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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Allen Nance, Embedded Micro Systems

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
The scientific objectives of the research project 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 objectives of the proposed work are to design and deploy 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 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

We built a spare ROC2 radio occultation receiver, and then revised the design and built two more ROC2 receivers. We upgraded one of the initial receivers also to the new design which creates an IP connection between the internal GNSS receiver board and the single board linux computer (SBC), incorporates the capability for the GNSS receiver board to log data internally for backup, and implements a software power switch. We now have S/N ROC2.1 (initial design), ROC2.2 (initial design + upgrade) and ROC2.3 and ROC2.4 (new design).

We made one trip to LMD in Paris, France, to integrate the equipment in the balloon gondola and two trips to test the communication interface with the LMD zephyr on board computer that manages data transmission for the flights. We combined one trip to LMD with a trip to CNES in Toulouse, France, to give an invited scientific presentation and coordinate the integration and deployment. (presentation attached to this report). We combined one trip to LMD with participation in an ECMWF workshop, “Observational campaigns for better weather forecasts” and meetings at Oxford with researchers on stratospheric processes.

We analyzed the ROC2 receiver data from three test flights onboard the NOAA GIV research aircraft for the AR2018 field campaign from 26 January 2018 through 3 February 2018 out of Seattle. We investigated the observation quality and data rates. We retrieved refractivity and dry temperature profiles and compared them with ECMWF operational model analysis for a case study investigating the upper level temperature and potential vorticity structure during the evolution of atmospheric river storms.

We deployed ROC2.2 on a flight of opportunity on the NOAA G-IV to make measurements during their GRAV-D mission beginning February 2019. The instrument recorded data continuously on ferry flights from Florida to Hawaii and to Samoa. This will provide data in the tropical atmosphere and allow us to assess the data quality and especially allow us to assess the lower limit of the profiles in the tropical atmosphere. Recordings were made during the ferry flight from California to Hawaii during the AR Recon intense observational periods (IOP) leading up to a significant rainfall event February 14, 2019. This serendipitous recording will allow us to gain further experience in evaluating the quality of the data in the context of mesoscale modeling of the event.

Specific Objectives

N/A

Significant Results

ROC2 receiver demonstration data
Observations during atmospheric river reconnaissance flights

The ROC2 receiver flew with an avionics antenna on the NOAA G-IV on three flights during the AR Recon campaign in 2018. The data from a flight on January 26, 2018, has been analyzed to provide retrievals of refractivity and dry temperature. We retrieved 23 refractivity profiles during the 7.5 hour flight, 16 of which were from GPS satellites and 7 of which were from Galileo satellites. The excellent quality of the retrievals from the Galileo satellites was a surprise, given that we did not have high expectations for the GPS-only antenna. We recorded two closely spaced Galileo and GPS occultations and found the observations to be highly consistent. We also flew a Septentrio PolarX5 receiver, which has a similar Septentrio GPS OEM board to the one inside the ROC2 receiver, to have independent comparison data. The two receivers provided refractivity profiles that were very closely matched, verifying the quality of the ROC2 receiver data. These profiles are shown in Figure 1.

