Strateole2 C1 Balloon Launch Campaign Report: Diagnosis and potential solutions for interference on the Strateole2 ROC2 receiver

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1. Background

The ROC2 radio occultation receiver was deployed in the Strateole2 technology demonstration campaign in 2019 to derive temperature profiles to be used to investigate properties of equatorial waves in the stratosphere and wave forcing of the Quasi-Biennial Oscillation (QBO) in zonal stratospheric winds. ROC2 retrieved high vertical resolution profiles with variations from the background temperature profile that revealed the presence of 20 day period Kelvin waves and shorter 4-5 day period inertia-gravity waves. The instrument was successful in making 45 profiles per day for 17 continuous days from the Strateole2 superpressure balloons, and demonstrated the potential for comprehensive sampling of the atmosphere with 5 balloons in the planned 2021 C1 science campaign. However during the 2021 deployment, the same instrumentation on the same platform suffered from severe interference that prevented the recovery of any data to date. This statement of work proposes to determine the cause and find a solution for the problems that were discovered in order to assure the success of ROC2 measurements for the future 2024 Strateole2 C2 science campaign that seeks to quantify wave activity in the opposite phase of the QBO.

The ROC2 radio occultation instrument makes observations of GNSS signal carrier phase to derive atmospheric delays from which the refractive index of the atmosphere can be derived, and from that, the temperature and pressure. The phase observations rely on cross-correlation of a low amplitude GNSS signal with a signal replica in the receiver at 1.57542 GHz (L1) and 1.2276 (L2) and 1.17645 (L5). Any strong emissions at frequencies near these can interfere with signal tracking by decreasing the GNSS signal to noise ratio of the cross-correlation (CNo) and interfere with the ability to retrieve carrier phase observations. The ROC2 equipment was tested on the ground at the beginning of the field deployment, and from the beginning showed large variations in CNo and associated gaps and discontinuities in the measured carrier phase. Significant efforts were made to determine the cause of the interference and mitigate it while in the field, which are described in more detail below.

The efforts were unsuccessful, however, it was possible to determine that the likely cause was electromagnetic interference (EMI) generated by the power supply that regulated the solar panel charging of the battery that provided power to the instrumentation. In addition, interference from Iridium data transmission caused confounding variations in ROC2 performance which were to some extent mitigated with the strategies described below. However, the exact nature of any remaining interference generated from the Iridium transmission will require further investigation after the more significant effects of the power supply are resolved.

2. Signal interference

The primary evidence for linking the interference to the power supply was the repeating pattern of GNSS signal tracking loss that was correlated with the charge cycle of the battery voltage and the solar zenith angle. The time of transition from night to day, at which point the battery charging began, varied over the duration of the balloon flight as the balloons traveled east, distinguishing it from a regular 24 hour diurnal pattern.

