NSF Annual Report

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Collaborative Research: Tropical waves and their effects on circulation from 3D GPS radio occultation sampling from stratospheric balloons in Strateole-2

1 Participants

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Michael Murphy, Postdoc, (SIO/UCSD)
Steven Liang, Graduate Student (UCSD)

Supporting personnel (current and over the course of the project)
Eric Wang, Postdoc (SIO/UCSD)
Frankie Martinez, Undergraduate (UCSD)
John Souder, Engineer (SIO/UCSD)
Sean McPeak, Engineer (SIO/UCSD)
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Dave Jabson, Engineer (Brainstorm Engineering)
Hong Liang, Visiting Scholar (SIO, CMA)
Stephanie Mumma, Staff Research Associate (SIO/UCSD)
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Other Organizations:

Collaborators:
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Albert Hertzog and Riwal Plougonven, Laboratoire de Météorologie Dynamique (LMD), École Polytechnique, Palaiseau, France
Philippe Cocquerez and Stephanie Venel, Centre National d'Etudes Spatiales (CNES), Toulouse, France
Lars Kalnajs and Terry Deshler, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder;
Sean Davis, NOAA Earth System Research Laboratory (ESRL), Boulder, CO, and Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder;
Francois Ravatta, LATMOS, Guyancourt, France

2 Accomplishments

Major goals of the project
Strateole-2 is a campaign for long-duration stratospheric balloon flights across the tropics to study atmospheric dynamics and composition. The scientific objectives of the research project using ROC2 observations are the following:
1) Quantify relationships between upper troposphere to lower stratosphere wave properties and tropical convection needed to improve model representations of wave driving of the quasi-biannual oscillation (QBO);
2) Determine the relationship of upper troposphere waves to the presence of cirrus clouds that can be used for improving model representations of these clouds;
3) Quantify global characteristics of waves that determine tropical cold point temperature variability for use in improving models of stratospheric dehydration.

The proposed work designs and deploys next generation GPS receivers for Radio OCcultation (ROC2) on board long-duration stratospheric balloons. These instruments will execute a continuous sequence of precise positions for Lagrangian gravity wave measurements based on horizontal velocity and height variations. Using recordings of low elevation angle occulting GPS signals, temperature profiles will be derived on either side of the balloon trajectory to sample the equatorial wave field in three dimensions. This will provide an unbiased view of 3D versus 2D wave properties at fine vertical scale and large horizontal scale.

What was accomplished under these goals?

Major activities

The ROC2 receiver was deployed successfully in the Strateole2 technology validation campaign December 6, 2019 through February 1, 2020 (Figure 1; Figure 2). It flew 57 days, 18 hours, and 30 minutes, recording data on board continuously with only a few data gaps (Figure 3; Table 1). Preliminary data analysis show good penetration of the profiles from flight level to about 5 km (Figure 4). However, a major difficulty was encountered for all balloons with the Iridium data communication system that limited the data rate to approximately 2 Mbytes per day split between all of the instruments on a single gondola, rather than the expected approximate 9 Mbytes per day, with 4.5 Mbytes per day allocated specifically to ROC2 (Figure 8).

We decided to prioritize sending back continuous data with an accumulating backlog rather than implement a reduction in data rate that would compromise the quality of the retrieved data (Figure 9). The balloon was slowly leaking helium from the start, requiring releasing ballast at regular intervals. This shortened the flight to when the ballast was completely expended, and the balloon was brought down when it approached a more densely populated area over Mali, where it was lost and not recovered (Figure 3). We transmitted and received a total of 24 days of data of which 17 days were consecutive (Figure 10), which came close to achieving our minimum scientific objective to sample waves with a period of up to 3 weeks. Other activities carried out during the year leading up to this campaign are described below.

Specific Objectives

Instrument development
Construction of the remaining instruments for the Strateole2 science campaign continued during the year. To summarize, in year 2 we completed construction of Four ROC2 receivers: S/N ROC2.1 (initial design), ROC2.2 (initial design + upgrade) and ROC2.3 and ROC2.4 (new design). In year 3, we upgraded ROC2.1 and ROC2.2 to the new design by replacing the interface board and adding the direct IP connection between the internal GNSS receiver board and the single board linux computer (SBC). The IP connection eliminated previous problems seen in the continuity of the onboard data logging by providing an alternate data logging path.

Two additional receivers were built with the new design, ROC2.5 and ROC2.6. All receivers are now in the same hardware/firmware configuration and all have been tested in flight configuration onboard aircraft. ROC2.3 (Figure 1) was flown in the Strateole2 technology validation campaign and has been lost. Four receivers are now available for flight during the science campaign planned for October 2021 (ROC2.1, ROC2.4, ROC2.5, ROC2.6). ROC2.2 remains the breadboard model for testing in the lab, so one additional receiver is planned to be built as a spare (ROC2.7) for the science campaign. The hardware design has been proven to perform well. The software has proven to function satisfactorily, however, we plan several improvements to increase reliability of file management on board.

Seychelles campaign challenges
During the year, one trip was made to LMD and LATMOS in France for testing the equipment in the flight configuration. One trip was made to the Seychelles for final integration, testing, and launch of the balloon where we worked closely with the French teams from Laboratoire de Meteorologie Dynamique (LMD) and the French Space Agency (CNES). The principal technical problems during the campaign were due to the Iridium data transfer managed by the LMD Zephyr payload on board computer (OBCZ) (Figure 8; Figure 10), and an unknown problem with the LMD Zephyr solar power management system and the ROC2 that occurred daily for about half an hour just

following the battery being fully charged after sunrise (Figure 7). The power management system functioned correctly on the ground in 24 hour-long tests, however it was not possible to test the ROC with the solar charging system on the ground. We are working with LMD to schedule a time for us to collaborate to address these problems.

Tests with the standalone XEOS Resolute receiver

Given the difficulties with the Zephyr Iridium transfer, in the field we began investigating capabilities of Iridium data transfer in the equatorial regions with many people that support NSF research that incorporates Iridium technology. XEOS supports NSF polar research with its standalone low-power Resolute GNSS receiver that incorporates an Iridium modem within the instrument package (Figure 12). The Resolute is based on a Septentrio GNSS receiver OEM board that is quite similar to the model we use in the ROC2, so is expected to have very similar GNSS tracking performance. It has lower power requirements than the ROC2. With an NSF supplemental request, we arranged for testing of the Resolute in the Seychelles.

Based on the promising early tests with the XEOS Resolute receiver from the ground (Figure 13; Figure 14), we have requested to CNES that we participate in the additional test flights they had scheduled from Kiruna in June 2020, that they have proposed for additional testing of the CU LASP FLOATS instrument. This experiment would allow us to recover the Resolute instrument. We realize that the timing of the Kiruna test will probably be changed due to the current COVID19 restrictions and will be prepared for testing when that does go forward. We are submitting a supplemental funding request to NSF to support purchase and technological demonstration of the performance of the Resolute receiver for the tests carried out while in the Seychelles, and to further this objective.

We have proposed to LMD and CNES that we fly standalone Resolute receivers on the 6 CNES EUROS gondolas that do not carry any other instrument payload, in order to assure an adequate data set is collected for the science objectives. We would still plan to fly the ROC2 receiver on the Zephyr gondolas after improvements are made to the Zephyr on board data management and transmission. If the Kiruna tests are successful, we would submit an additional supplement if prospects are good to go forward with science flights on EUROS. We are working with CNES to schedule a time for us to collaborate to address this request.

Additional instrument functional tests on flights of opportunity

We deployed ROC2.4 on a flight of opportunity on the NOAA G-IV to make measurements during the AR-Recon 2020 Campaign from January 22, 2020, through March 15, 2020. It was deployed with a horizontal and vertical linearly polarized antenna, taking advantage of the two-antenna channel capability of the ROC2 receiver. This will also provide scientific data to assess the feasibility of measuring effects of hydrometeors on GNSS signals as a diagnostic tool for microphysical studies. An additional Septentrio Asterxu GNSS receiver was flown at the same time on the NOAA G-IV for conventional ARO observations. This will permit intercomparison of performance of the two receivers. This was useful as it led to understanding that the auxiliary (2^{nd}) antenna is limited in the number of signals (ie L2 or L5, not both) it can track compared to the main antenna.

The ROC2.5 and ROC2.6 were deployed during the AR-Recon 2020 Campaign on two Air Force C-130 aircraft. The aircraft were only equipped with L1 antennas, therefore have limited capabilities for accurate RO measurements to contribute to the data assimilation experimental objectives of AR Recon. However, the flights provide valuable functional tests for the two receivers.