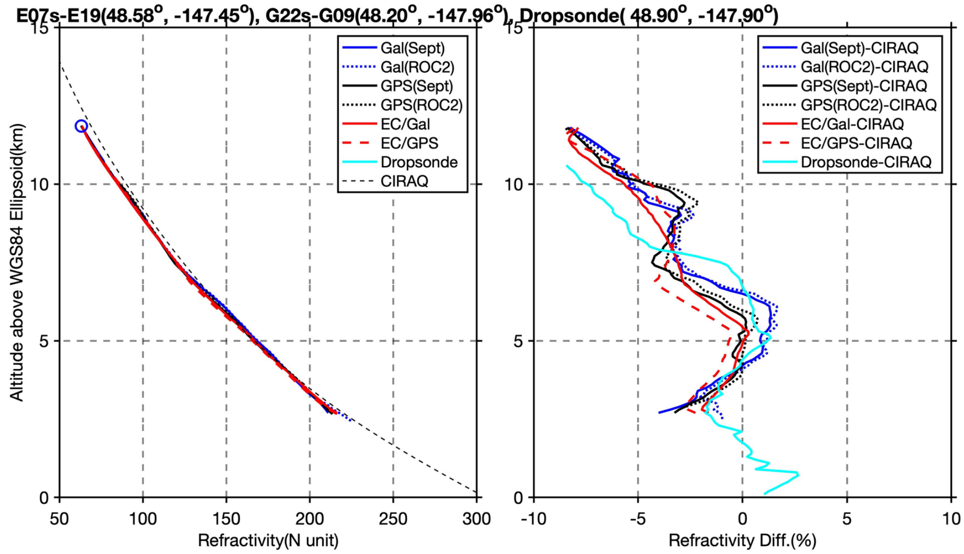

Figure 1 GPS refractivity profile from Septentrio PolarX5 (solid black line) and ROC2 (dashed black) receivers. Galileo refractivity profile from a nearby location is shown for Septentrio (blue solid) and ROC2 (blue dashed). Refractivity extracted at the horizontal tangent point locations from the ECMWF model operational analysis are shown for the GPS profile (red dashed) and Galileo profile (red solid). The closest dropsonde is shown in cyan.

The flight tests were valuable opportunities to test the instruments that are being developed, however the data are also scientifically valuable for the ongoing research into forecasting improvements for severe weather associated with atmospheric rivers. In particular, a test case was run where the impact of the dropsondes on the forecast precipitation of an atmospheric river storm was evaluated by doing control run with the Weather Research and Forecasting (WRF) model with dropsondes and a data denial run without dropsondes. The ARO observations are used as an independent dataset to evaluate the quality of the analysis after data assimilation. The bias and RMS of the model minus ARO observations were slightly improved in the experiment which assimilated dropsondes, as they should be given that we expect assimilating the additional dropsonde data would bring the model closer to the truth.

The WRF model run from the dropsonde assimilation experiment are used in Figure 2 to explain the observed differences when comparing the dropsonde and ARO temperature profiles. The ARO occultations on the south side of the flight track are shown in this figure, and all 5 ARO profiles show lower temperatures at 10.5 km altitude than the nearest dropsonde profiles, and ARO profiles have higher temperatures at 7 km than the nearest dropsondes. This is show to be consistent with the WRF model fields at 10.5 km that show a sharp temperature gradient parallel to the flight track with lower temperatures on the south side where the ARO profiles are. The WRF model at 7 km has lower temperatures on the north side of the flight track (figure not shown). The WRF model runs give added confidence that the ARO data is showing realistic atmospheric variations.

