QARMAN: POST-FLIGHT MISSION OVERVIEW, DATA ANALYSIS, AND LESSONS LEARNED FROM VKI RE-ENTRY CUBESAT

Amandine DENIS [(1)], Ertan UMIT [(2)], Damien LE QUANG [(1)], Vincent VAN DER HAEGEN [(1)], Thierry MAGIN [(1)], Olivier CHAZOT [(1)]

[(1)] von Karman Institute for Fluid Dynamics, Chaussée de Waterloo, 72; 1640 Rhode-Saint-Genèse; Belgium; +32 (0) 2 359 9401, denis@vki.ac.be
[(2)] Royal Observatory of Belgium, Avenue Circulaire, 3; 1180 Brussels; Belgium; +32 (0) 2 373 02 11

ABSTRACT

QARMAN is the "QubeSat for Aerothermodynamic Research and Measurements on AblatioN", an ESA-funded project lead by the von Karman Institute of Fluid Dynamics (Belgium). QARMAN is the world's first CubeSat designed to survive atmospheric re-entry. The main aim of the mission was to demonstrate the usability of a CubeSat platform as an atmospheric entry vehicle. Moreover, QARMAN is designed to collect scientific data during re-entry through Earth atmosphere.

QARMAN is a 3U CubeSat. The re-entry phase calls for a very specific thermal design, which is based on a front cork-based ablative thermal protection system, and on internal heavily insulated survival units protecting "key equipment" required for re-entry and final data transmission. QARMAN also features deployable solar panels as a payload, providing a passive mean for stabilization and accelerated deorbiting through drag increase.

QARMAN was deployed in orbit from the ISS on 19 February 2020. It was operated for 5 months, demonstrating proper functioning of the main subsystems. The AeroSDS payload (solar panel deployment) was successfully demonstrated in Space, thus reaching TRL 9. QARMAN unexpectedly stopped transmitting on 14 July 2020. Analysis identified UHF transceiver malfunction and battery thermal failure as potential failure root causes. QARMAN finally reentered the Earth atmosphere on February 5th, 2022.

1. QARMAN MISSION

1.1 Mission Objectives

QARMAN is the "QubeSat for Aerothermodynamic Research and Measurements on AblatioN" of VKI, initially developed in the framework of QB50 project. Different than other QB50 CubeSats, QARMAN was designed to collect scientific data during its entry to Earth's atmosphere. Atmospheric entry and associated aerothermodynamic phenomena are considered as critical research topics for the safety of the spacecraft. The QARMAN Project aimed at creating an affordable research platform to perform scientific studies in these fields. The QB50 project was concluded in 2017; the QARMAN project was continued on its own.

1.2 Mission scenario

As shown in Figure 1, the QARMAN mission can be divided into 4 sub-phases, going from orbital deployment to atmospheric reentry.

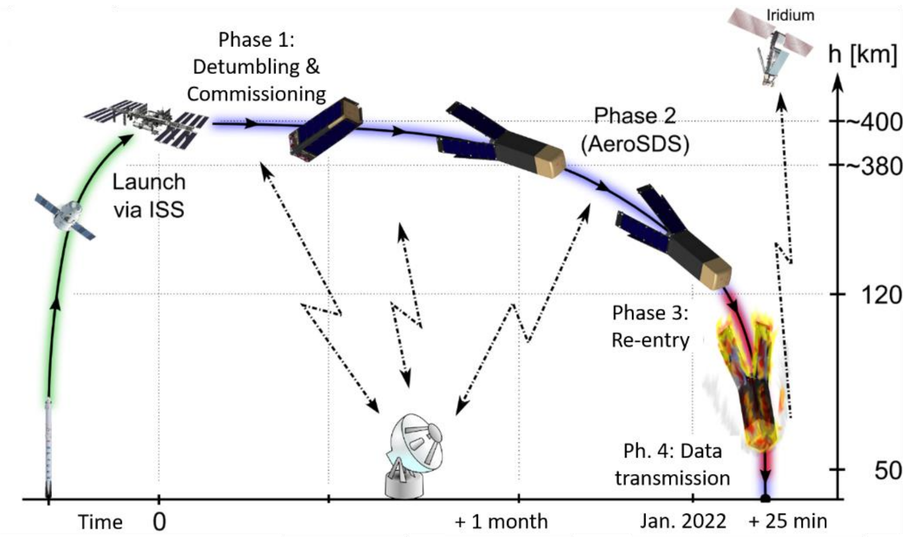

Figure 1: QARMAN mission consists of 4 phases.

Phase 1: Commissioning & Detumbling

Right after deployment, at an altitude of approximately 400 km, the commissioning phase starts. The vital subsystems are booted, and the UHF antennae are deployed after 45 minutes in order to establish the first ground contact. Using magnetorquers, the satellite is detumbled and stabilized from the initial tumbling rates (expected to be below 10 deg/sec). The performances of each subsystem are then assessed in order to reach full commissioning of the platform. This phase was expected to last from a minimum of 2 weeks up to one month in the nominal scenario.

Phase 2: AeroSDS

At the end of phase 1 after 1 month of operations in orbit, the AeroSDS panels, consisting of the ceramic panels with integrated solar cells, are deployed into a dart configuration with an angle of 15 degree with respect to the satellite longitudinal axis. The system provides aerodynamic stabilization and an increased drag area, progressively reducing the satellite altitude faster compared to the stowed configuration.

Phase 3: reentry

Phase 3 is the reentry, which can be considered the core part of the mission, where the major return for the science campaign and technology validation is expected. This is also the most critical part of the mission, as the satellite is subject to very high temperature and hypersonic velocities. Gas temperatures around the satellite are expected to exceed 10000 K, while the satellite flies through the upper atmosphere at a speed up to Mach 27. To protect the electronics during the reentry, a thermal protection system is designed, based on high-tech insulation (e.g. Pyrogel, FiberFrax and ceramic walls) and ablative material (P50 Cork).

Phase 4: data transmission

The cloud of free electrons surrounding the satellite during the reentry phase causes a communications blackout, where no data can be transmitted to mission control. The acquired data are stored on flash memory and the compressed data are transmitted towards the Iridium constellation once the blackout has terminated, expected at an altitude of 45 km. The data budgets are calculated such that all data can be safely transmitted in the short time frame between the end of the black-out window and the satellite's crash on ground.

2. QARMAN DESIGN

2.1 Payload design

QARMAN CubeSat hosts 4 payloads to fulfill the mission objectives:

1. **AeroSDS payload:** The Aerodynamic Stability and De-orbiting System (AeroSDS) aims at demonstrating the feasibility of a passive system providing stability for a CubeSat below 380 km of altitude. The increasing drag coming from atmosphere for very low orbits is used for having a double effect: attitude stabilization and progressive orbital decay, due to the increased area/mass ratio. Four solar panels are deployed and locked in position by a custom designed hinge mechanism, as shown in Figure 2.