The ROC2.1 receiver was deployed on a flight of opportunity in the Circum-Antarctic Shelf Experiment (CASE) at the request of one of the principal investigators. Numerical ocean circulation models require seafloor bathymetry beneath the ice and ocean state boundary conditions. The CASE experiment uses airborne gravimetry to map the seafloor to provide bathymetry beneath the ice for numerical ocean circulation models, which are being used to study ocean-ice-atmosphere interactions at rapidly melting ice shelves. That aircraft is already equipped with high precision GNSS navigation receivers. The PI from that effort, Dr. Jamin Greenbaum, offered to host a ROC2 receiver, with the hope that the ROC2 could make atmospheric measurements of the boundary layer that may affect snow accumulation and atmospheric modulation of sea ice distribution.

Archiving

The collection and archiving of the data from the Strateole2 campaign was successful, given the unforeseen limitations in data rate of the data transmission system. The technology campaign, and the three deployments on flights of opportunity, add to the previous deployments in AR Recon 2018 and the 2019 Grav-D mission, to provide a substantial dataset in different environments and different antenna-receiver configurations for future analysis. Because of the extensive field effort this past year, the processing and analysis of the data has not kept pace. The preliminary analysis of the quality, continuity, and reliability of the data from these many flights of opportunity have served well for functional testing of the receivers. Because the scientific analysis of datasets from the flights of opportunity are not critical to the success of the NSF Strateole2 mission, they are lower priority for analysis than the data from the Strateole2 technology campaign, which is currently ongoing.

Recovery Efforts

We have requested via the state department, who has contacted the Government of Mali to search for the gondola, which landed in an area that is not secure militarily. We have not had any response yet from the Government of Mali. The gondola did transmit ROC2 data for one day after landing, so we believe the instrument to be intact. In the unlikely event that the gondola can be recovered, there is a large amount of additional data stored on board. We recorded data from GPS, GLONASS, GALILEO, and BEIDOU constellations on board on all frequencies from a single antenna, which would provide at least 18 additional days of data, with at least 50% more occultations during the entire time period of data collection. The other recovery effort by LMD through a CU LASP colleague at Johns Hopkins University and by CNES through the French embassy appears to have ended unsuccessfully.

Significant Results

The Strateole2 campaign

The ROC2 receiver was deployed successfully in the Strateole2 technology validation campaign December 6, 2019 through February 1, 2020. It flew 57 days, 18 hours, and 30 minutes (Figure 3), recording data on board continuously with only a few data gaps (Figure 5Figure 3). We transmitted and received a total of 24 days of data, 17 of which were consecutive, which came close to achieving our minimum scientific objective to sample waves with a period of up to 3 weeks (Figure 6; Figure 8). The ROC2 data is currently being processed and quality controlled, and is on track for release to Strateole-2 project PIs by August 28, 2020. The TSEN data (temperature, pressure, position, velocity) for the entire 8 balloon data set is available for the use of everyone within the Strateole-2 project.

We have not yet completed the initial processing of the data, however we made a preliminary retrieval of excess doppler shift for a setting occultation on 12 December 2019 (Figure 4), roughly over Indonesia. The excess doppler shift increases from 0 to about 0.6 m/s before loss of tracking. Based on simulations of the excess phase, doppler, and bending angle as a function of time from a climatological background model for this particular observation geometry for GPS satellite 03, the tangent point height corresponding to 0.6 m/s is about 5 km. This is promising for the future retrievals. Sampling the vertical structure from flight level (20 km) to 5 km would provide a good dataset for resolving fine-scale vertical waves in the upper troposphere / lower stratosphere.

Key outcomes or other achievements:

The ROC2 recorded 24 days of data, the longest continuous time period being from 2019-12-06 through 2019-12-23 (Figure 6; Figure 10). The ROC2 recorded 5 second pseudorange and carrier phase observations from a single antenna on L1 and L2 frequencies for the GPS and Galileo satellite constellations at 5 second sample rate. The GPS observables will be used to calculate precise positions for the balloon, then in a second step the carrier phase observations for setting and rising satellites will be analyzed to determine the atmospheric delay from which profiles of temperature will be derived.

We recorded data from three satellite constellations (GPS, GLONASS, GALILEO) on one day (2019-12-15) and data from the BEIDOU constellation on one day (2020-01-14) for one day and recovered that data (Figure 10). These data will allow us to evaluate the potential gain in the number of occultations when running in all GNSS mode. For that day we will have much denser sampling of the gravity wave field, at least for a narrow range of wave types with periods less than a day. We also recorded data from two antennas for one day for evaluating balloon rotational motion and the precision of the positioning results, however we were not able to recover that data (Figure 5). Given the limited data rate, we may redesign the deployment configuration for a single antenna.

We are currently advancing with the first step of the analysis, to determine the precise position of the balloon, and further refine gravity wave motion at higher frequencies via the higher precision vertical position that is calculated relative to that provided in real time by the ZEPHYR gondola GPS navigation system. This was shown to have an accuracy of 20 cm in the vertical and 8 cm in the horizontal, in the analysis of comparable data from the Pre-Concordiasi campaign in 2010 (Zhang et al., 2016). The first step of the retrieval process, to calculate excess Doppler shift due to refractivity, is shown for one example (Figure 4). This example with maximum Doppler shift, corresponds to penetration depth of approximately 5 km.

What opportunities for training and professional development has the project provided?

We have worked closely with our collaborators at NorthWest Research Associates during the Strateole-2 campaign. In particular, Martina Bramberger (Figure 1) accompanied the PI, Jennifer Haase, to the field to participate in the integration, testing, and launch procedures during the campaign. She became more familiar with GPS and GNSS analysis concepts, and also gained very valuable field experience working with myself and with the research team from University Colorado, Boulder, responsible for the FLOATS and RaCHUTS experiment. She learned to prepare, launch, monitor, and analyze frost point hygrometer radiosonde equipment. She worked together with the UCSD postdoc, Bing Cao, to prepare an AGU poster that included a description of the project objectives, since the AGU meeting occurred 3 days after the launch of the balloon.

The postdoc from China, Bing Cao (Figure 1), was not able to travel to the Seychelles to assist with the launch of the instrumentation that he had worked so hard to prepare because of the uncertainty in being able to re-enter the US. This policy has had a significant impact not only on training and professional development for the postdoc, has made it more difficult to achieve a successful deployment for the project. However, he gained additional training and experience working closely with engineers during the development, such that he is now quite confident in his ability to manage an instrument development project. He is passing that knowledge down, in turn, to Steven Liang, who started working with the project as an undergraduate and then went on to complete his master's degree at UCSD, then rejoined the team working part time. We have one additional undergraduate involved in the project, Frankie Martinez. She provides project support, in time not spent on research duties on another project.

Now that the ROC2 receiver has been developed, we have made it accessible to other members of the research group for use for other projects, and gain experience collecting and analyzing GNSS data. A new postdoc, Ignacio Sepulveda, assisted a summer undergraduate intern, Phoebe Hudson, to measure sea level and investigate the use of reflected signals for calibrating models for storm surge in remote locations. They both gained a good deal of experience in the project. The student has continued onto graduate studies, and the postdoc is using the dataset for training in writing his first proposal. This is key training that he requested, in order to be a stronger candidate for faculty positions.

How have the research activities been disseminated to communities of interest

We presented results of data analysis from the ROC2 receiver test deployments on aircraft and provided status updates on the Strateole-2 projects at the American Geophysical Unions annual meeting and two focused scientific conferences: the ECMWF Observational Campaigns for Better Weather Forecasts Workshop, and the EUMETSAT International Radio Occultation Working Group Workshop.

In the ECMWF Workshop, in June 2019, the Strateole-2 Campaign was presented by our collaborator Albert Hertzog at LMD as an example of a targeted field campaign that will contribute to process studies that improve models by enabling and validating more advanced methods of parameterizing gravity waves in numerical weather models, as well as real-time data assimilation of in-situ balloon observations. At that conference, we also presented a poster on our recent work on retrieval methods and data assimilation of the ROC2 field test observations from the NOAA G-IV aircraft for improvement of modeling of atmospheric rivers.

We took advantage of the overseas travel to meet with Dr. Scott Osprey at Oxford, head of the QBOi initiative of the World Climate Research Program (WCRP) Stratosphere-troposphere Processes And their Role in Climate (SPARC). QBOi is an initiative to intercompare QBO simulations from climate models. He expressed positive enthusiasm, to plan for a joint Strateole-2 and QBOi/SPARC workshop following the first technology campaign, to encourage use of the Strateole-2 dataset for the intercomparisons.

In collaboration with Martina Bramberger at Northwest Research Associates, we delivered an invited presentation to the U.S. CLIVAR Process Study-Model Improvement Panel in June 2019 to explain how the research project plans to improve modeling and reduce biases, and whether it benefits the larger community. This is part of their effort to assure synthesis and integration of observations, and gauge the success of integrating the modeling and observational components of the campaign. We made an informal visit and presentation at Oxford, and met with Scott Osprey who is the lead on the QBOi intercomparison initiative at SPARC.