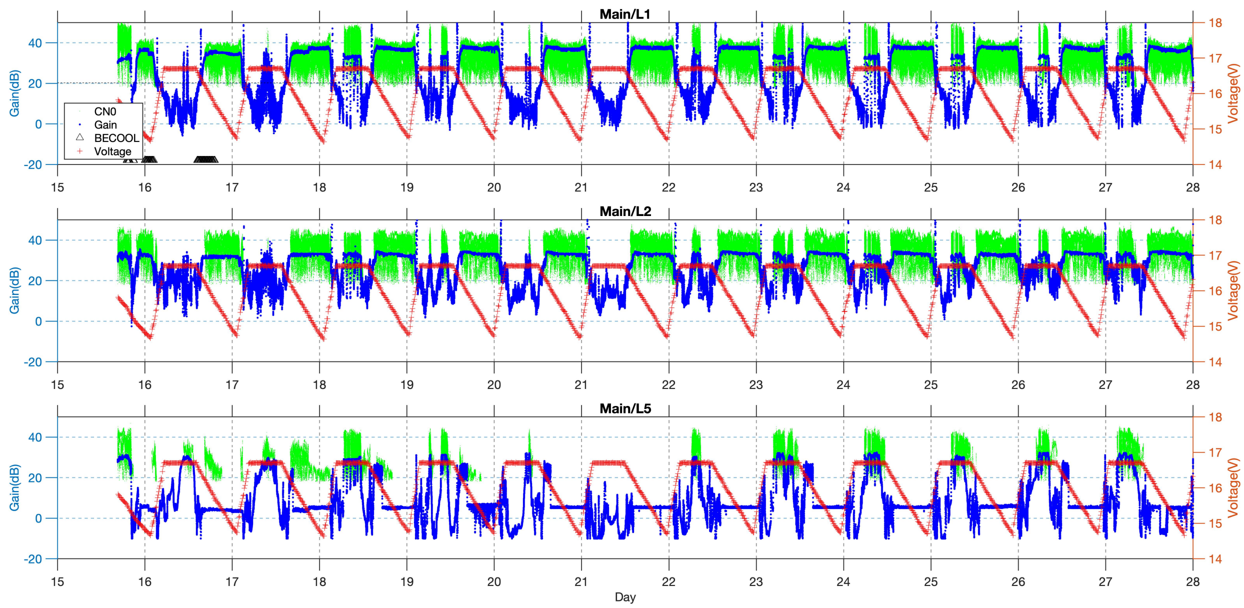

Figure 1 For receiver ROC2.8, red symbols show battery voltage during the day (constant at ~16.7 V), decreasing during the night, and rapidly increasing at dawn. Green symbols show CNo values and indicate when observations are present. Blue symbols show front end gain for each frequency, which varies with the Automatic Gain Control (AGC) function of the receiver depending on the strength of the incoming signal. Low values of gain indicate an anomalously high power input to the receiver.

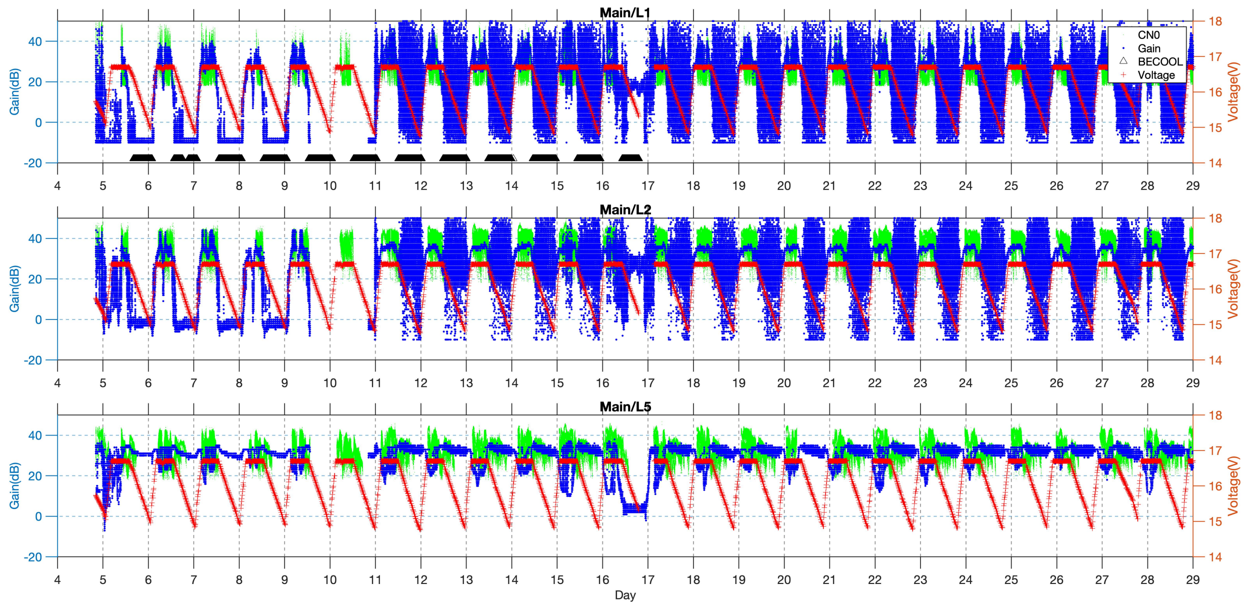

Figure 2 For receiver ROC2.5, showing voltage, CNo, and gain as in Figure 1. Note that observations are present during the daytime (constant voltage) as opposed to receiver ROC2.8 where observations were present during nighttime (decreasing voltage). This behavior is yet unexplained.

3. System description

The block diagram for the STR1 gondolas containing the ROC2 instrument is provided for reference prior to presenting the field test results and mitigation approach.