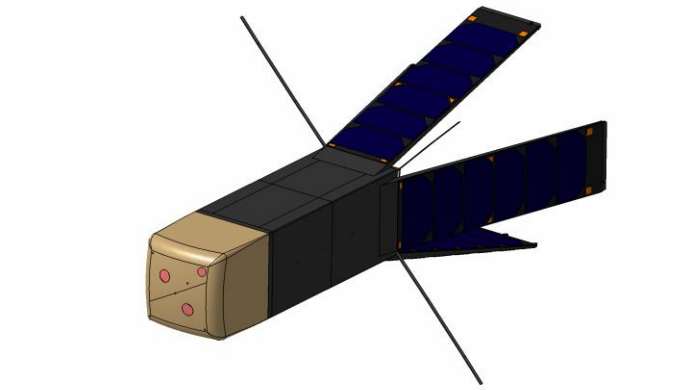

Figure 2: QARMAN with deployed AeroSDS configuration.

2. **Thermal Protection System (TPS) payload:** The aero-thermodynamic constrains of QARMAN reentry impose to use an ablative thermal protection system (TPS). Due to the specific form factor and trajectory of QARMAN, the heat load is an important constrain on the design. Due to this high heat load, the TPS needs to be ablative in order to withstand the heat flux. Moreover, the pyrolysis gases are transported out of the material by diffusion and convection and exhaust into the boundary layer, providing a further barrier for the heat exchange (blowing) and undergo additional chemical reactions, consuming more heat. The selected material for this purpose is Amorim P50. The front third of the QARMAN CubeSat is dedicated to this TPS, as shown in Figure 3.

Figure 3: QARMAN prototype, showing the front P50 TPS (left).

3. **Aerothermodynamic Experimental Payload (XPL):** Atmospheric entry and associated aerothermodynamic phenomena are considered critical research topics for the safety of spacecraft. This payload aims at demonstrating the feasibility of investigating the challenging physics of atmospheric entry. The payload consists of a set of six experiments, XPL01 to XPL06:

- **XPL01: Front TPS efficiency**. The temperature evolution and recession rate of the ablative TPS are investigated during the atmospheric entry.
- **XPL02: Front TPS pressure.** Two pressure measurements record the pressure distribution along the front TPS in the diagonal direction, on the opposite side of the thermal plugs.
- **XPL03: Stability.** This payload aims to determine the stability of the satellite during phase 2 of its mission by measuring the static pressure on the side panels of the satellite.
- **XPL04: Transition.** The aim of this payload is to determine the position of the onset of an eventual transition from laminar to turbulent flow streamwise along the lateral panels, within the resolution of the sensor repartition. This is achieved by placing pressure and temperature sensors along the side panels.

- **XPL05: Side panel TPS efficiency.** The side panels are equipped with thermal sensors to monitor the temperature increase during the entry phase of the satellite in order to assess the efficiency of the side panel TPS.
- **XPL06: Radiation.** The embedded emission spectrometer onboard QARMAN intends to provide the first spectrally resolved data in the flight regime of from 7.5 km/s at 120 km of altitude and 5 km/s at 50 km altitude. This payload is extensively described in [1] and [2].

4. Iridium network communication payload: During an atmospheric reentry, the presence in high concentration of free electrons within the plasma sheet formed around the vehicle has a direct impact on any electromagnetic waves going through it. In the case of radio waves used for communication from the reentry vehicles, the signal is affected and might be attenuated. To overcome this problem without changing the trajectory profile, the idea is to change the location of the antenna and instead of communicating directly to the ground, use a satellite constellation in space to relay the signal to the ground. For QARMAN the Iridium constellation is used as relay for the signal and the transmitting is based at the rear of the vehicle (anti-velocity direction).

2.2 Platform design

QARMAN is a parallelepipedal satellite of roughly 34*10*10 cm^3 for 5.200 kg, fitted with deployable solar panels (Figure 4). As described in the previous Section, approximately 1/3 of the volume is devoted to the Thermal Protection System, made of Amorim P50 cork. The TPS is instrumented (thermocouples, pressure plugs) and host the spectrometer.

Figure 4: QARMAN flight model in stowed configuration.

Mechanical configuration

Due to the specific re-entry constraints, the chassis is an in-house design, shown in Figure 5. The titanium chassis consists of a front plate (left) and a back frame (right), connected through two ladder-shaped structures and the XPL survival unit shell. The front plate receives the front TPS. On the back plate the four hinges for the AeroSDS panels are mounted.

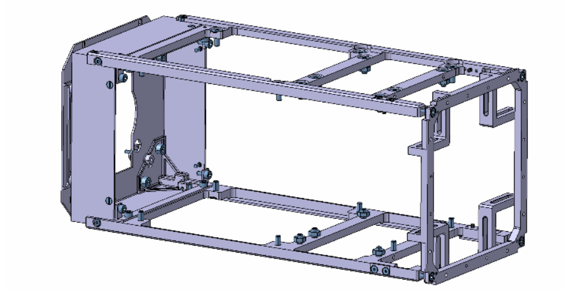

Figure 5: QARMAN chassis.

The front plate of the satellite receives the cork TPS. The design consists of the Cork front TPS itself and an intermediate titanium substructure. The thermal plugs needed for payload XPL01, the pressure taps for XPL02 and the spectrometer for XPL06 are accommodated into the front plate and cork TPS. The back frame receives the four hinge mechanisms of the AeroSDS panels, as well as the ladder shaped side structure and the back plate. The design is shown in Figure 6.

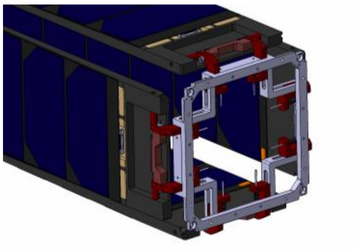

Figure 6: Back frame and hinge.

A tuna can-shaped back panel in SiC is mounted on the back frame. This back plate serves also as a base for the UHF antenna system including deployment mechanism. The Iridium antenna is accommodated inside the tuna can and all the gaps are filled with pyrogel. The backplate PCB hosts also the RBF socket and the kill switches. In the final design update, additional "spacer feet" have been added, to permit the interfacing with other CubeSats inside the NanoRacks deployer. GPS antenna is located on the backplate.

The chassis also hosts the side TPS assembly made of 4 titanium side panels covered with insulations and housing the side pressure ports and thermocouples.

The configuration of the solar panels consists of 4 panels, deployable with a fixed inclination angle of 15˚. The in-house designed deployment mechanism generates two simultaneous movements when the panels are released for deployment: a rotational movement around the hinge axes, and a translational movement down along the hinge bracket slits of the back frame.

Three survival units (SU) host and protect the electronic equipment required for reentry and data transmission phases.

- The XPL SU is positioned right behind the cork nose and serves to protect the XPL PCB from the heat generated during the re-entry. This houses the pressure transducers and thermocouple amplifiers which measure pressure, respectively temperature in the nose region. Moreover, it houses the electronical connections from the spectrometer and photomultiplier. The box consists of a Titanium box and cover. Inside, the XPL PCB and its Aluminum heat sink is mounted on stand-offs. The remainder of the volume is filled with Pyrogel layers to insulate it.
- The OBC SU comes right behind the XPL SU. Analogue to the XPL SU, it consists of a Titanium box and cover. It houses the OBC+Iridium+batteries PCB, mounted on stand-offs. Likewise, the remainder of the volume is filled with Pyrogel.
- The AeroSDS SU hosts the PCBs necessary for the acquisition of the thermocouples and strain gauge signals from each panel. It is located within the AeroSDS cover, which seals the opening in the side-walls necessary to support the motion of the AeroSDS during deployment, preventing the in-flow of hot air into the functional unit of QARMAN.

