battery (% charge, voltage and currents) and the temperature of said battery. Secondary values that can help understand the variables mentioned above are the status of MPPT algorithms, converter output currents, state of the heaters and active mode ("Day" / "Night" / "End of day").

The battery voltage is the first indicator of the power system's health. As can be seen on Figure 7 and Figure 8, the MC2 managed to quickly get to 100% charge with no overvoltages or undervoltages during the night. Typical minimum state-of-charge at the end of each night was at 42 in this dataset, while this would be low for a satellite mission, in the case of balloons there is plenty of margin for night-time operations and margins in case of failures. The complete charging of the battery is therefore achieved about 4h30 after the start of the day. This also means that the remaining 7h30 of daytime are done with a full battery and excess energy available.

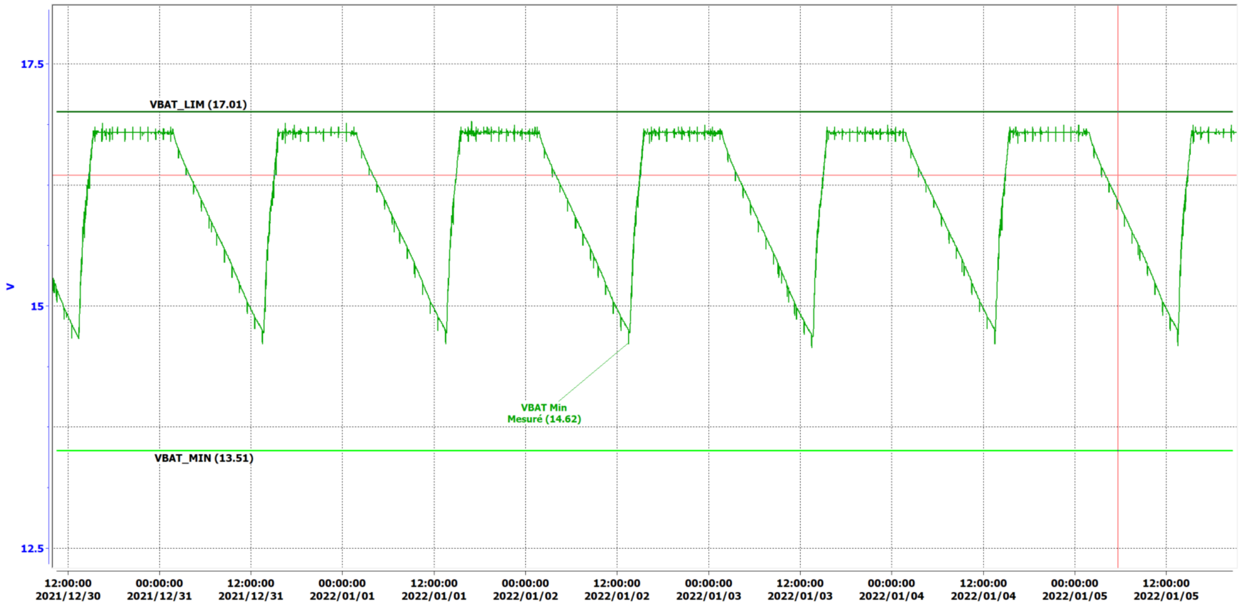

Figure 7: Battery voltage during a 7 days period

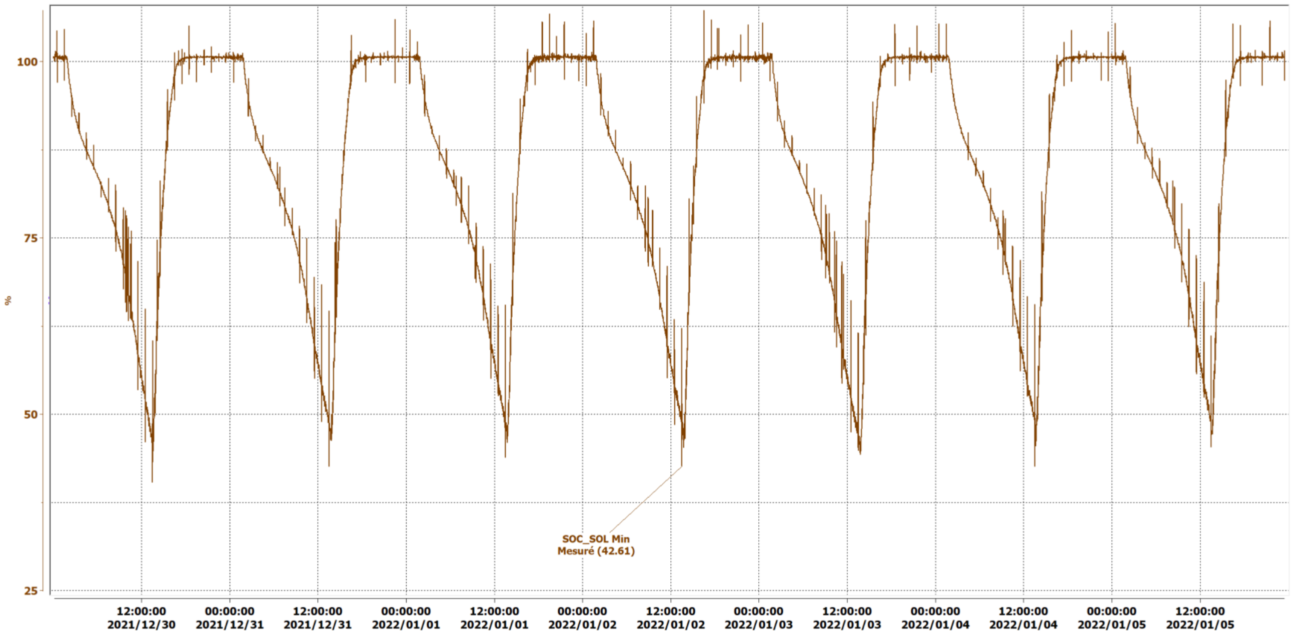

Figure 8: State of charge (in % of the capacity) during a 7 days period