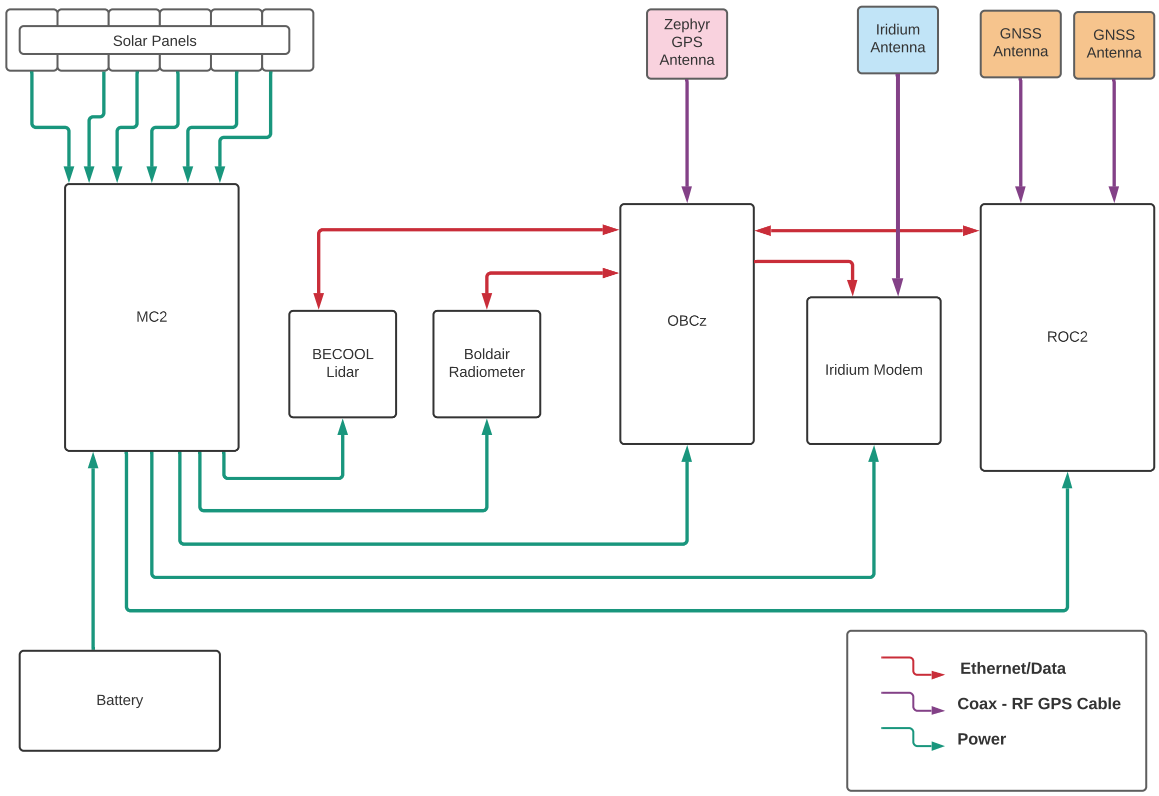

Figure 3 Zephyr STR1 gondola block diagram. MC2 is the power management system. OBCz is the Zephyr on board computer that controls power and data transmission from the gondola as well as power control and data exchange with the individual instruments.