Avionics

Table 1 summarizes the avionics subsystems of QARMAN. As presented above, the equipment required for reentry and data transmission phases are embedded within a survival unit. The equipment required for orbital life only is located in the remaining volume, along the OBC SU.

Table 1: Avionics subsystems of QARMAN.

Subsystem	**Manufacturer/model**
OBC	In-house design based on MSP430F5438A microcontroller
Iridium modem	*Iridium Core 9523* Satellite Transceiver Module
Batteries	2*Kokam LiPo SLPB723870H4
XPL DAQ	In-house design
AeroSDS DAQ	In-house design
EPS	Clyde Space FleXible EPS
Solar cells	Azure Space 3G30A
ADCS	QB50 ADCS unit developed by Surrey Space Center of University of Surrey and Electronic Systems Laboratory of Stellenbosch University
COM	Astronautical Development, LLC Li-1 UHF/VHF Radio
GPS	Novatel OEM615
Iridium antenna	M1621HCT-P-SMA (helical)

Figure 7 to Figure 9 show the physical layout of sub-systems in QARMAN.

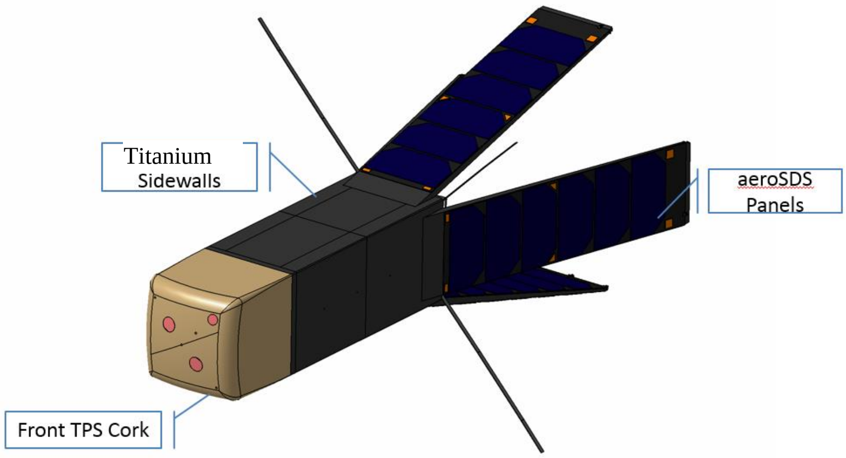

Figure 7: QARMAN Deployed, exterior view.

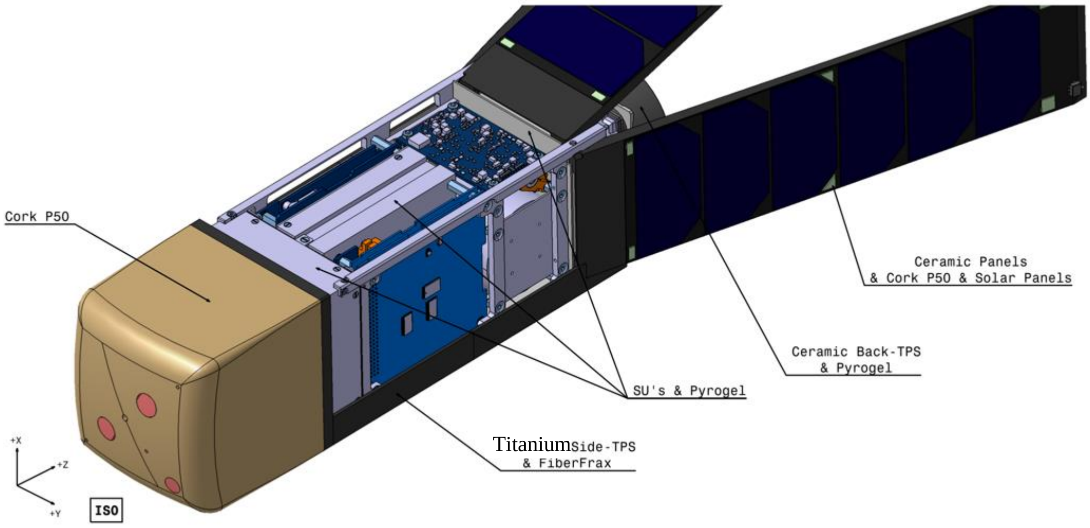

Figure 7: interior view – top.

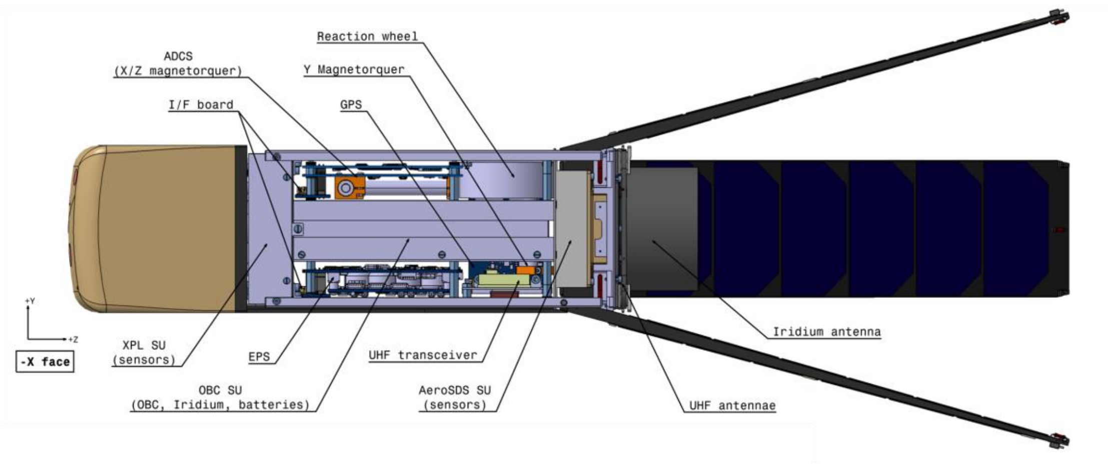

Figure 9: QARMAN, interior view – side.

3. ASSEMBLY, INTEGRATION, and TESTS

QARMAN protoflight model was initially integrated in 2016, but a failure during the initial vibration campaign called for a major redesign (ceramic side panels were replaced by titanium ones). The final integration happened in 2018-2019 at VKI premises and resulted in the final QARMAN protoflight model. QARMAN protoflight model was then subjected to a system-level test campaign, comprising both ambient and environmental tests. The ambient tests are mainly end-to-end and mission tests. The environmental tests are made of a vibration test campaign and a thermal test campaign. The qualification and acceptance test campaign of QARMAN took place between 27 March and 29 May 2019, in VKI (Rhode-St-Genese, Belgium), V2i (Liège, Belgium), and ISAE-SUPAERO (Toulouse, France). The vibration test (random loads, preceded and followed by sine sweeps) demonstrated compliancy with the launcher requirements, and subsequent functional tests were successful. The thermal test campaign consisted of a bake-out followed by thermal vacuum cycling. Four cold and hot cycles were run, including functional tests, and showed proper behavior of QARMAN under the expected thermal environment.