The temperature measurements on the battery depicted in Figure 9 show that the temperature can be between +40°C and -17°C in this sample. During “End of day” the temperature is effectively regulated between +30°C and +40°C. The sharp peaks that can be seen during this period are the result of excess energy being sent to the heaters.

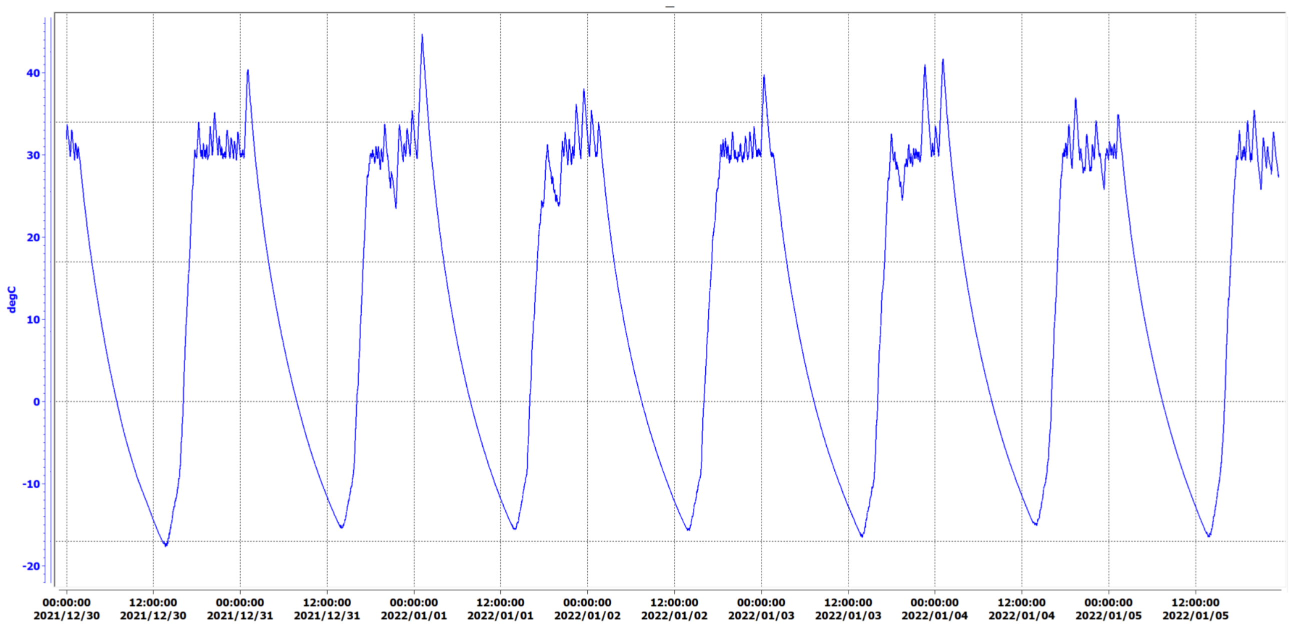

Figure 9: Temperature measured at battery TRP (in °C)

Then, the current monitoring on the battery give the graph on Figure 10. It shows the effectiveness of current regulation at 2.5A at the beginning of the day when the battery is charging, then the current is almost at zero until the night starts. This proves that the regulation algorithm is capable of providing enough power for all systems (including the “End-of-day” heaters) without drawing too much current on the battery.

During the night the current flow is almost constant, the small increase is only due to the decreasing voltage.

Short pulses that repeat cyclically can also be seen on this graph. These are caused by the satellite communication, every hour the onboard computer uploads its telemetry for the control center.