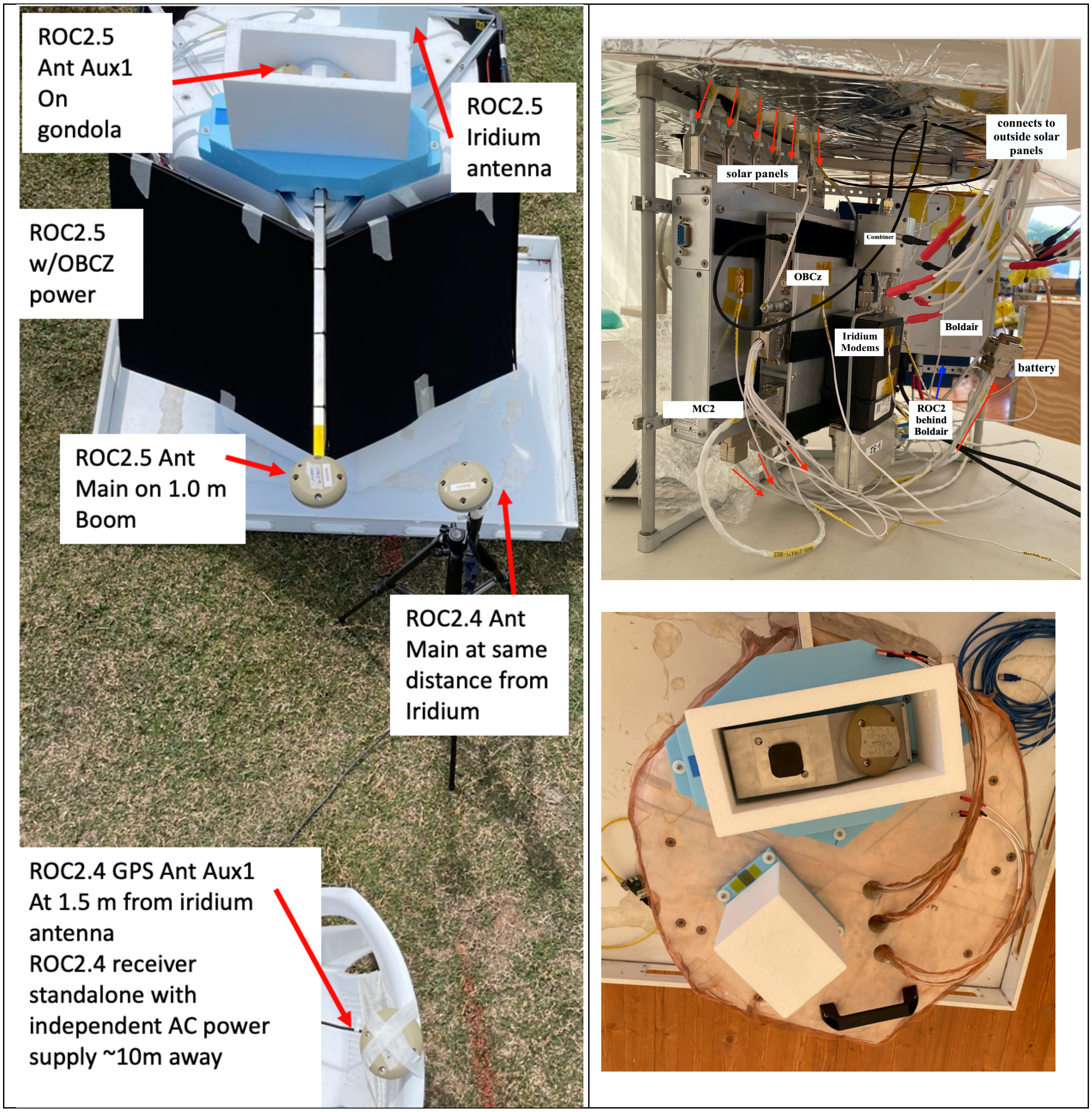

Figure 4 Instrument and antenna configuration on gondola. Left: ROC2.5 gondola during testing with solar panels. ROC2.4 was also deployed in standalone mode to monitor any radiated interference. Top right: configuration of MC2, OBCz, and Iridium modems within the gondola. The lower edge of the blue ROC enclosure is visible on the back right side. Lower right: ROC2 Auxiliary antenna on the top of gondola, small black passive Zephyr GNSS antenna for rough position and timing, white closed box contains iridium antenna.

4. Field testing

Our field team was deployed to Seychelles from Oct 3 through Nov 23 for the balloon payload preparation and launch activities. We assembled and tested each of 5 ROC receiver packages for functionality and performance in the tent provided by CNES for the science teams to carry out the work at the airport launch site.

Within the science tent, immediate signs of variable iridium interference were detected on ROC2 instruments. Iridium transmission was present on the STR1 gondola and on other science gondolas during the integration phase. Per the suggestion of LMD engineers, the receivers were grounded to the gondola chassis. The effects of grounding were tested on ROC2.5 and ROC2.6 inside the tent and proved inconclusive, which was a common occurrence for testing inside the tent. Several tests were carried out with standalone ROC2 receivers on their independent power supplies, which also produced intermittent problems with signal tracking. We believe this to be a result of the radiating iridium signals from the gondolas being prepared for other instruments.

After the launch of ROC2.7, signs of intense inference during flight were recorded that had not been seen on any ground tests. We believe that the two causes of this interference are iridium signals captured by the GNSS antennas and interference from the power supply as intense interference was correlated to the solar cycle.

To minimize this effect and create a more controlled environment, the remaining testing was performed roughly 20 feet outside the tent using a test battery to simulate the flight configuration. To resolve the iridium radiation issue on the STR1 gondola, we tested the GNSS antenna at different distance from the iridium antenna. We tested 1.0 meters, 1.5 meters, and 2.0 meters using ROC2.5 and ROC2.6. Although this test illustrated better data when the GNSS antenna was further away from the iridium it was not reproduceable on the ground and deemed inconclusive.