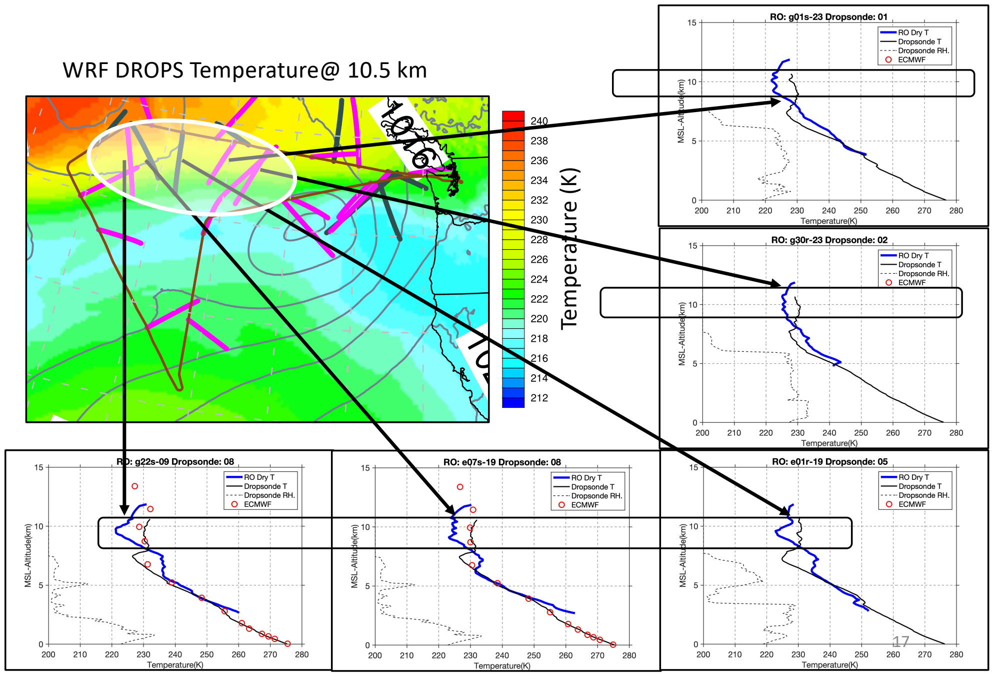

Figure 2 Temperature differences between closest dropsonde and ARO profile on the south side of the flight track are consistent with the temperature gradient (top left) at 10.5 km and 7 km from a mesoscale simulation of the event using the Weather Research and Forecasting (WRF) model.

The flight tests were also critical for testing some of the operational elements of the instrument. In particular we discovered a problem with the serial port transfer of data from the GPS board to the internal linux single board computer which resulted in small gaps of less than 0.1% in the data. Unfortunately, this is enough to seriously degrade the position calculation necessary prior to calculating the excess phase due to the atmospheric effects. Because we had redundant receivers deployed, we were able to provide the position through other receivers. We have since resolved the problem by readjusting the baud rate for data transmission to be consistent with the limitations of the current linux single board computer (SBC). Because of these and other difficulties with the SBC, we are in the process of redesigning the next version of the ROC to incorporate an alternative choice for the SBC for the 2020 science campaigns.

Simulations of wave observations

The radio occultation profiles are retrieved from an integral measurement of delay along the signal ray path. The simplest retrieval techniques assume a spherically symmetric atmosphere where refractivity varies only with height. Because this assumption is violated in the presence of horizontal wave structures in the atmosphere, we examine the extent to which this biases estimates of wave properties when using these simple retrieval techniques. Three-dimensional refractivity fields were created with a temperature variation described by a wave with horizontal wavelength of 800 km and vertical wavelength of 10 km. We assumed an exponentially increasing amplitude with height. We implemented an approximate raytracing method to calculate the magnitude of the expected wave variations in the phase observations, and then investigated the distortion of wave properties in the retrieved profiles.

A previously reported bias in the retrieval technique (Figure 3) presented at AGU 2017 has been corrected and removed (compare with Figure 4. The work is now planned to be submitted for publication. The right panel illustrates the bias in the retrieved apparent wavelength of the perturbation due to the combined effects of the bias in the retrieval and the 1D retrieval assumption.

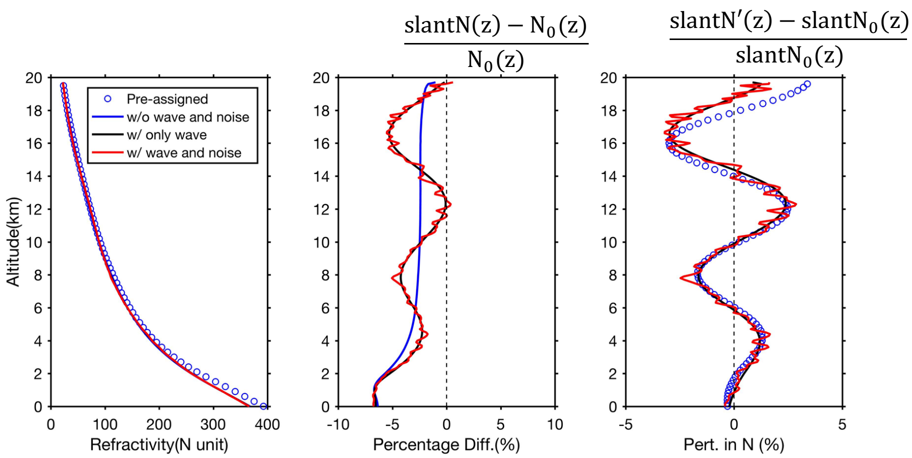

Figure 3 (Left) Retrieval of refractivity calculated in assumed N(z) profile (blue) with wave (black) and with wave and noise (red) before the source of the bias was discovered. (Center) percentage difference between retrieved and input N(z) profile illustrating bias (blue).