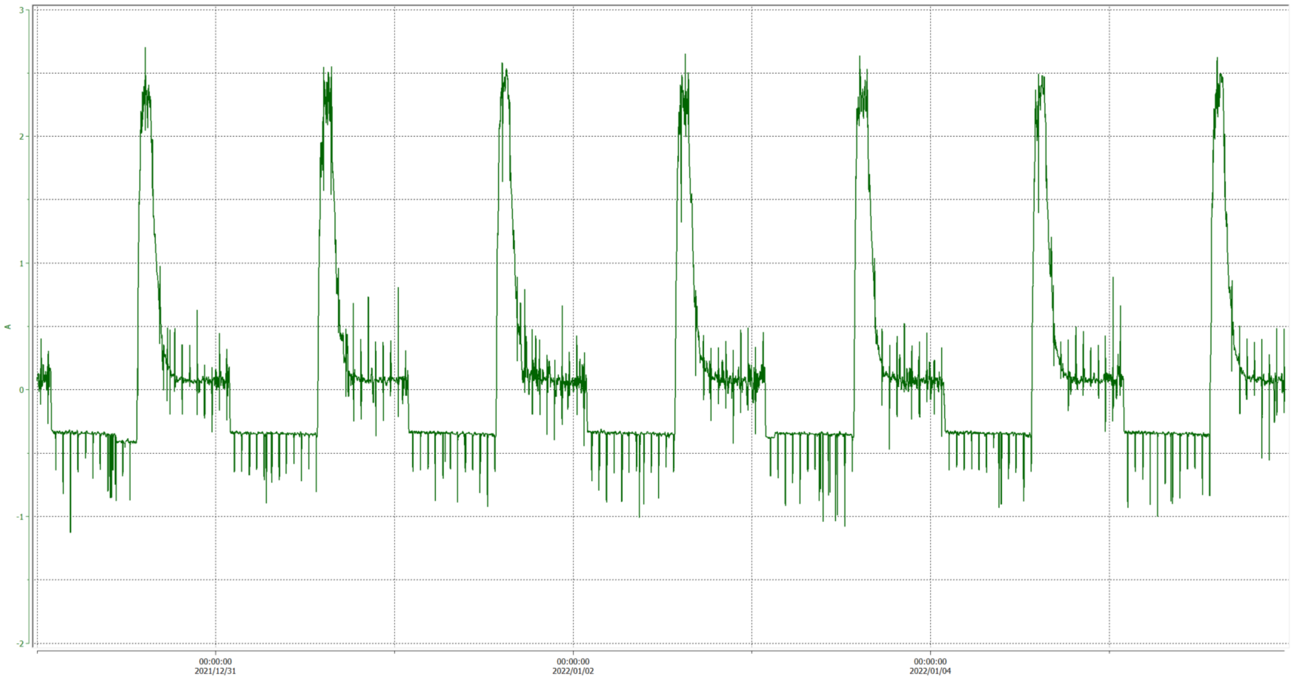

Figure 10: Current entering the battery (in A)

6 CONCLUSION

The inflight telemetry recorded during the Strateole-2 campaign demonstrated the efficiency of the MC2 power system. The design was suitable with a wide range of power requirements and mission profiles between the EUROS and ZEPHYR systems. The choice of battery, choice of solar panels, design of the converter and its algorithms all proved to lead to a successful design.

Using the thermal/electrical coupled simulation gave the team some insights on how to setup the control algorithms and what parameters could help with surviving the harshest inflight conditions. Whenever a balloon faced an uncommon situation such as the mission requiring higher power draw or the weather causing colder temperatures, the team was capable of understanding the sources of risks and margins available.

The method used to pre-heat the gondola before an eclipse would be applicable to any of our gondolas or satellite that is capable of living with large temperature variations and that experience long eclipse duration or intermittent available power.
The viability of this method is increased by the high efficiency of the thermal isolation of the interior of the gondola and the amount of excess power available that can be invested into heating the system. More progress could even be made by locating more thermal mass inside the gondola to help with the heat capacity of the system. Moving ballast inside the gondola could achieve this "hot water bottle" effect.
The most critical elements are the battery and the heaters. The heaters must be powerful enough to take advantage of available energy and control it properly to avoid over-heating the gondola as much as possible. The battery must also accept a wide-enough temperature range to make sure that night-time heating is not needed and that the high and low temperature extremes do not damage it.
This could be applicable for nano and micro-satellites missions where low orbit and equatorial orbits means that eclipse are more frequent and of longer duration. Saving some power at night may then allow to carry new operations instead of heating.

This methodology could also be used on planetary exploration missions such as rovers where temperatures are extremely cold and the day-night cycle is present. For example, in the case of the Martian Moon eXplorer mission a rover will be dropped on the moon Phobos. There the rover will experience temperatures between -4°C and -112°C, a day-night cycle of 7h39 but also an eclipse season where mars will block the sun. The methodology discussed here would prove useful in such cases.

7 REFERENCES

[1] *Strateole-2 Using balloons to improve our understanding of the lower equatorial stratosphere*, leaflet available at https://strateole2.cnes.fr/en/strateole-2-0 , CNES, 2021.