Despite the inconclusive results, we implemented the decision to move one GNSS antenna further away from iridium antenna for the flights, partially based on more controlled experiments carried out previously at SIO. The in-flight data from ROC2.5 and ROC2.8 demonstrated that moving one GNSS antenna 1.0 meter and 1.5m, respectively, away from the iridium antenna enhanced the performance of the receiver to capture satellite signals. In flight there was a clear difference between the antenna directly on the top of the gondola, which recorded no data, and the antenna on the booms, which recorded some data.

Keeping one GNSS antenna at 1.5 m distance from the iridium antenna, we moved to testing copper mesh surrounding the gondola to create a Faraday cage to shield the antennas from any electromagnetic radiation emanating from within the gondola. This improved signal tracking on the GNSS antenna placed away from the iridium antenna and only slightly improved signal tracking on the GNSS antenna on top of the gondola.

Concerning the Iridium communications, in 2019 when transmitting only GPS constellation data, the modem was not able to transmit the expected amount of data, resulting in continuous data being stored on board and data being recovered on the ground with an accumulating delay over time. The result was about 21 days of data transmitted for 54 days of data recorded. We understand this was due to the programming of the transmissions that did not efficiently use all of the available transmission time. This was improved for 2021 so that the modem was transmitting data more of the time. In addition, as a backup and also to enable even greater transmission rates that would allow ROC to send back data from all four GNSS constellations , LMD had implemented for 2021 two Iridium modems on the same gondola to transmit data, with a combiner so that both would use the same iridium antenna. We tested the impact of this hardware change and ran a test that limited the rate of iridium transmission by removing the secondary iridium modem and combiner. All in all, these ground tests showed some positive signs of improvement in combatting the iridium interference.

Because of the correlation with the power charging cycle, we attempted to reproduce the problem on the ground by discharging a battery in advance, then running the system on the discharged battery, then during the test connecting the solar panels. We saw an immediate degradation in signal quality upon connecting the solar panels. The distance and shielding mitigation techniques could not resolve interference produced by the solar panels and thus prompted us to test ferrite beads on solar panel cables, cables from MC2, and ROC power and data cables. This test did show slight improvement when the solar panels were turned on but could not be reproduced during other solar panel tests. In-flight data shows this was not sufficient to improve data quality.

The most relevant tests are summarized in the table in appendix 1. The summary of modifications implemented are shown in Table 1. Many additional tests were performed but are not included in detail here for the sake of brevity. These included comparing performance with a passive GNSS antenna, digital filtering using proprietary capabilities of the Septentrio GNSS receiver OEM board, attenuating the Iridium signal, testing an analog Reactel Iridium filter, and a GPS only antenna with less sensitivity near Iridium frequencies. None of these provided significant improvement.

Table 1 Summary of mitigation approaches implemented for each ROC2 instrument.

STR1-2 (ROC2.7)
- launched 2021-10-21 – terminated (comms)
  - Main ant tilted 30 deg on gondola
  - Aux ant flat on gondola
  - No ferrite, no mesh, no boom, non-compliant ground, 2 Iridium modems

- STR1-4 (ROC2.5)
- launched 2021-11-04 – in flight
  - Main ant on 1 m boom
  - Aux ant tilted 30 deg on gondola
  - 17 ferrite beads on all MC2 lines
  - No mesh
  - Compliant ground, one iridium modem

- STR1-3 (ROC2.8)
- launched 2021-11-15 – in flight
  - Main ant on 1.5 m boom
  - Aux ant on gondola
  - 17 ferrite beads on all MC2 lines
  - Compliant ground, one iridium modem, Cu mesh on top

- STR1-1 (ROC2.6) not launched
  - Main ant on 1.5 m boom
  - Aux ant tilted 30 deg on gondola
  - 17 ferrite beads on all MC2 lines
  - Compliant ground, one iridium modem
  - Cu Mesh on top +2 sides
  - Older generation solar panels from 2019

- STRX (ROC3.1-xeos) not launched
  - Main ant on 1.5 m boom
  - Combiner from ROC3.1 to zephyr Iridium antenna
  - Ferrite beads on all MC2 lines
  - Compliant ground, Cu mesh on top
  - 1 zephyr iridium modem, 1 xeos iridium modem

5. Approach for diagnosis and possible solutions

Following the extensive field tests exploring the conditions presenting interference, we have already collected the available technical information from LMD, CNES, and Studelec (the enterprise that constructed the power supply). Upon return to the laboratory, we gathered input from engineering staff at SIO who were involved with the design and construction of the ROC receiver and with expertise in RF and electronic systems for a preliminary assessment and discussion of the path forward. Close collaboration with engineers from LMD and CNES will be critical, therefore we have exchanged information in the approach outlined below, and plan to continue to work together to find solutions, including in person visits when required. The following approach is outlined as a statement of work for a follow-up effort, with deliverables listed in the next section.