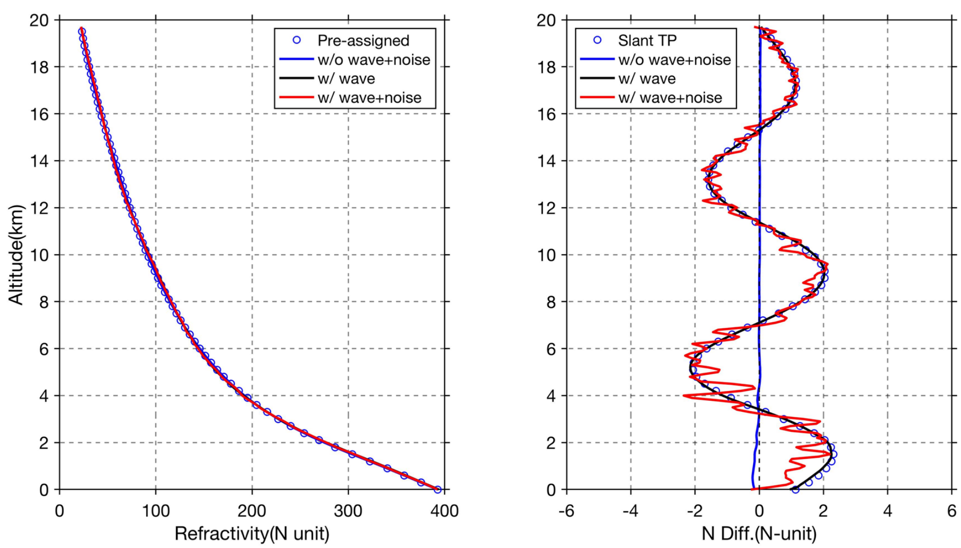

Figure 4 (Left) Retrieval of refractivity calculated in assumed N(z) profile (blue) with wave (black) and with wave and noise (red) after the source of the bias was discovered. (Right) difference between retrieved and input N(z) profile.

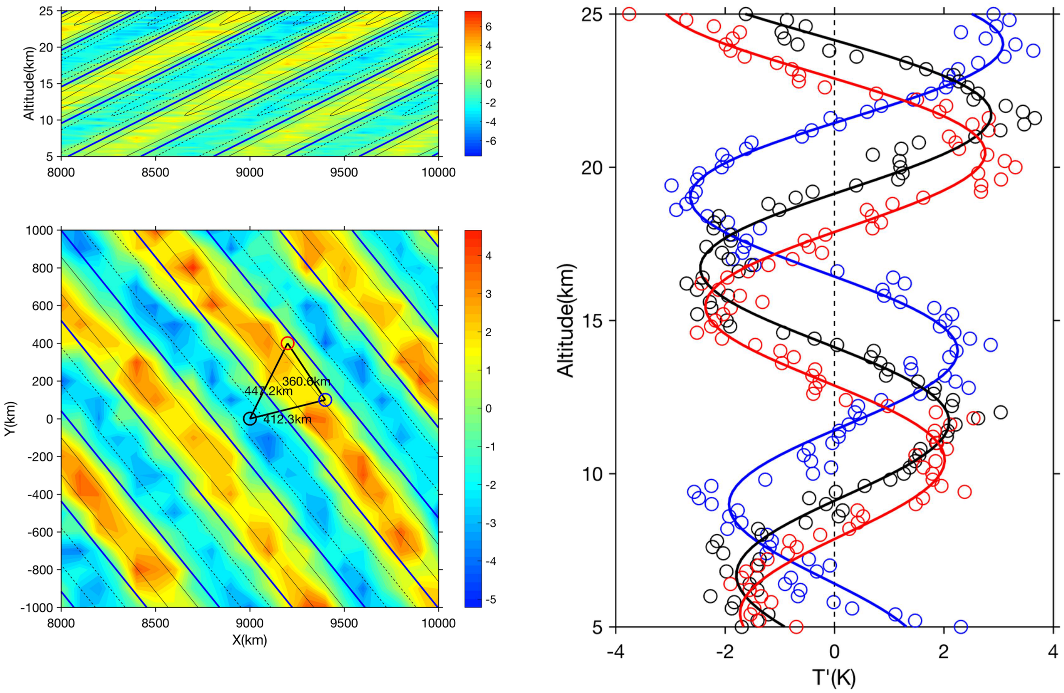

Figure 5 Wave variation of temperature in the vertical (top) and horizontal at 25 km height (lower left). (Right) Temperature profiles at the three points shown in the map at left (solid lines) and retrieved temperature profiles from three radio occultation simulations (dots).