In parallel to the protoflight test campaign described above, a full-scale test of QARMAN (using a dedicated model) was carried out in CIRA - SCIROCCO plasma wind tunnel in order to validate the extensive thermal simulations that had been carried out on the re-entry conditions of the spacecraft.

4. LAUNCH and EARLY OPERATIONS

QARMAN lifted-off on December 5th, 2019, from Cape Canaveral, USA, on-board a Falcon-9 rocket (mission CRS-19). The Dragon capsule carrying QARMAN berthed at International Space Station (ISS) on December 8th, 2019. QARMAN remained stored on-board the ISS (inside its NanoRacks CubeSat Deployer where it had been integrated in early October 2019) until in-orbit deployment. QARMAN was deployed into orbit by the NanoRacks CubeSat Deployer (held by the ISS Japanese robotic arm) on February 19th, 11:20:00 UTC. From thorough inspection of the deployment pictures (high-resolution pictures taken by the astronauts during deployment and made available by NASA & NanoRacks), QARMAN showed to be in nominal configuration: antennas and panels stowed, all fasteners in place, no visible defect.

Figure 9: QARMAN being deployed into orbit from the ISS, 19/02/2020. Credit: NASA.

Figure 10: Picture of QARMAN taken during deployment, showing nominal configuration. Credit: NASA.

5. IN-ORBIT OPERATIONS AND MISSION DATA ANALYSIS

From the first day of the mission, QARMAN beacon was received and decoded at VKI but also by many amateur-radio stations around the world. The beacons showed nominal parameters, indicating a good health status of QARMAN. The weeks following the in-orbit deployment have been dedicated to TLE discrimination, beacon monitoring, and platform commissioning.

The deployment of the solar panels was scheduled to occur 33 days after injection in orbit, and happened as planned on March 23rd, 2020. Together with the deployment, QARMAN transitioned to mission phase 2. These two events were confirmed by subsequent beacons.

Telecommands have been attempted daily from mission day 1 without any success, until a first telecommand was finally acknowledged and responded on March 24th. From that point, telecommands kept being sent daily with a very low success rate of a few percent.

On July 14th 2020 (mission day 146), a last beacon signal was received from QARMAN at 9:22:32. No signal was received during the next pass over Europe, in the evening of the same day. No signal has been received since then.

TLE indicate that QARMAN finally reentered the Earth atmosphere on February 5th, 2022. Despite continuous monitoring, no signal could be acquired during reentry.

5.1 Overview of the post-processed results of the mission operational data

Beacon data

Beacon data were collected either directly at VKI or by a ground station of the SatNOGS network. Data from both origins (VKI and SatNOGS) are merged into a single Excel table. The main results extracted from this dataset are presented below.

Figure 11 shows the available temperature data (OBC, ADCS, UHF boards) over QARMAN lifetime. This graph is further commented in 5.2 (failure analysis).

Figure 12 shows the battery voltage and the current consumption on 3.3V bus over QARMAN lifetime. Battery voltage is relatively stable, oscillating between 8 V and 8.25 V (full charge). Current consumption on 3.3 V bus is oscillating around 130 mA, which is the expected nominal value. The few data points around 35 mA for mid-May 2020 reflects the ADCS (main current consumer) being OFF for having reached the over temperature threshold.

Figure 13 shows the bootcount (= number of times the OBC has started up) and the uptime (number of seconds since last boot). The OBC is programmed to reboot if no telecommand is received over the last 72 hours. The effect of this protection mechanism is clearly observed on the graph. Uptime never exceeds 72hours before the first telecommand succes (24th March). Afterwards, uptime is generally longer. The longer uptime was 16 days and 23h, while the average is 15 h and the median 2 days and 4h.

Figure 14 shows the power generated by the solar arrays. Top graph shows the total power, while the subsequent graphs shows the power generated by +X, -Y, -X, +Y (from top to bottom, respectively). Blue lines indicates the internal side of the panels in deployed configuration, black lines indicates the external side of the panels in deployed configuration. Power is only generated by "inside" panels (which are outside is stowed configuration) until panel deployment (23rd March); afterwards "outside" panels are illuminated and generate power as well. Proper panel deployment is thus confirmed.

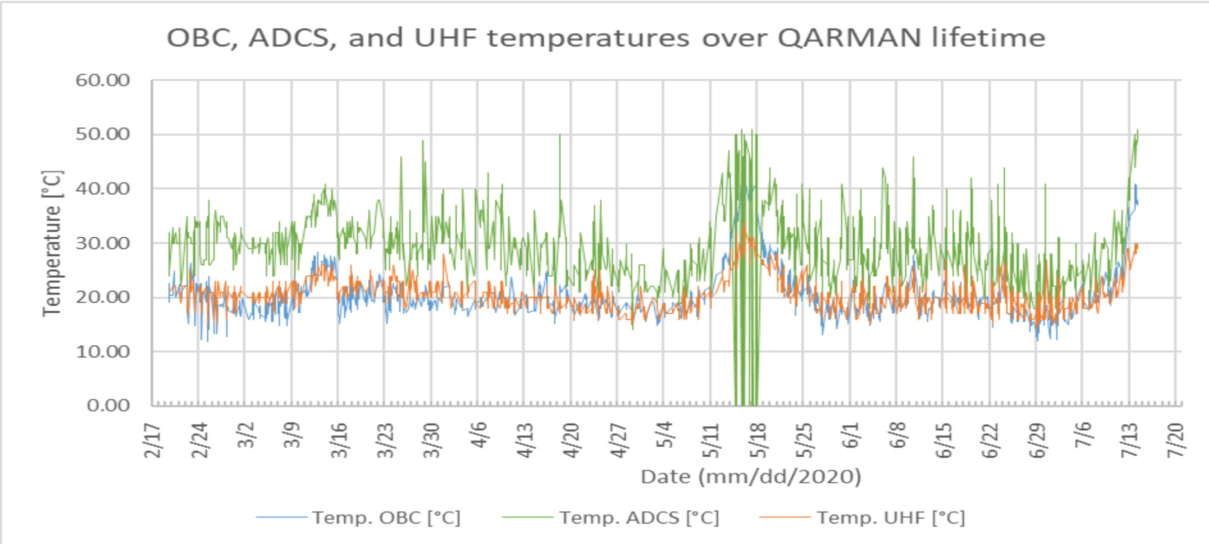

Figure 11: OBC, ADCS, and UHF temperatures over QARMAN lifetime.