The MC2 regulates the battery charge using MOSFET devices that switch off and on to optimally regulate the charge. They have PWM (pulse width modulation), which will modulate the pulses and therefore produced varying spurious frequencies with each pulse over the course of the charging cycle.It depends on the load, so it slows down as the battery approaches full charge. During daytime it changes from on to off very slowly. The rapid switch can generate electromagnetic interference (EMI) ranging from DC to very high frequency. This is the suspected source of interference. There are standard ways to mitigate this and provide clean power by following up with a DC/DC regulator or filter. It is likely that MC2 does not have enough filtering, and we will explore whether additional filters can be added internally or external to the MC2. We will also check that there are no components inside ROC that are generating EMI, however the ROC units deployed in Strateole-2 2021 were tested on aircraft flights and recovered occultation profiles without any noticeable EMI problems. It is of note that the ROC unit that flew in 2019 had a short loss of tracking for approximately 10 minutes at the time when the battery came up to full charge at the beginning of each solar day. We have not gotten a full report, but it appears that ROC was the only instrument that had a serious problem with EMI during Strateole2. The possible other exception is the GPS on the RACHUTS end unit which often did not lock, but could not be definitively correlated with the MC2 cycle. Significantly, the UBlox GPS unit used by Zephyr for location and timing had very few data that failed the quality control criterion. It is not understood why that is the case except to note that continuous phase data was not required for the Zephyr GPS, so as long as 4 satellite pseudorange (distance) observations were available to calculate a position, it satisfied its performance requirements.

The likely reason that CNES went with a custom rather than off the shelf charge management system is the specialized need for remote monitoring of the power state of the unit, its components, and the instruments. It may not have been tested for EMI. There are commercial charge regulators that have been designed to satisfy European requirements for limiting EMI (EMC) per the 2014 directive 2014/30/EU. However, the choice of constructing a custom charge regulation unit seems to have opened up the possibility for significant impacts on the ROC science instrument.

The challenging situation of course spawned a discussion of what changed since 2019 when the ROC2 retrieved data successfully over 21 flight days. ROC2 design and construction had not changed, in fact the spare that was built for the 2019 campaign was one of the receivers tested in the field in 2021. The MC2 and OBCz were constructed in the same way and deployed with the same model Iridium modems. Solar panels with insignificant differences were used in 2019 and

2021. At this point, however, it is necessary to consider that what should be insignificant differences in parts or components are indeed significant, and this could be in the purchase of any component of the integrated system acquired in the 2 year span. Therefore our approach is to identify the subsystem that is responsible and create specs and verification tests at the subsystem level.

5.1. Reproduce repeating pattern of interference on the ground

We have arranged with LMD to ship the flight gondola from the STR1-1 flight carrying ROC2.6 to SIO so that we can perform tests on site of the performance. The BeCOOL lidar and BOLDAIR instruments will be removed prior to shipping. The final STR1-1 flight was canceled because the balloons were inspected and appeared to be defective. These tests will specifically be using exactly the flight configuration gondola. The tests will be run in an indoor environment at SIO for tests limited to the MC2 unit, but the majority of tests will be carried out outside in the configuration with the solar panels that reproduces the charge loads as seen in flight.

5.2. Measure noise characteristics of power management system (MC2)

Placing ferrite beads on the power line from MC2 to ROC mitigated interference in one solar panel test but did not resolve the problem during flight. This illustrates however the important tests to carry out with analysis of the variability in the power with an oscilloscope, for all cabling in the power system during the conditions replicating the solar charge cycle in flight. We will determine if post filtering the power lines is an effective solution.

5.3. Measure possible radiated noise from MC2 in controlled environment

Because of the electromagnetically noisy environment during the field campaign (multiple gondolas simultaneously testing, airport operational equipment) it was difficult to determine if noise from the MC2 was conducted through the cables only or whether it was also radiated. We will use a spectrum analyzer to measure any radiated emissions and determine the origin and location. The SIO engineering team has a spectrum analyzer capable of measuring the origin of the EMI. The ROC2 Septentrio receiver OEM board also has the capability for monitoring the spectrum at the RF front end. This capability will be used to confirm signals picked up on the spectrum analyzer are impacting the GNSS receiver.