We presented a poster at the American Geophysical Union, in December 2019, to report on using the ROC2 during flights of opportunity to measure and analyze potential wave signatures at higher latitudes during an atmospheric river event. This work provided a basis for testing some of the algorithms that will be applied to the Strateole2 data. These presentations highlight the potential use of NSF sponsored instrument development for an expanded range of research topics.

Background information on the Strateole-2 Project is provided at:

https://strat2.org

A subset of information is available to the public on that site showing balloon trajectories and real time data.
https://webstr2.lmd.polytechnique.fr

Outreach to the general public was organized around personal twitter accounts linked to institutional sites.
(see https://twitter.com/gps_hammer, https://jhaase.scrippsprofiles.ucsd.edu)

New releases at institutional sites also covered the event:
https://scripps.ucsd.edu/news/and-away

A news report is in preparation by Nature News, following an interview at SIO in February.

What do you plan to do during the next reporting period to accomplish the goals?

The next reporting period will be focused on 1) the necessary testing and development to assure problems with data communication and the one hour per day GNSS tracking gap are resolved, and 2) processing the GNSS data for precise balloon trajectories and retrieving atmospheric profiles from the GNSS data.

We are planning for a 2.5 day workshop entitled "International Strateole2 Science Workshop on Waves in the Equatorial Atmosphere" to be held at Scripps Institution of Oceanography 10-12 May 2021. Coordination with international partners is ongoing.

3 Products

3.1 Publications

Journal Articles and Dissertations:

Haase, J. S., M. J. Alexander, A. Hertzog, L. Kalnajs, T. Deshler, S. M. Davis, R. Plougonven, P. Cocquerez, and S. Venel (2018), Around the world in 84 days, *EOS*, *99*.

Cao, B., J. S. Haase, M. J. Alexander, M. Bramberger, M. J. Murphy, Jr., and F. M. Ralph (2019), Investigation of inertia gravity waves observed by dropsonde and airborne radio occultation during an atmospheric river event in the northeast Pacific, paper presented at American Geophysical Union Annual Meeting, San Francisco, CA, 9-13 December 2019.

3.2 Technologies or techniques

ROC2 radio occultation receiver using carrier phase tracking for UT/LS profiling. We highlight here the exploratory use of the ROC2 receivers by an expanded user group, for airborne RO (ARO) profiling for forecasting in atmospheric rivers, for boundary layer studies in Antarctica for ocean-ice-atmosphere interactions, and for GNSS-IR reflection measurements of tides.

3.3 Inventions, patent applications, and/or licenses

Nothing to report

3.4 Web Sites

Title, URL, Short description of web site:

https://webstr2.lmd.polytechnique.fr/
Real-time display of balloon trajectories is available to the general public. The web site created by LMD was very effective for monitoring and managing data in real time, and submitting instrument commands during the campaign. A Strateole-2 PI password is required to access the telemetry and monitoring data from this web page.

sftp://sshstr2.ipsl.polytechnique.fr
During the campaign, raw data was available at a ftp site at the CCMZ control center, for download by instrument teams for pre-processing. A Strateole-2 PI password is required to access the telemetry and monitoring data from this web page.

https://data.ipsl.fr/s2dac/
Real-time display of forecast balloon trajectories, model and satellite products for the campaign duration. A Strateole-2 PI password is required to access this web page. The final data release one year after the end of the campaign will include public access to the products through this page.

https://strateole2.slack.com/
A slack project with multiple channels was also critical for project success, where communications regarding command requests and replies were exchanged. A Strateole-2 PI password is required to access this web page.

https://eos.org/project-updates/around-the-world-in-84-days
General public article about the Strateole-2 Project.

https://strateole2.cnes.fr/fr/strateole-2
Project description in CNES database of projects.

http://agsweb.ucsd.edu/strateole2/
Overview description of the ROC2 dataset. Publications and presentations on Strateole-2 ROC2 Science. Background information on the 2015 Strateole-2 science workshops. Open to the public.

https://strat2.org
Background information on the Strateole-2 Project.

http://strateole2.org
Strateole2 whitepaper

http://www.lmd.polytechnique.fr/VORCORE/McMurdoE.htm
Long-Duration Balloon Science web site

3.5 Datasets and data management plans

For reference, the key points of the 17 October 2016 data agreement are summarized here:

- Within 6 months of the end of the balloon campaign, i.e. August 28, 2020, all PIs will submit their data to the S2DAC data repository for the use of all Strateole-2 investigators.
- Within 12 months of the end of the balloon campaign, i.e. February 28, 2021, all of the Strateole-2 quality checked (QC) datasets will be registered with a Digital Object Identifier (DOI) and will be freely available to the scientific community through the S2DAC web site.

The following acknowledgements will be included in all publications using the Strateole-2 ROC2 dataset: "The ROC2 data were collected as part of the Strateole-2, which was sponsored by the National Science Foundation (NSF), Centre National d'Etudes Spatiales (CNES), and the Centre National de la Recherche Scientifique / Institut National des Sciences de l'Univers (CNRS/INSU). The acquisition of the ROC2 data was led by Dr. Jennifer S. Haase at the Scripps Institution of Oceanography, University of California, San Diego, under the support of NSF. The data are archived at https://agsweb.ucsd.edu/strateole2, at the Strateole-2 Data Archive Center at https://data.ipsl.fr/s2dac/, and at the University of Colorado, Boulder, Laboratory of Atmospheric and Space Physics https://xxx.lasp.colorado.edu. Strateole-2 ROC2 data DOI is XX.XXX.

4 Impact

Impact on the development of the principle discipline of the project (atmospheric science):

The new ROC2 observations will help determine the frequencies, propagation directions, and horizontal and vertical structure of tropical waves in the upper troposphere/lower stratosphere. These observations in combination with observations of clouds will impact climate modeling by determining whether the relationship between UTLS wave structure to tropical convection is adequately represented. It will improve cirrus representation in models by providing information about wave induced temperature variability and impacts on cirrus formation. Quantifying the wave types and characteristics will help understand cold point tropopause variability and stratospheric dehydration. The project will also investigate wave mean-flow interactions that drive stratospheric circulation to improve modeling of the Quasi-Biennial Oscillation.

The opportunities to deploy the ROC2 on aircraft during several atmospheric river reconnaissance field campaigns (2018, 2019, 2020) has resulted in accumulating a large dataset that can also be used for scientific investigations for atmospheric river research, in particular defining the vertical moisture structure in the low-level jet and how that distribution affects precipitation forecast accuracy. We are already using the data to evaluate the impact on forecasts in collaboration with the Center for Western Weather and Water extremes.

Impact on other disciplines
The project educates a group of early career scientists in advanced GNSS technology that moves the nation forward, as the US develops experience using multiple GNSS constellations. The experience using modernized GPS signals and additional global constellations of navigation satellites, such as Beidou and Galileo, has an impact on geodesy and remote sensing.

What is the impact on the development of human resources:

The project contributes to the development of human resources, in particular the intellectual growth and development and leadership skills of postdocs and graduate students. It provides training in scientific, organizational, and management skills necessary for a large scientific field campaign. The project has encouraged the participation at all levels of women in atmospheric science research and field work, that has been historically dominated by men, by providing mentorship by two female PI-s, Dr. Alexander and Dr. Haase.

What is the impact on physical resources that form infrastructure?

The deployment of the ROC2 instrument establishes strong connections with the French Space Agency ballooning program, that ultimately enables more research in the future to take place from these unique platforms.

The proof of concept of the observational techniques provides a new means for observing the tropical UT/LS that can be exploited for other research. This version of the instrumentation which targets only the upper troposphere with reduced size and complexity is accessible to a broader range of users without such a heavy demand for specialized knowledge.

It is already being used to provide data during each atmospheric river field campaign, and we hope to develop it as a permanent deployment on the NOAA G-IV and Air Force C-130s. This year we expanded its use for reflected GNSS signal measurements of tides.

What is the impact on institutional resources that form infrastructure?
N/A

What is the impact on information resources that form infrastructure?
N/A

What is the impact on technology transfer?
Deploying the small instrument on an aircraft has opened the way for expanded use of the technology, given the accuracy/cost tradeoff, relative to full open loop tracking GNSS recorder (GISMOS). We have had discussions with Google Loon about deploying the receiver for a proof of concept using their balloons, and look to have a collaborative preliminary study in the second quarter of 2020. We are planning to submit a proposal to investigate commercializing the technology, with several potential industry partners, to work towards deployment on commercial airlines. The receivers have been used for exploratory projects recording ground-based GNSS-IR reflection data over the ocean at the Scripps Pier, and shown to be consistent with other studies demonstrating relatively high accuracy as a measurement of ocean tides.