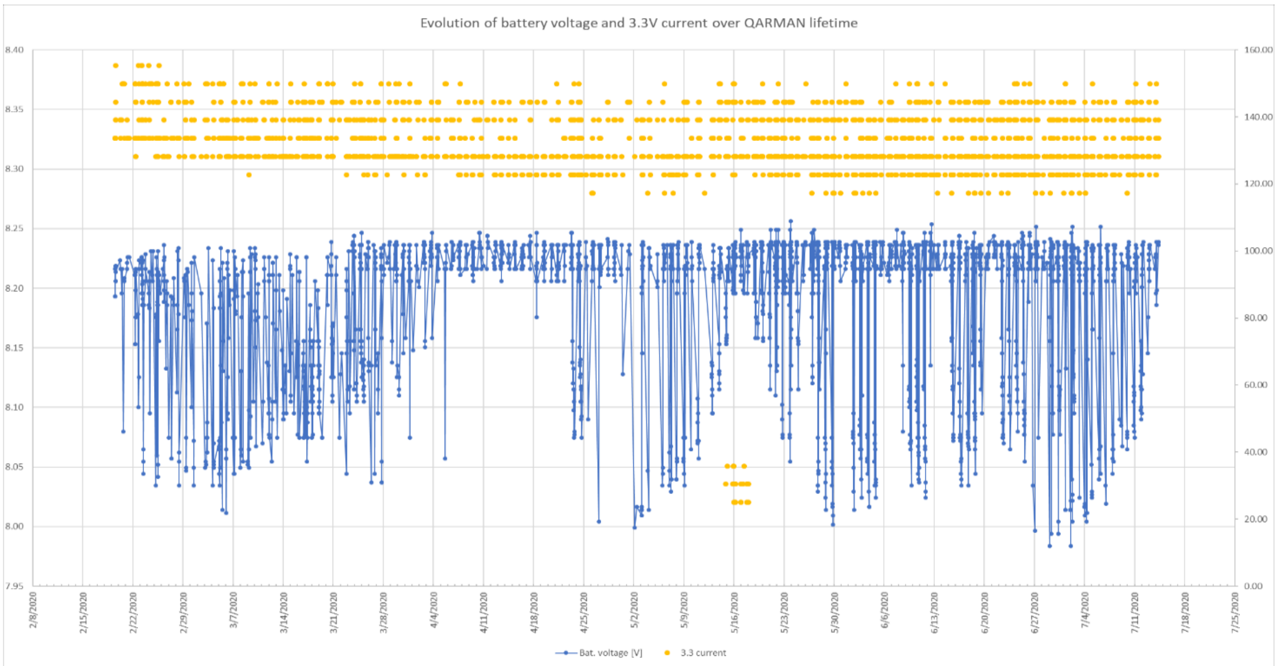

Figure 12: Battery voltage and 3.3V current over QARMAN lifetime.

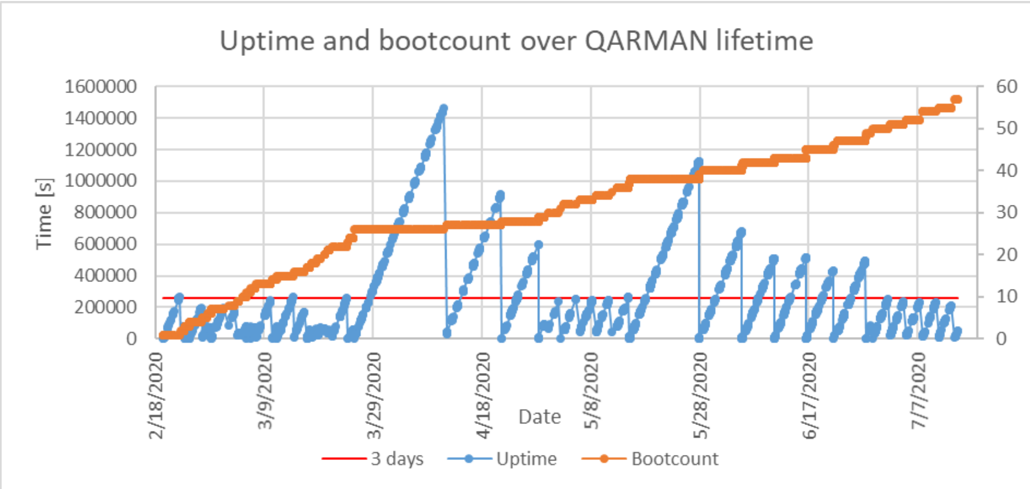

Figure 13: Uptime and boot count over QARMAN lifetime.

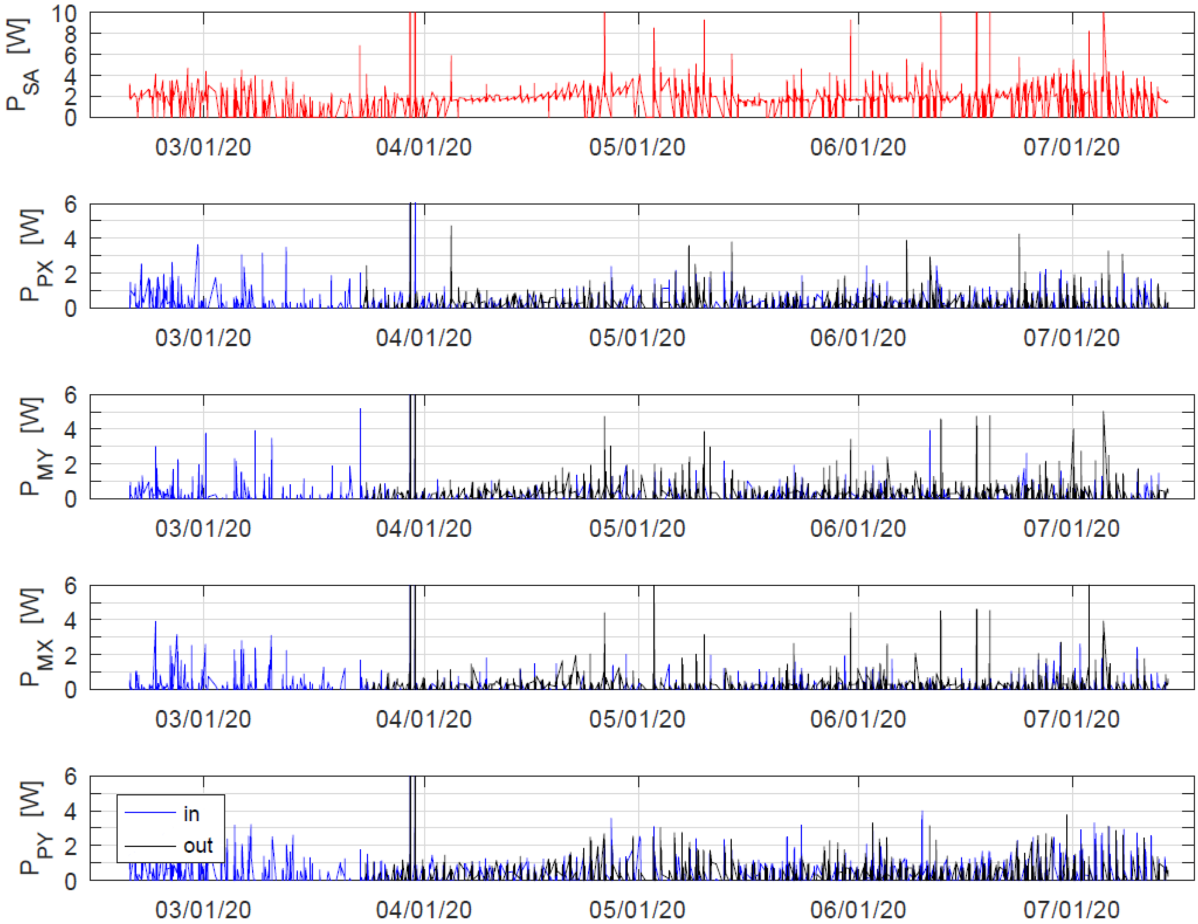

Figure 14: Power generated by the solar arrays over QARMAN lifetime.