5.4. Isolate and spec out replacement components

If the source is isolated or some portion is determined to be conducted to the ROC2 receiver, then the SIO engineering team will test solutions for filtering such as passing data and power through the ROC2 chassis using feed-through EMI filters. The data connection between ROC2 and OBCz might benefit from optical isolation of the RS232 channel. We can evaluate the use of isolated RF SMA antenna connectors. Also we will evaluate the effectiveness of putting ROC into a better shielded aluminum enclosure. However it is always better to reduce noise at its source. We will attempt to isolate the component(s) that are causing the problems and test whether other options exist for the DC/DC converter and charger regulator, in particular, that could provide viable solutions. Any solution would need to consider that MC2 is a key component of the EUROS and Zephyr Systems and that any design modifications would require verification and qualification, that could take significant time, which may mean that only minor modifications would be feasible.

Any proposed hardware solution would also need to satisfy the requirement to operate down to -30 C, as well as up to the observed maximum temperatures in the gondola which reached 45 C in 2021. The components would also have to conform to European standards for EMI, which does not appear to be the case for the existing MC2. The existence of these standards however, gives an indication that a feasible option can be found.

5.5. Breadboard tests of replacement components

We will evaluate potential solutions with breadboard tests using a MC2 board where we bypass or remove certain components. This information on the properties of the different components will be communicated to CNES for evaluation in their plans for future MC2 fabrication and purchases and discussed at the planned collaborative team meetings. Because of the requirements for state-of-health monitoring, there may be limited modifications possible for the MC2. We require from our collaborators the schematic for the current system (we have an existing version of this documentation) and the software and theory of operation for the MC2. Jerome Bordereau and other colleagues at CNES have all the necessary expertise on the MC2, who will be able to help as needed, and will have the support of StephanieVenel (director of the CNES ballooning group). Augustin Caro, Claire Cenac, and Albert Hertzog from the Zephyr team at LMD will also be able to help as needed.

5.6. Verification of specific solar panels

The model of solar panel changed from 2019 to 2021. The most obvious feature is the positive and negative leads attach to the top of the solar panel in 2021, whereas the leads come out the bottom and top in the 2019 model. We will have access to both models of solar panels to test the potential impacts of this, although it is a low probability that this superficial change could be the one that has an impact, there could be other less visible differences.

5.7. Verification of Iridium-GNSS antenna separation requirements

The LMD team used a spectrum analyzer and a standalone GNSS antenna to measure antenna cross contamination at 1620 MHz. However, the characteristics of the interference are evident on L1, L2 and especially L5 frequencies for the gondolas in flight. Usually iridium interference appears most strongly on the L1 frequency closest to the Iridium band. So this indicates Iridium is not the primary problem, but our testing will quantify potential iridium interference. Previous tests of ROC and iridium without the OBCz and MC2 components indicated that a distance separation of 1.5 to 2 m is sufficient to achieve good quality GNSS observations on all frequencies. We were not able to see any more minor potential interference due to Iridium because of the more significant problems with the MC2. Once these are resolved however, we will verify that during regular data telemetry this is truly the case. If the Iridium does turn out to have a larger effect than anticipated even at 1.5 meters then we will investigate using a narrow beam Iridium antenna.

5.8. Verification of mitigation approach for scheduling Iridium Short Burst Duration and data telemetry

The timing of SBD transmissions used by Zephyr to transmit and receive infrequent command messages at the gondola showed a clear effect on CNo at specific times, and a minor variation in receiver front end gain during data telemetry. This effect was addressed in the field by the LMD team, by reducing the amount of time allocated to SBD transmission, and also concentrating data transmission at the beginning of each session to leave a longer period without any Iridium transmissions. The success of this strategy was difficult to test in the field because, once again, the effects were overwhelmed by the EMI from the MC2, and also because there was limited time for long term testing of the reliability and effectiveness for longer (~6 hour) session lengths. Therefore this will also be verified in the final testing.

5.9. Plans for fabrication and testing of power supplies for 2024

The key result of the testing is information provided to the CNES MC2 team on possible components that avoid or mitigate EMI from the MC2. Assuming they design and fabricate future MC2 units for the 2024 campaign, we will test the new units with the ROC in the flight configuration to help assure success in a potential 2024 campaign. The unexpected differences in performance between 2019 and 2021 motivate us to collaborate in order to avoid the possibility of any unanticipated changes occurring in the next group of MC2 units that will be purchased for 2024. Therefore we will provide a testing / verification plan for the system to be completed after manufacture of the next MC2 unit and in the instrument integration period prior to the campaign to assure there will be no unexpected surprises in 2024.