What is the impact on society beyond science and technology?

The wave properties that are investigated in this research will lead to better wave parameterizations in numerical models and improvements to climate modeling that ultimately impacts society and its ability to respond to climate change.

Test data collected during aircraft reconnaissance missions for pacific storms are being used to improve short term prediction of flooding through improved process modeling. This is done in collaboration with the Center for Western Weather and Water Extremes, so will also have an impact on improving water resource management in the state of California. This is leading to a dataset of significant size that can be used to address the question of whether radio occultation (space and aircraft) sampling of mid-latitude storms in the troposphere is biased and how to improve the use of the datasets within the moist atmospheric river objects in operational forecasting.

5 Conference Presentations

Cao, B., J. S. Haase, M. J. Alexander, M. Bramberger, M. J. Murphy, Jr., and F. M. Ralph (2019), Investigation of inertia gravity waves observed by dropsonde and airborne radio occultation during an atmospheric river event in the northeast Pacific, paper presented at American Geophysical Union Annual Meeting, San Francisco, CA, 9-13 December 2019.

Haase, J. S., M. Bramberger, M. J. Alexander, A. Grimsdell, A. Hertzog, and P. Cocquerez (2019), Strateole-2: Investigating the tropical tropopause layer with long-duration superpressure balloons paper presented at US CLIVAR Process Study and Model Improvement Panel Webinar Series, 25 June 2019.

Haase, J. S., et al. (2019), Potential Contributions of Airborne Radio Occultation Observations in Field Campaigns to Forecast Improvement of Hurricanes and

Atmospheric Rivers, paper presented at Observational campaigns for better weather forecasts, European Centre for Medium-Range Weather Forecasts, 10-13 June 2019.
Haase, J. S., B. Cao, J. Michael J. Murphy, M. Zheng, and E. K.-N. Wang (2019), Supplementing dropsondes with airborne radio occultation (ARO) observations during AR-Recon 2018: focus on model verification in advance of data assimilation, paper presented at International Atmospheric Rivers Conference, La Jolla, CA, 15-19 April 2019.
Cao, B., J. S. Haase, J. Michael J. Murphy, E. K.-N. Wang, and M. J. Alexander (2019), Airborne/Balloon-borne radio occultation: first results from an atmospheric rivers field test and prospects for the Strateole-2 gravity wave campaign, COSMIC Program Office, UCAR, Boulder, CO, 19 March 2019.
Murphy, M. J., Jr., J. S. Haase, S.-H. Chen, J. Bresch, F. M. Ralph, and B. Cao (2019), Spatial variations in moisture and precipitation forecast errors from satellite and dropsonde data assimilation in northern California atmospheric river events, paper presented at American Meteorological Society Annual Meeting, Phoenix, AZ, 6-10 January 2019.
Serra, Y. L., et al. (2018), The Risks of Contracting the Acquisition and Processing of the Nation's Weather and Climate Data to the Private Sector (vol 99, pg 869, 2018), *Bulletin of the American Meteorological Society*, *99*(6), 1109-1109.
Kalnajs, L., A. Hertzog, P. Cocquerez, M. J. Alexander, S. M. Davis, T. Deshler, G. Durry, J. S. Haase, A. Hauchecorne, R. Plougonven, F. Ravetta, J.-B. Renard, and S. Venel (2018), Stratéole 2: An Ultra long duration superpressure balloon campaign to study the equatorial upper troposphere and lower stratosphere, Abstract P53A-05, paper presented at AGU Fall Meeting, Washington, D.C., 10-14 December 2018.
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Cao, B., J. S. Haase, M. J. Alexander, and W. Zhang (2017), GPS radio occultation simulation experiments for the upcoming Strateole-2 superpressure balloon campaign investigating equatorial waves, A21I-2290, paper presented at AGU Fall Meeting, New Orleans, LA, USA, 11-15 December 2018.
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6 Acknowledgements

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7 Changes / Problems

Changes in approach and reasons for change

We are investigating the potential deployment of the XEOS resolute receiver that has self contained iridium data transfer

Actual or anticipated problems or delays and actions or plans to resolve them.

We are developing a testing plan for the ROC2-Zephyr OBCZ in an attempt to resolve the power problem when running on the Zephyr solar polar management system, and to resolve the communication problems with Iridium. Because the Zephyr OBCZ iridium data management functioned nominally at Guyancourt, France, and not in Seychelles, this would seem to require some offset testing.

Changes that have significant impact on expenditures.
Because of major problems with Iridium data transmission (Figure 14), we are requesting a funding supplement to purchase a XEOS Resolute GNSS receiver with incorporated iridium modem and investigate the performance transmitting data at equatorial latitudes. Because the Resolute manages its own communications it could potentially fly onboard the CNES Euros gondolas that currently are not planned to carry any instrument other than TSEN in the October 2021 science campaign. In order to do this, we need to participate in the June 2020 flight tests with CNES in Kiruna, Sweden, and make modifications to the existing (heavy) Resolute receiver enclosure. Should flights be successful, we propose to procure enough receivers to fly on the 6 extra balloons. This idea does not exclude the possibility of flying the existing ROC2 receivers on the Zephyr gondola, if the Zephyr transmission problems are solved.

Significant changes in use or care of human subjects.
N/A

Significant changes in use or care of vertebrate animals.
N/A

Significant changes in use or care of biohazards.
N/A

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9 Figures

The ROC2 instrument and Seychelles field team.

Figure 1 Clockwise from top left: Bing Cao, SIO Postdoc, packing the ROC2 instrument components for deployment. Jennifer Haase making the electrical and communications connections for ROC2 in the Zephyr gondola. Madeleine Haase, field assistant and safety officer, examining the ROC2 antenna enclosure (right top) and Iridium antenna enclosure (left top). Martina Bramberger assisting with the pre-flight weighing of a Zephyr gondola.