Telemetry data

Telemetry data, i.e. data received in response to a telecommand, are decoded through the TMTClab ground station software and stored into an Excel table. TC/TM exchange was mainly used for the purpose of testing the link integrity and better understanding the difficulties encountered with uplink. 115 telecommands have been successful over 3 months (only successful telecommands were logged in the file). It represents roughly a few percent (1-5 %) success rate, which is extremely low. For all successful telecommand, the returned values are as expected, showing good health status.

Figure 15 shows the number of successful TC over 6 azimuth categories (azimuth of QARMAN with regard to VKI ground station at the time of the TC). Telecommands are most successful for an azimuth between 240 and 300°, which is roughly over the Atlantic Ocean. That can be explained by the lower ground-generated radio noise over the zone, therefore a better signal-to-noise ratio.

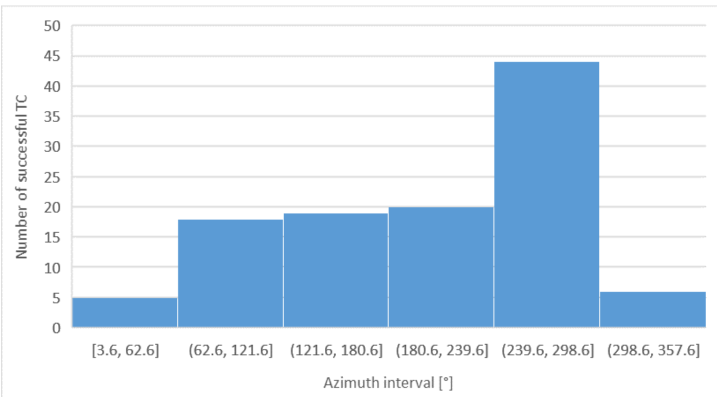

Figure 15: TC success according to the azimuth of QARMAN.

Some TC were issued to get the RSSI from the UHF transceiver. That should give an estimate of the incoming signal strength. Figure 16 and Figure 17 plot the RSSI over the elevation and azimuth, respectively. There seems to be no correlation between RSSI and QARMAN position (elevation or azimuth), once the signal is received (this latter fact seems however to be correlated with azimuth, as presented above).

Figure 18 shows the number of successful TC versus the uplink frequency used. Indeed, this uplink frequency was varied, sweeping between the nominal 437.350 MHz and 437.425 MHz (a "lab frequency" communicated by the transceiver supplier), in an attempt to improve the uplink performances. It should be emphasized that only successful (acknowledged) TC were logged, so Figure 18 does not show a success rate but is highly dependent on the number of trials for each frequency. It shows the largest number of acknowledged TC for the nominal frequency (437.350 MHz), which was the most used for uplink. Second largest number is for the "lab frequency" (437.425 MHz) which was also largely tried out. Intermediate frequencies show similar results of a few acknowledged TC.

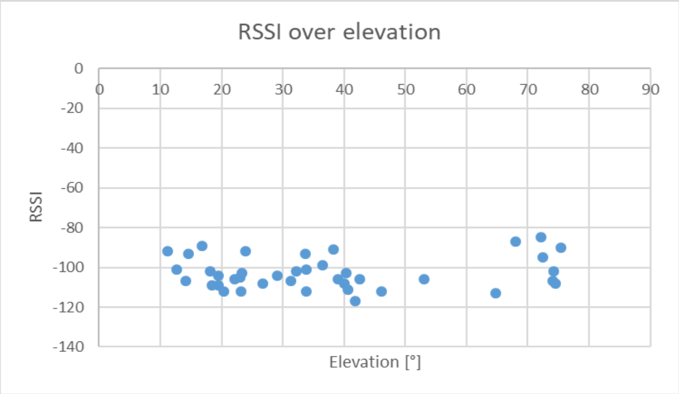

Figure 16: RSSI value over QARMAN elevation.

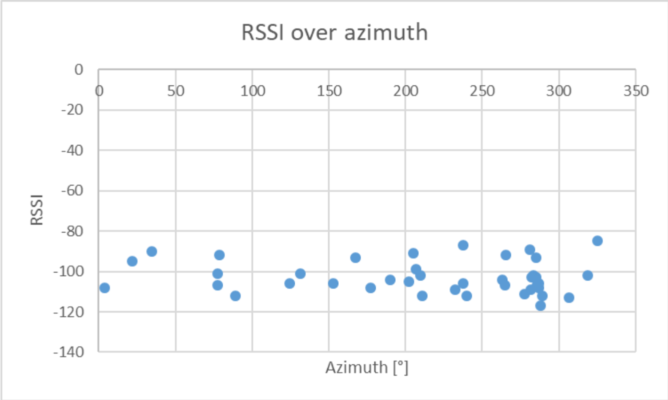

Figure 17: RSSI value over QARMAN azimuth.

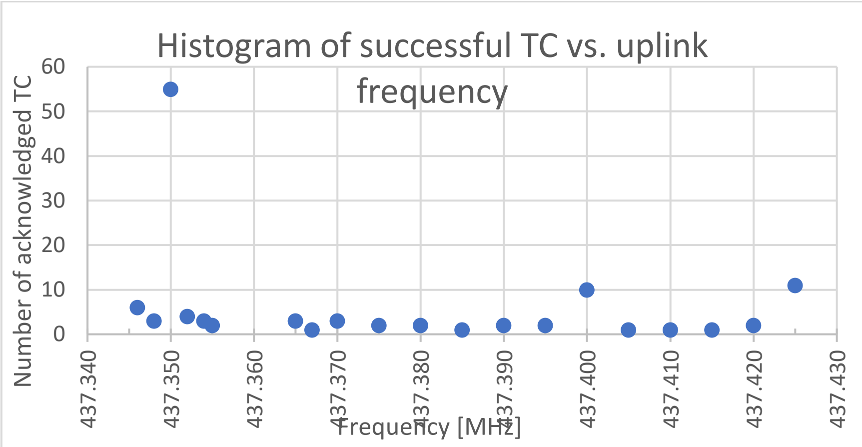

Figure 18: Histogram of successful TC vs. uplink frequency.

TLE data

TLE data are retrieved from spacetrack.org. They are postprocessed with Excel to extract altitude and semi-axis information. *Figure 19* shows the evolution of the apogee and perigee altitudes, as well as the semi-major axis, from in-orbit deployment over the mission interval. On this Figure, one can notice a change in the slope of the semi-major axis, corresponding to date of the deployment of the solar panels. The effect of AeroSDS on altitude decay is thus demonstrated.