Appendix 1

Further information on field test results can be found at this link:
https://www.dropbox.com/s/w6xw18siaup54n4/test_results_2021-11-15_compressed.pptx?dl=0

Purpose	Start	End	Unit	Condition	Conclusion
Testing secondary modem	2021-10-12 04:30 UTC	2021-10-13 04:32 UTC	ROC2.7	• Inside tent • 1 GNSS antenna tilted on top of gondola • 1 GNSS antenna flat on top of gondola • power adaptor • 2 modems • 500kb/hr data rate • gps_dual config	• Data rate improved with 2 modems • Noise visible when science teams are arriving for the day • Occasional spikes potentially due to Iridium SBD
RFI next to ROC2.7	2021-10-12 04:30 UTC	2021-10-13 04:32 UTC	ROC2.6	• Inside tent • Standalone, no iridium • rfi configuration • 2 modems • main GNSS antenna aimed at iridium • aux GNSS antenna aimed away	• Noise visible when science teams arriving for the day • Occasional spikes correlated to spikes seen on ROC2.7
Grounding ROC2 to gondola chaise	2021-10-26 04:27 UTC	2021-10-26 16:31 UTC	ROC2.6	• ROC2.6 inside tent • Main GNSS antenna titled away from iridium • Aux GNSS antenna tilted towards iridium • No OBCz transmission • Power adaptor • Grounded instrument • Removed WIFI cable	• Loss of satellite tracking on AUX GNSS antenna when other iridium is powered on and off • Inconclusive
Testing different antenna difference after grounding ROC2	2021-10-26 07:23 UTC	2021-10-26 15:45 UTC	ROC2.5	• ROC2.5 inside tent • Power adapter • Iridium on • 2 modems • Aux GNSS antenna 2m outside tent • Main GNSS antenna 1.5m and then 1.0m outside tent • Grounded instrument • Removed WIFI cable	• GNSS antenna performed batter further away from iridium • Grounding had no discernable effect • Inconclusive due to other instrument iridium transmission turning on and off inside tent

Simulating recharge phase of battery	2021-10-28 06:29 UTC	2021-10-28 13:09 UTC	ROC2.5	• ROC2.5 outside tent • Discharged battery • Iridium transmitting • 2 modems • Main GNSS antenna on 1.0m boom • Aux GNSS antenna on gondola • 1hr no solar panels • 2hr with solar panels • 2 ferrite beads last 30 minutes of test	• Solar panel caused interference • Ferrite beads show some improvement, but test was too short to be conclusive
To capture RFI from ROC2.5	2021-10-28 05:59 UTC	2021-10-28 13:13 UTC	ROC2.4	• ROC2.4 outside in black pelican case • 2 modems • Main GNSS antenna next to ROC2.5 main GNSS antenna on boom • Aux GNSS antenna 3 meters from ROC2.5 iridium	• Interference was seen on both the main and aux GNSS antenna for ROC2.4 • Lost tracking completely on aux GNSS for ROC2.4
Ferrite beads and testing different antenna distance	2021-10-29 05:36 UTC	2021-10-29 11:40 UTC	ROC2.6	• ROC2.6 instrument is inside tent • 2 modems • Iridium transmitting • Main GNSS antenna 1.5m away from iridium outside tent • Aux GNSS antenna on gondola • 7 ferrite beads • Test rfi configuration	• Ferrite beads did not show a discernable affect when affect
Faraday cage and 1 modem	2021-11-03 06:34 UTC	2021-11-03 13:16 UTC	ROC2.6	• ROC2.6 outside tent • Iridium transmitting • Testing 2 modems, 1 modem, no combiner • Copper mesh • 17 ferrite beads • Main GNSS antenna on 1.5m boom • Aux GNSS antenna on gondola	• One modem slowed down data rate • No combiner and 1 modem helped improve data quality
Passive antenna as Aux antenna	2021-11-04 07:04 UTC	2021-11-04 14:04 UTC	ROC2.6	• ROC2.6 outside tent • Iridium transmitting • 1 modem • Copper mesh • 17 ferrite beads	• Passive GPS antenna showed same interference as a GNSS antenna on aux

				• Main GNSS antenna on 1.5m boom • Zephyr passive GPS antenna on aux connection	