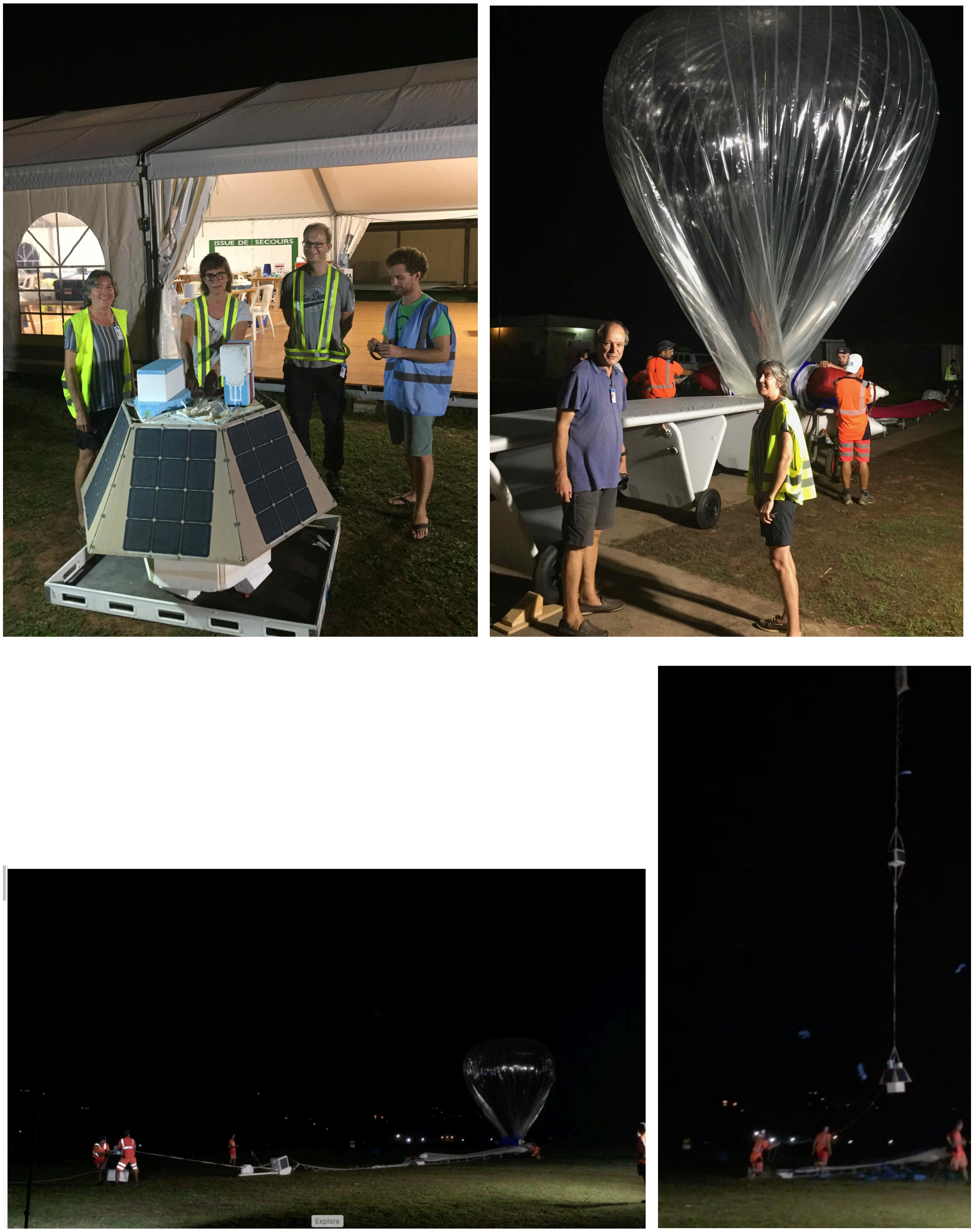

Figure 2 Clockwise from top left: STR1 Gondola ready for launch with Jennifer Haase (ROC2 PI), Claire Cenac (Engineer, LMD), Albert Hertzog (Strateole-2 Project Head, LMD), Emmanuel Brousse (Engineer, LMD); Inflation of the STR1 balloon with Philippe Cocquerez, CNES Balloon Program Head) and J. Haase; balloon launch.

Figure 3 Flight trajectories of the eight Strateole-2 balloons during the technology validation campaign 12 November 2019 through 28 February 2020. The 06_STR1 balloon carrying the ROC2 receiver is shown in yellow.

Table 1 List of balloons with instrument being carried. EUROS is the flight control gondola. ZEPHYR is the science payload management computer. The ROC2 is on ST2_C0_06_STR1.

	Flight	Latitude	Longitude	Nominal Altitude	Launch (UT)	Termination (UT)	Duration	Instruments
	ST2_C0_01_STR1	-7.41	-133.615	20 km	2019-11-12 20:43	2020-02-28 00:22	107 days, 3 hours, 39 mins	EUROS ZEPHYR TSEN
	ST2_C0_02_STR2	-9.965	162.902	20 km	2019-11-11 20:39	2020-02-23 02:03	103 days, 5 hours, 24 mins	EUROS TSEN
	ST2_C0_03_TTL3	-3.334	-81.428	18 km	2019-11-18 19:20	2020-02-28 11:05	101 days, 15 hours, 45 mins	EUROS ZEPHYR TSEN LPC RACHUTS
	ST2_C0_04_TTL1	17.191	90.368	18 km	2019-11-27 22:07	2020-02-02 13:00	66 days, 14 hours, 53 mins	EUROS ZEPHYR TSEN LOAC SAWFPHY
	ST2_C0_05_TTL2	-1.493	-119.984	18 km	2019-12-05 21:17	2020-02-23 21:03	79 days, 23 hours, 46 mins	EUROS ZEPHYR TSEN Pico-SDLA FLOATS
	ST2_C0_06_STR1	14.68	-5.157	20 km	2019-12-06 01:00	2020-02-01 19:30	57 days, 18 hours, 30 mins	EUROS ZEPHYR TSEN BOLDAIR ROC BECOOL
	ST2_C0_07_STR2	1.534	68.758	20 km	2019-12-06 23:26	2020-02-28 11:05	83 days, 11 hours, 39 mins	EUROS TSEN
	ST2_C0_08_STR2	1.998	173.474	20 km	2019-12-07 20:21	2020-02-22 23:20	77 days, 2 hours, 59 mins	EUROS TSEN

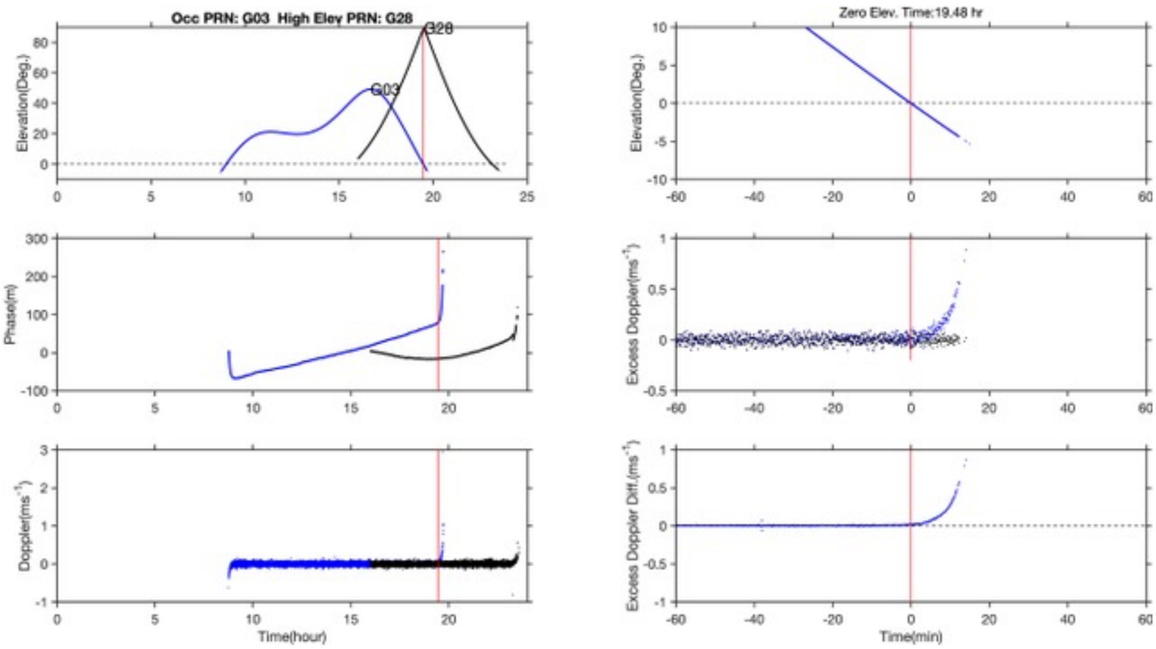

Figure 4 First excess doppler profile retrieved from ST2-C0-06-STR1 ROC2 receiver reaches a maximum of about 0.6 m/s (lower right). Based on simulations, this corresponds to an approximate minimum tangent point height of 5 km, which is excellent penetration depth in the tropics for the objective of sampling vertical structure of waves in the upper troposphere/lower stratosphere.