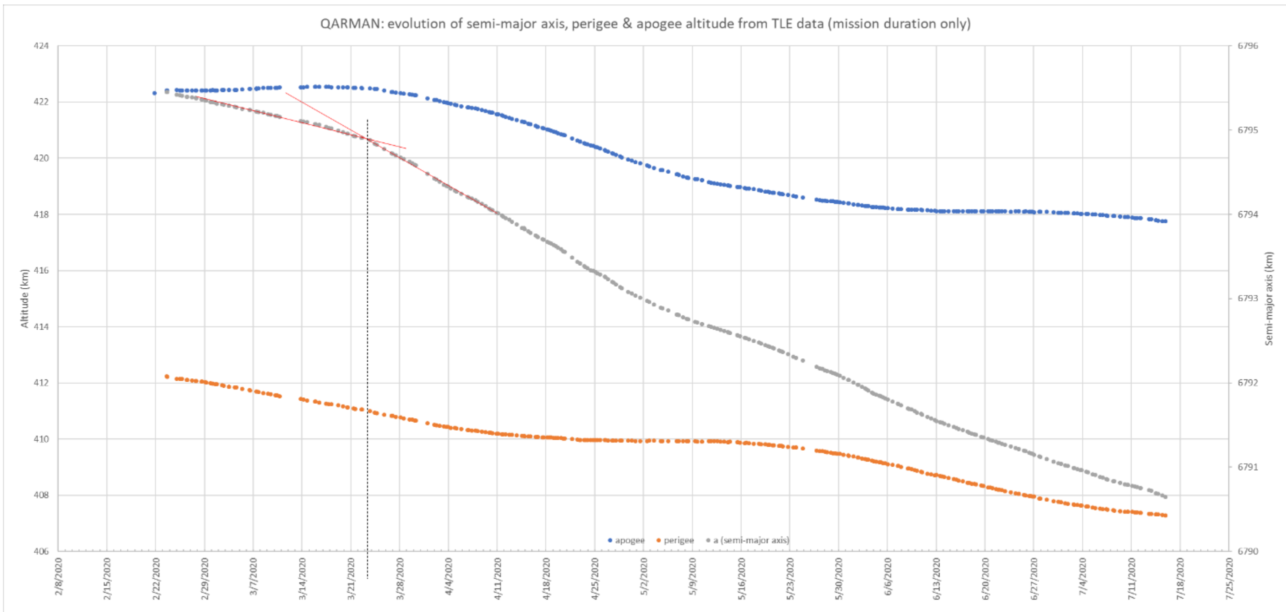

Figure 19: Semi-major axis, apogee & perigee altitudes, extracted from TLE. (mission duration only)

5.2 Investigation of mission failure: loss of signal

Observations

No beacon has been received at VKI ground station since July 13th, 2020, 20:43 UTC. No beacon has been received by SatNOGS network since July 14th, 2020, 9:22:32 UTC. No command has been successful since then.

As can be seen on Figure 11 above, the last received beacons show increasing temperatures for OBC, UHF, and ADCS. A similar temperature raise had been observed around mid-May but remained unexplained. At that time, it did not impact the nominal functioning of QARMAN and temperatures went back to normal after a few days, after the FDIR triggered a temperature threshold shutdown of the ADCS at 50°C.

Root cause analysis

A mission analysis ran with STK software showed two periods of QARMAN being exposed to constant sunlight, instead of the typically alternating 60 min sunlight / 30 min eclipse[1]:

- On May 15th, 2020, for 63h34min;
- On July 13th, 2020, for 97h39min.

These two periods coincide with the temperature peaks observed on Figure 11 above. Figure 20 shows the sunlight duration by orbit, superimposed on the temperature graph (sunlight duration peaks are cut out for readability's sake, values indicated with text on the graph). The fluctuations of the temperatures clearly follow the sunlight duration, leading to assume they are correlated. The loss of signal happened during an extended illumination period.

[1] This situation can be explained by the combination of the nodal precession with the high inclination of QARMAN orbit.

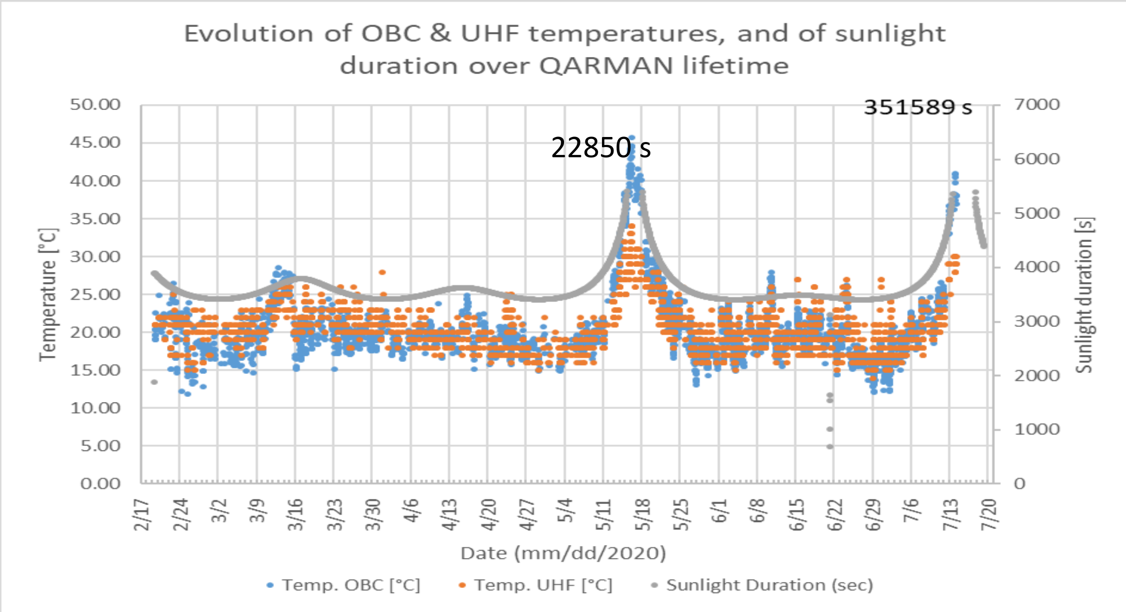

Figure 20: Sunlight duration and OBC & UHF temperatures over QARMAN lifetime.

The elements presented above point towards a thermal-induced failure caused by an extended sunlight period. The most critical component regarding temperatures is the batteries. It should however be noted that +50°C is not a destructive limit, but rather a recommended maximum temperature for preserving the battery capacity. Still LiPo batteries are known to be susceptible of thermal runaway and battery failure is considered a plausible failure root cause. This scenario was further investigated by running extensive thermal analyses (including model correlation) within the post-failure root cause investigation process.

Figure 21 shows the predicted temperatures of the main equipment over the period of interest, while Figure 22 plots the simulated temperature ranges over the operational ranges. Both Figures show that none of the equipment is predicted to overpass its temperature operational range. The closest to the limit is the batteries, reaching 42.24°C which is 7.76°C from the 50°C limit. However, this limit should be understood as a limit for keeping nominal performances (capacity) but not as a destructive temperature.