The distortion of the retrieved wavelength of the perturbations is greater for an occultation geometry where the tangent point drift is perpendicular to the wavefronts compared to an occultation geometry with tangent point drift parallel to the wavefronts. For a monochromatic wave, and given three slant profiles, there are more than enough data to solve iteratively for the wave parameters given initial guesses for the horizontal wavenumber vector. We are currently developing these solution techniques.

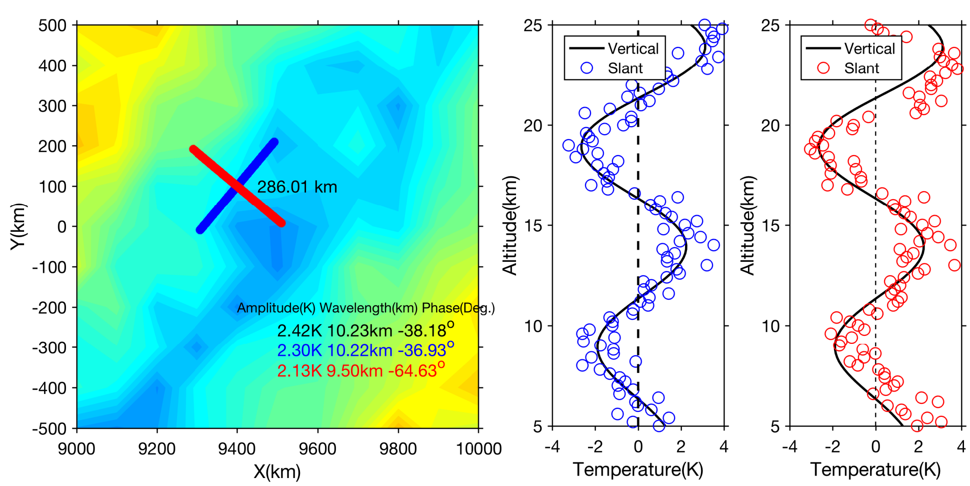

Figure 6 (Left) Location of two occultation tangent point drift paths, one where tangent point dirft is parallel to the wave structure (blue) and one where tangent point drift is perpendicular (red). The Vertical temperature profile at the intersection of the two drift paths is labeled vertical in the two right panels. (Center) the retrieved temperature perturbations for the parallel (blue) drift path. (Right) the retrieved temperature perturbations for the perpendicular drift path (red).

Key outcomes or other achievements:

The satisfactory operation of the ROC2 receiver and the development of the retrieval techniques have been demonstrated through deployment on the NOAA G-IV jet.

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

Establishing collaborations with other research groups is an important step for postdoctoral researchers to make. In the context of this Strateole-2 Long Duration Balloon Campaign project, because the project is designed to provide observations that support a broad research community, there will be many opportunities for interaction and collaboration with other research groups, both internationally and nationally, in domains as diverse as climate modeling, UTLS processes, stratospheric chemistry, data assimilation in NWP, and GPS geodesy, and Global Navigation Satellite System (GNSS) research in general. The Strateole-2 workshops, Stratosphere-troposphere Processes And their Role in Climate (SPARC) workshops, and COSMIC workshops are focused arenas for making and reinforcing networking opportunities for the young scientists involved in the project.
This year, one postdoc from my research group presented research results at the American Meteorological Society Annual Meeting on topics related to GNSS radio occultation. However, our project has provided fewer opportunities because of current travel restrictions for international students and scholars. The postdoc most involved in the work, Bing Cao, and who has made the most significant contribution to the instrumentation development, will not be able to travel to the Seychelles to assist with the launch of the instrumentation in the first field campaign in 2019 because of the difficulties with obtaining the proper visa to re-enter the country. This policy has a significant impact not only on training and professional development for the postdoc, but also has a significant impact on project success, where alternative solutions will have to be found.
Therefore, to provide more opportunities for Bing Cao, we traveled to the COSMIC Program office where Bing was able to present his results to the research group responsible for operating the largest constellation of radio occultation satellites. This will provide him connections for future research and employment opportunities in directly related fields.
Two engineering undergraduates are assisting with testing the ROC2 software and documenting the ROC2 hardware. This provides excellent real-world training under the guidance of project engineers.
The new postdoctoral researcher working with our collaborators at NWRA, Martina Bramberger, assisted in the preparation and presentation of our webinar on Strateole-2 to the US CLIVAR panel on Process Study and Model Improvement Panel. This gave her