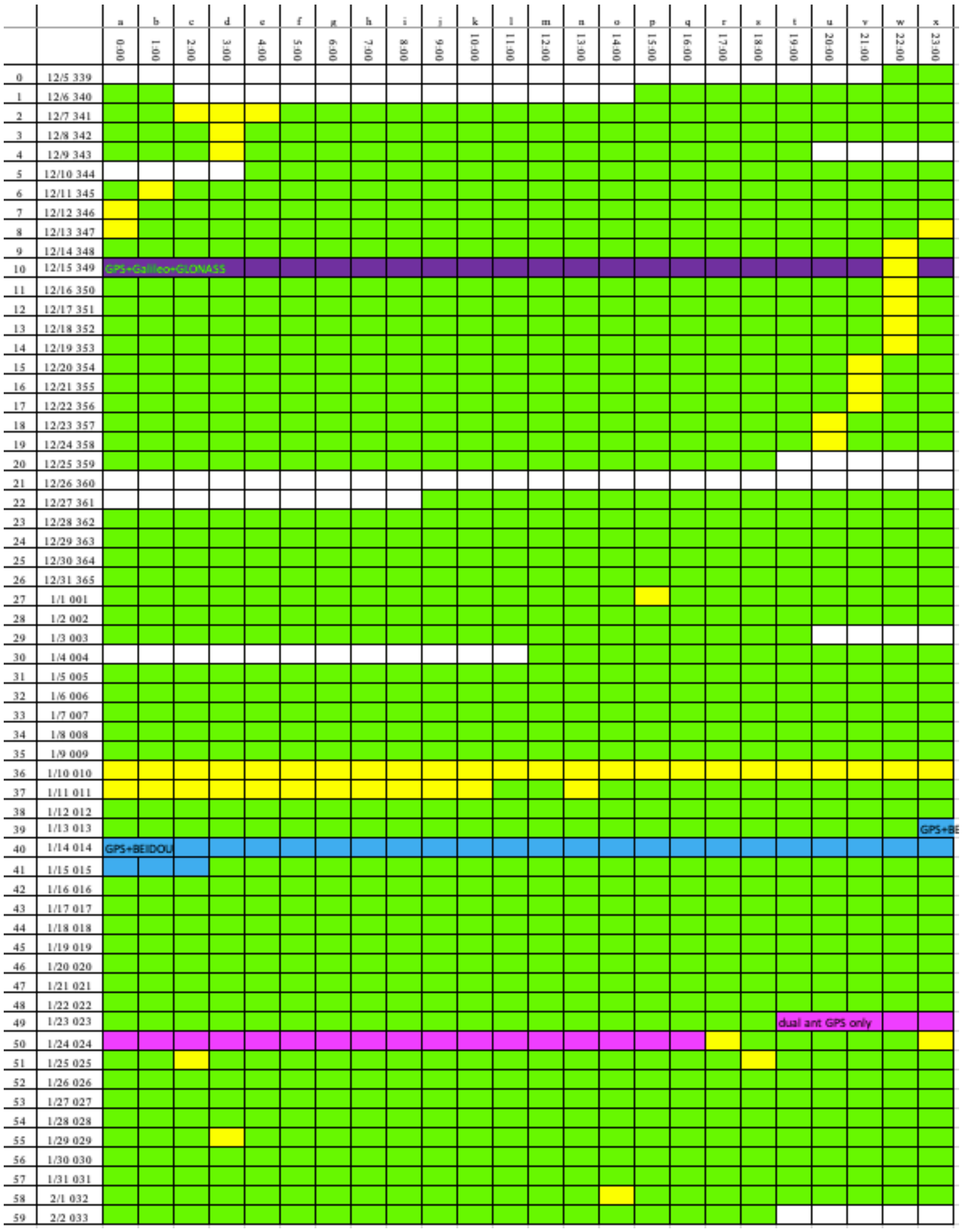

Figure 5 On-board recording log. Green: complete data. White: ROC2 instrument in Low Power mode and not recording. Purple: Intense Observation Period (IOP1) recording multiple GNSS constellations (GPS, Galileo, GLONASS). Blue: IOP2 recording GPS+Beidou GNSS constellations. Pink: IOP3 dual-antenna recording for balloon dynamics. Yellow: Gaps in data, some are due to GNSS signal tracking problems, isolated hour long periods are the subject of investigation regarding power management problems. Some are due to known reboot during debugging processes.

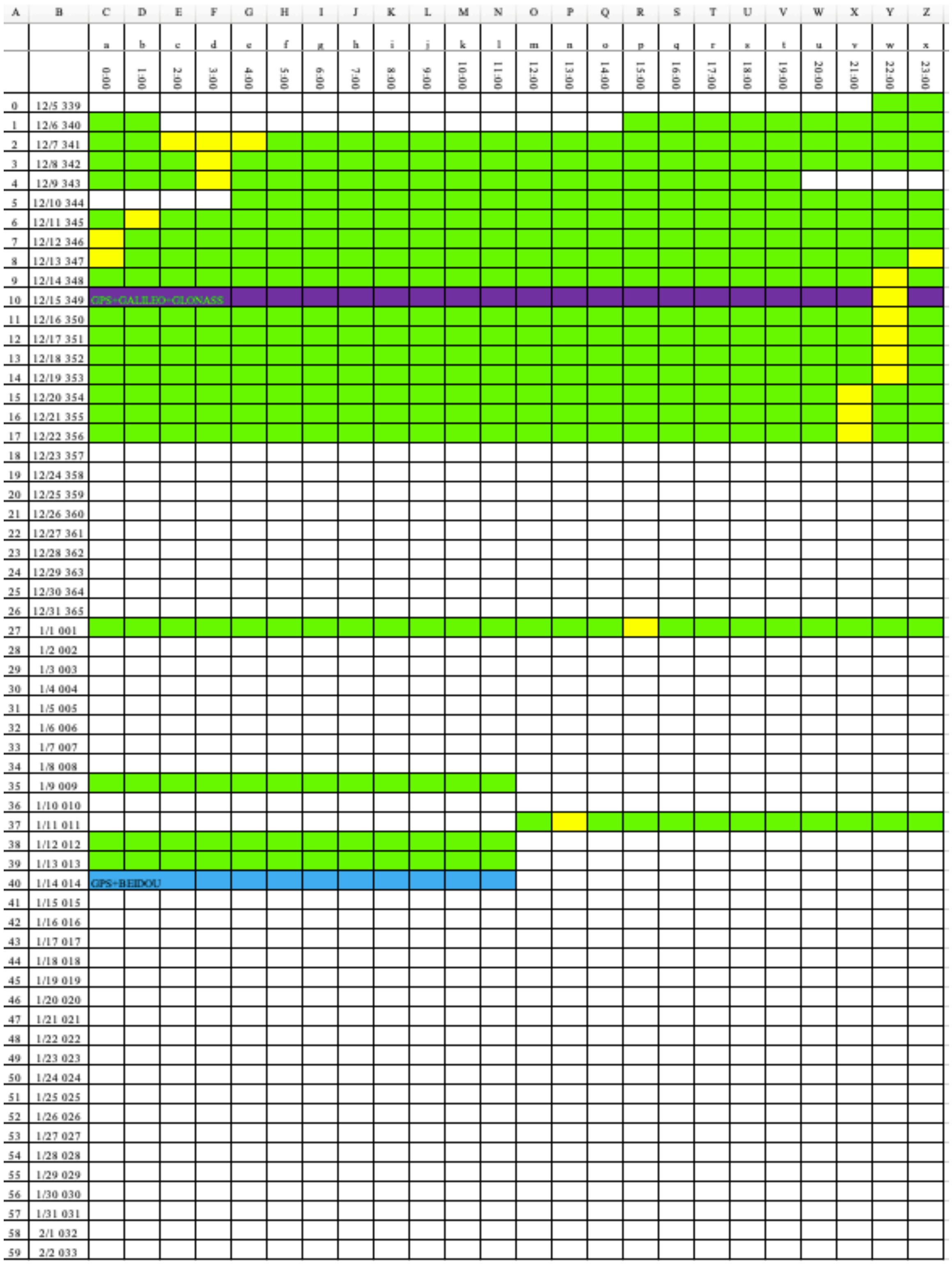

Figure 6 Log of data that was successfully transmitted to the CCMZ control center. Color key is the same as Figure 5.