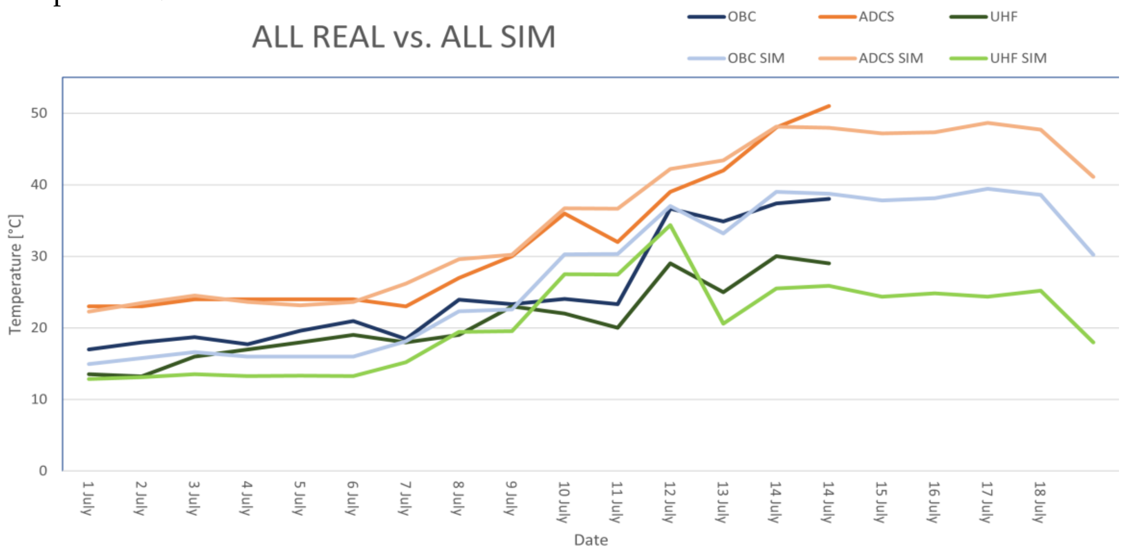

Figure 21: Predicted temperatures of the main equipment over July 2020.

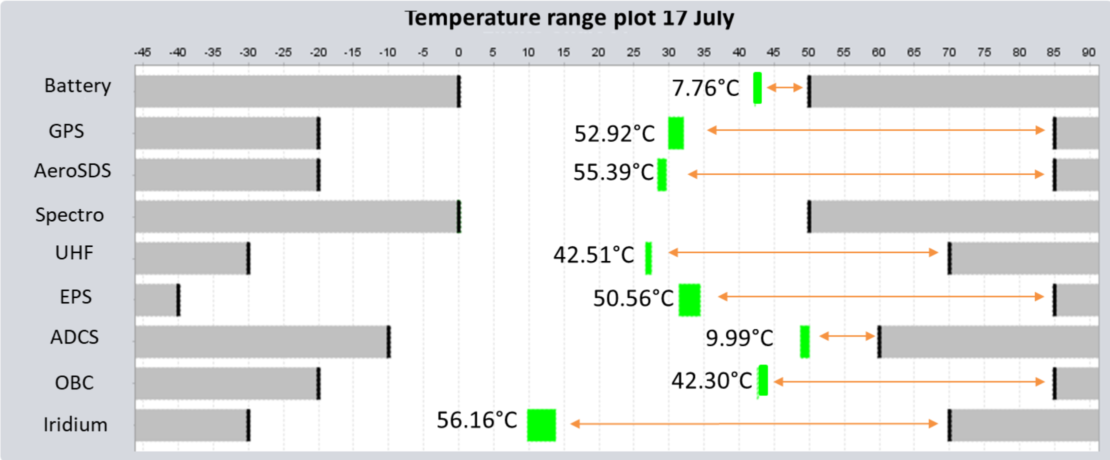

Figure 22: Maximum temperatures of main equipment vs. operational temperature range.

In conclusion, the thermal analysis does not permit to conclude with certainty on the root cause of the signal loss failure. After stacking all pessimistic assumptions, equipment still does not reach their maximum operational temperatures. Batteries can be considered at risk, reaching the upper part of their nominal range and being a critical element of the system. On the other hand, as described in earlier, the UHF transceiver has always been a weak point along the mission and could have critically failed.

6. CONCLUSIONS: ACHIEVEMENTS and LESSONS LEARNED

Many lessons can be learned from QARMAN lifecycle, as illustrated by the previous Sections of this paper. On a technical/design side, we would point out the difficulty of working with such a brittle material as ceramic (SiC) and the importance of a trusted and certified supplier. Use of non-conventional materials for structural parts should be carefully assessed beforehand. The cracks observed at the first vibration campaign could have been (possibly) identified by testing a single ceramic sample with random loads applied. This can be extended, more in general, to non-space materials with little or no flight heritage.

Linked to the above, the early selection of the launch opportunity can be very useful to define the launch loads and therefore the test requirements, in order to avoid to overtest space equipment (especially with very delicate components). On the other hand, this is difficult to be planned with high accuracy from the beginning (this is shared with QB50) and flexibility with regard to the launch opportunity has also been an asset.

On an operational point of view, lessons are learned from the two main anomalies reported in Section 5. The UHF transceiver difficulties had heavy consequences on the mission operations, uplink success being too low for establishing useful communications before the final signal loss. Our main recommendations with these regards are twofold:

- Extensive tests of the transceiver should be carried out before flight, with and without antennas, in all expected configurations. Antenna pattern measurement should also be considered as much as possible, and definitely in case of custom design.
- More on the strategic side, when selecting the supplier, proper extensive documentation is of uppermost importance, as well as customer support (including during mission).

Regarding the signal loss, and more specifically the thermal analyses, we would have the following recommendations:

- Mission analysis should be carefully updated all along the design process, especially in case of modification of the launch scenario and mission profile. Outcomes shall be passed on to thermal analysis. In case of change after PDR (when requirements are frozen) or CDR (when design is frozen) this change process should be handled formally with a configuration change board in order to ensure all relevant impacts of the change have been taken into account, assessed and risks properly mitigated.
- Accurate thermal analysis for critical components should rely on an accurate characterization of thermal/optical properties of materials. More specifically, for non-space materials datasheets are not always reliable for all conditions and analysis may suffer of non-negligible uncertainties. An initial phase to characterize material properties could be beneficial.
- The thermal model should be carefully validated based on test data, including a thermal balance test to the extent it is possible.
- Thermal test of the batteries in constrained configuration is recommended for reducing the risks.
- The beacon should include as much data as possible. For QARMAN case, more data points (temperatures for example) at smaller intervals would have been highly appreciated, as well as (at least rough) attitude data.

On a programmatic point of view, resources (manpower) for operations should be carefully planned, secured, and trained, possibly considering nightshifts for the first weeks. The (updated) duration of the mission should be considered for this purpose. Also, the data handling (collect, process, store) shall be set up and tested well in advance and automatized as far as possible before launch.
Finally, and in general, a PA/QA plan and a risk management plan should be put in place from the beginning and followed all along the project, especially for those with a high novelty degree.

QARMAN first objective was to **demonstrate the feasibility of a CubeSat as a re-entry platform**. It has been indeed demonstrated that a reentry CubeSat could be designed, built, tested, and qualified for launch, complying with international regulations (regarding space debris mitigation, radio frequency use, and national registration). QARMAN was successfully launched and showed the proper functioning of main subsystems, despite difficulties with the UHF transceiver, for 5 months. Moreover, all subsystems related to reentry had been previously successfully tested at scale 1 in SCIROCCO plasma wind tunnel. Therefore, this first generic objective is to a great extent achieved. As detailed in Section 5.2, a signal loss caused the premature end of the mission. However, it was still possible to confirm the proper deployment of the AeroSDS solar panels. The in-house designed complex mechanism, combining a rotation and a translation, is now validated and reached TRL 9. This represents a major IOD achievement.

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