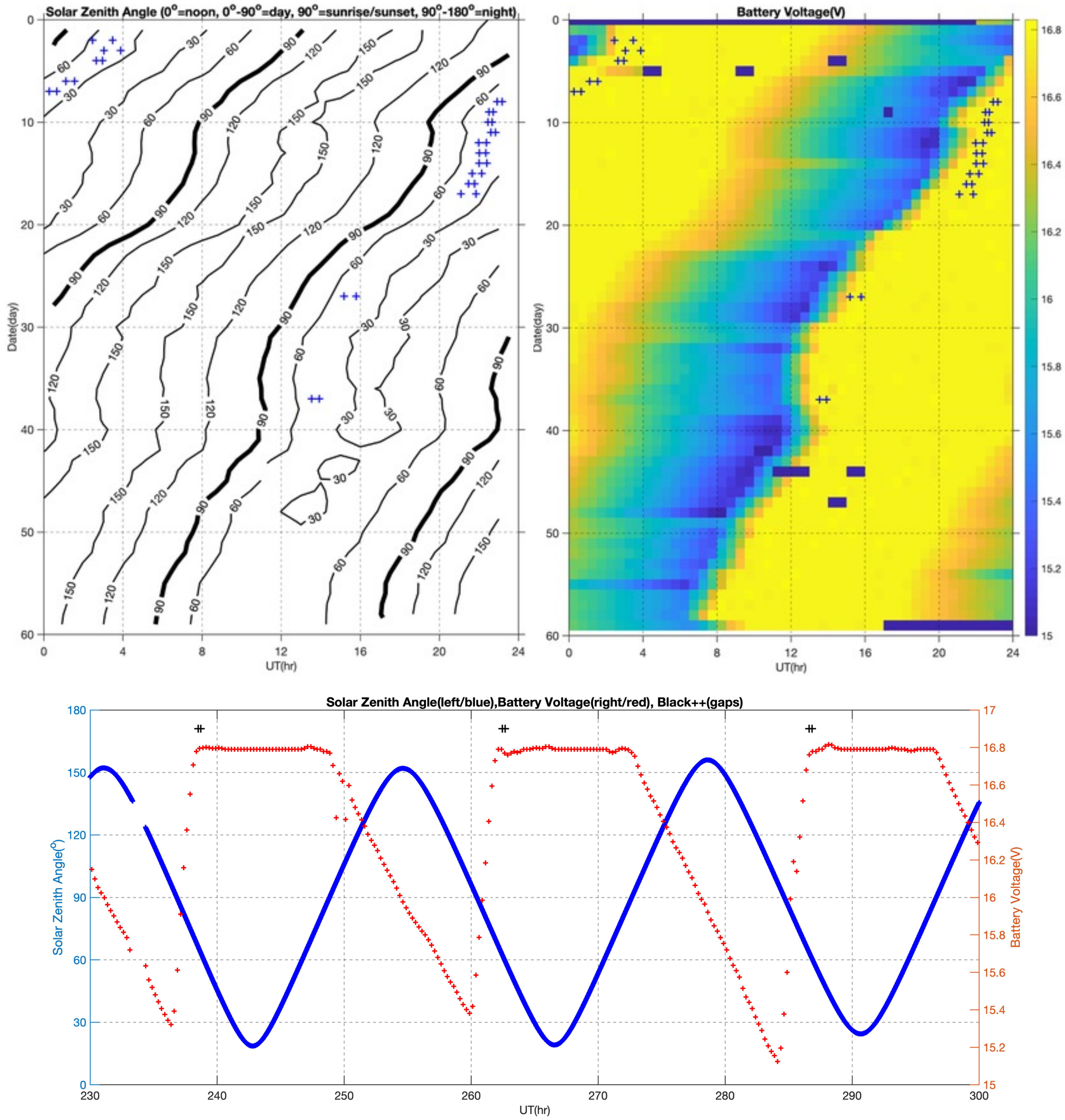

Figure 7 (top left) Solar zenith angle and (top right) battery voltage with UT time and days counted from the launch day. (bottom) The temporal series of solar zenith angle, battery voltage. The pair of crosses marks the start and end times of gaps in each day, identified from the recovered data. No crosses in other days because no data is recovered. However, there is a high probability that there are gaps in data from other dates even though we did not recover them.

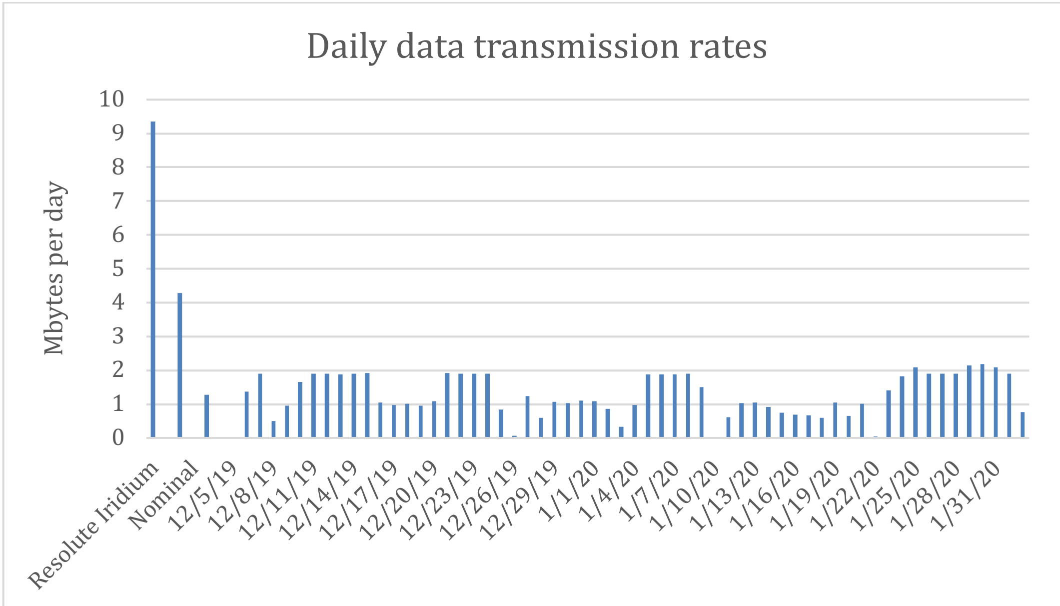

Figure 8 Daily data transmission rates achieved by the Zephyr Iridium connection. Nominal is the planned 4.5 Mbyte data budget tested in Guyancourt in June 2019. Resolute Iridium is the daily transmission rate of the Resolute GNSS receiver tested in Seychelles from the ground during the field campaign in December 2019. The bimodal distribution of transmission rates is due to the operational strategy adopted to accommodate the reduced available data rates (Figure 9).

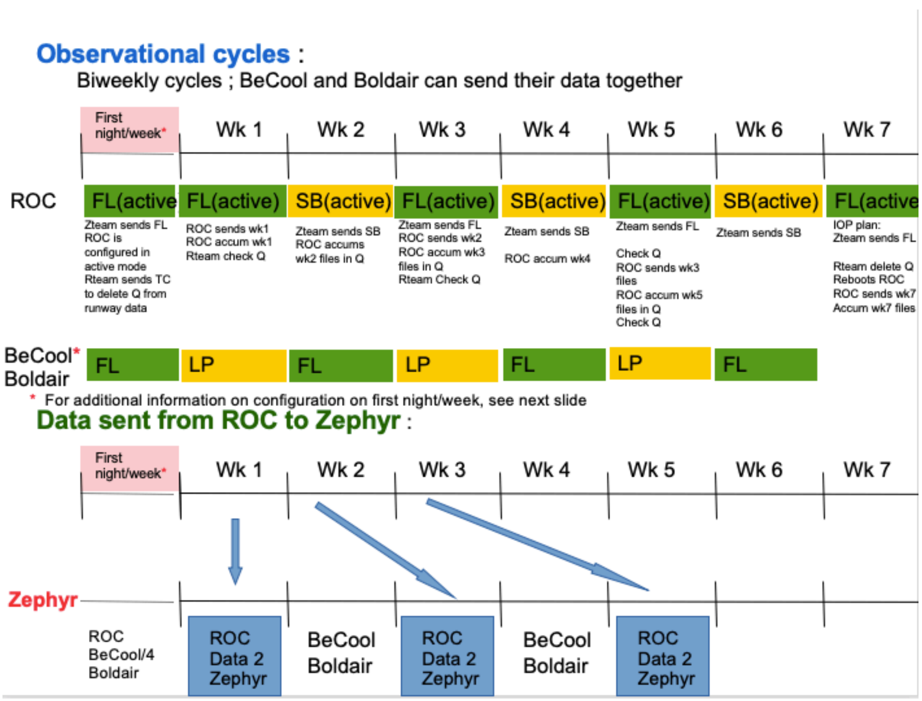

Figure 9 Operational strategy of alternating data transmission adopted to achieve minimum scientific objectives for the technology campaign. General concept is that BeCOOL and BOLDAIR transmitted data during the weeks when ROC2 was in standby mode during the night time, leading to half as much data transmitted those days.

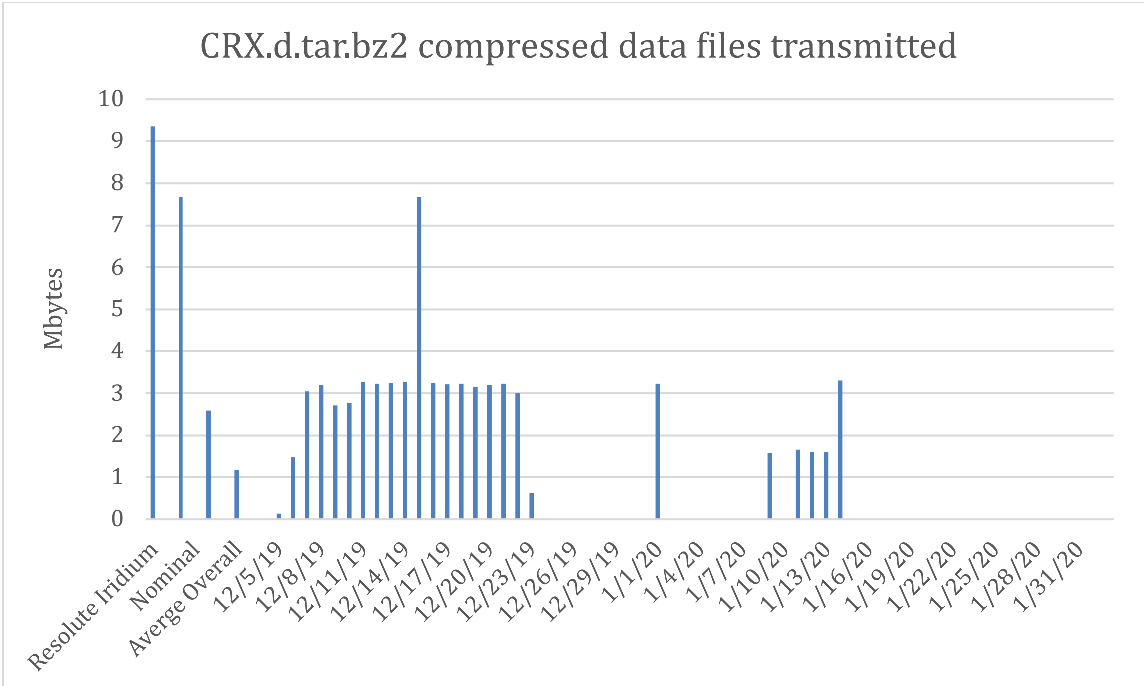

Figure 10 Amount of data successfully transferred for the days that were selected to be downloaded. A 17-day period of continuous recording was achieved from 2019-12-06 to 2019-12-23 that includes one day of multi-GNSS recording on 2019-12-15. The second IOP 2019-01-10 to 2019-01-14 includes observations of a potentially interesting inertial-gravity wave event, and includes one day of supplementary observations from the Beidou constellation on 2019-01-14. It required 57 days of flight to retrieve these 24 days of data. Nominal indicates the desired recording configuration of multi-GNSS data recording to maximize the number of occultations. Resolute iridium is included for reference and described further in

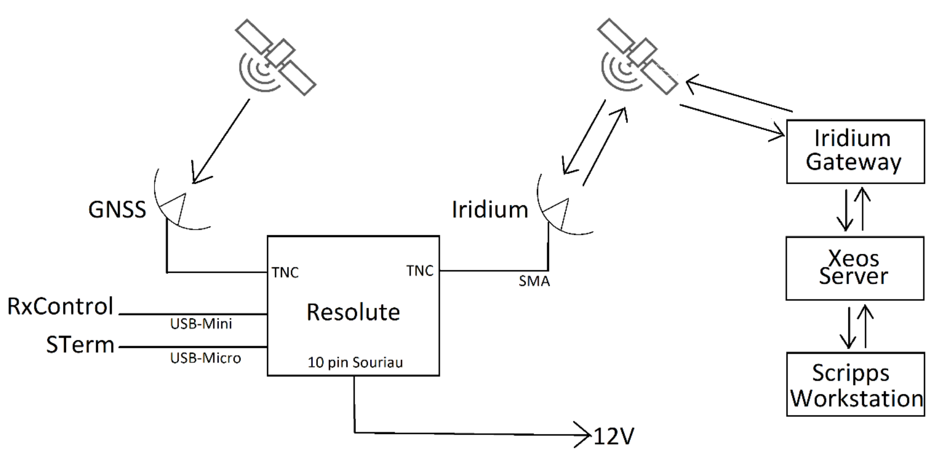

Figure 11 Seychelles ground station test configuration for the Xeos Resolute receiver to test potentiall available data transmission rates in the equatorial region. Data download server is manged by Xeos, included in the cost of the receiver.

	hour 1	hour 2
GNSS recording	Offset 0 m; Duration 1 hour	Off 1 hour
Transmit Tunnel	Off 1 hour	Offset 1 hour; Duration 1 hour Avg xmit time 31.4 min
SBD messages	Offset 110 minutes	Dur. 3 min / Off 2min

Figure 12 Recording and transmit configuration during Resolute receiver test. Because of a power problem with the specific Resolute unit (the unit has since been returned for repair), we could not run the GNSS recording simultaneously with the Iridium transfer. However, shows the key finding that one hour of GNSS data could be transmitted in less than an hour.

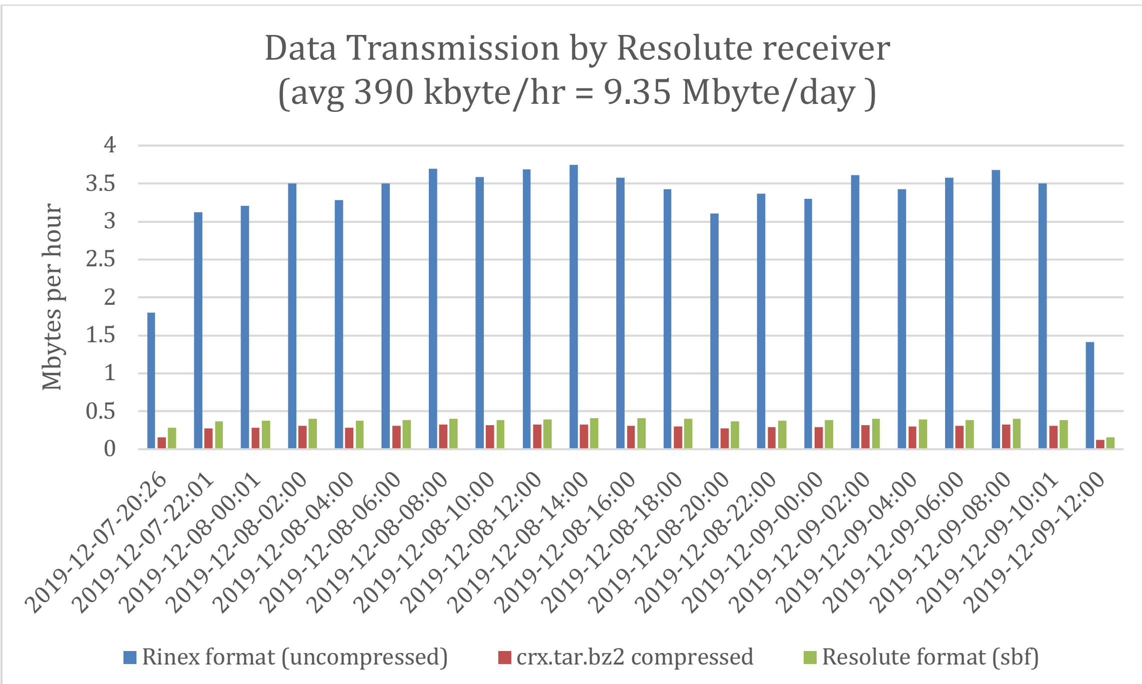

Figure 13 Results of the Resolute data transmission tests, with data sizes specified in equivalent uncompressed and compressed files. The data was actually transmitted in sbf format (green). In one hour, 390 kbytes of data were recorded by the GNSS receiver, and were transmitted, on average, in 31.2 minutes.

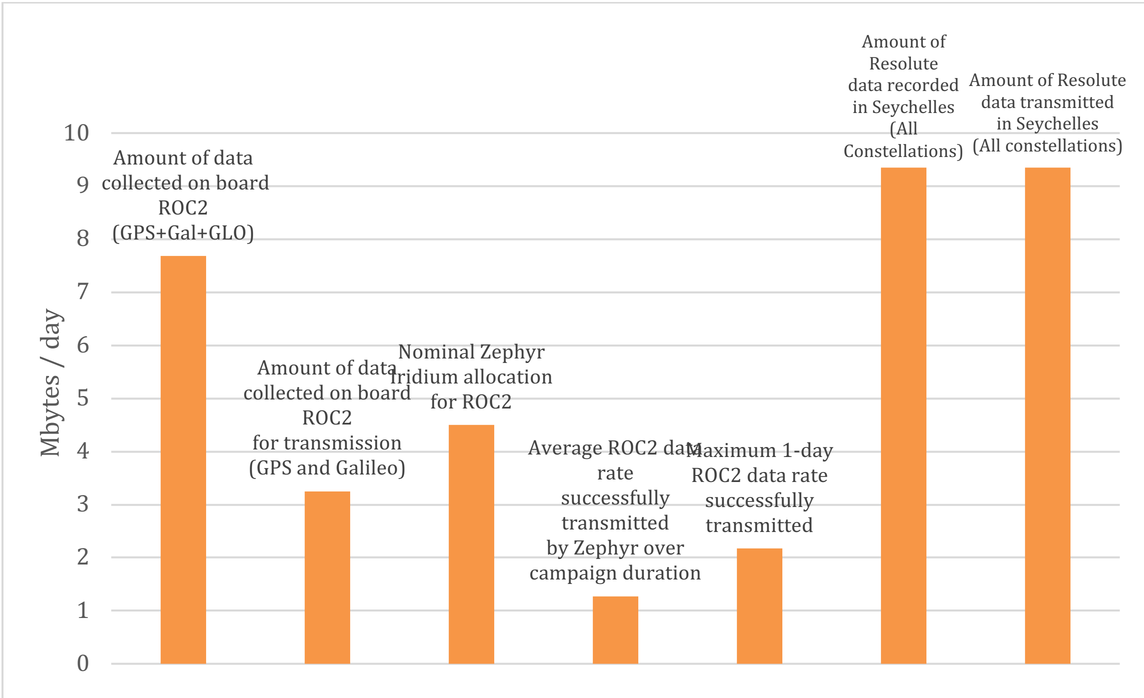

Figure 14 Comparison illustrating that the average data rate achieved in the campaign was well below the planned data rate, and well below the minimum requirements for the ROC2 receivers. Also illustrated is that the Resolute receiver demonstrated a data rate sufficient to transmit the entirety of the most optimal GNSS receiver configuration with all satellite constellations. Recording data from two antennas is not feasible with either configuration.