the opportunity to gain familiarity with the broader aspects of the Strateole-2 campaign and the opportunity to serve as the modeling expert representing the project.

How have the research activities been disseminated to communities of interest

High-level scientific presentations have been made by project participants at the American Geophysical Union and the American Meteorological Society. We have contributed to presentations by collaborating organizations in the larger Strateole2 project by CU Boulder LASP, the CNES, LMD/LATMOS, and SWRA. We presented the results at the International Atmospheric Rivers Conference in June 2018, at NSF in August 2018, and at the COSMIC program office in March 2019. (most recent presentation attached to this report).

The project update article for the American Geophysical Union EOS magazine was published to publicize the upcoming campaign and data collection effort to a broader community (attached to this report).

We participated in the ECMWF *Workshop observational campaigns for better weather prediction*, in June 2019, where 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 Scott Osprey at Oxford, head of the QBOi initiative to intercompare QBO simulations from climate models, to plan for a joint Strateole-2 and QBOi workshop following the first test campaign in fall of 2020. We gave an invited webinar on the integration of campaign observations and modeling to the US CLIVAR Process Study and Model Improvement Panel (PSMIP) in June 2019.

Our collaborators at LMD have prepared a web site with information about the campaign and access to the data at:
https://webstr2.lmd.polytechnique.fr

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

Of primary importance is upgrading the ROC2 receiver software to make it easier to use and more robust. The instrument will be flown in the test campaign in Seychelles in November 2019. There will also be an opportunity to fly one of the spare ROC2 receivers on more aircraft missions in winter 2019-2020. We plan to publish our wave simulation results in a short note and the first Galileo profiles in a journal article this summer.

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*.

3.2 Technologies or techniques

ROC2 radio occultation receiver using carrier phase tracking for UT/LS profiling

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 forecast balloon trajectories, model and satellite products for the campaign duration.

ftp.climserv.ipsl.polytechnique.fr
A file repository for uploading useful ancillary products related to real-time display on the strateole2 web site.

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/
Background information on Strateole-2 science workshops

http://strateole2.org
Strateole2 whitepaper

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

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 the atmospheric river reconnaissance field campaigns has resulted in accumulating a large dataset that can also be used for scientific investigations for atmospheric river research. We are already using the data to evaluate the impact in weather forecasting 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 the modernized GPS signals and additional global constellations of navigation satellites are developed, such as Beidou and Galileo, and thus 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.

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?
Plans for deploying the small instrument on an aircraft for tests may open the way for expanded use of the technology, given the accuracy/cost tradeoff. We are planning to submit a proposal to investigate commercializing the technology, with several potential industry partners, to work towards deployment on commercial airlines.

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, which produce severe flooding are being used to improve short term prediction of flooding through improved process modeling.

5 Conference Presentations

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.

Murphy, M. J., Jr. , J. S. Haase, B. Cao, F. M. Ralph, and K.-N. E. Wang (2018), Preliminary Evaluation of Airborne GNSS RO Profiles Collected during Atmospheric River Recon 2018, paper presented at International Atmospheric Rivers Conference, La Jolla, CA, USA, 25-28 June 2018.

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.

Haase, J. S. (2017), Combining space and airborne assets for remote sensing over the ocean, paper presented at Blue Tech Week, San Diego, CA, USA, 6-10 November 2017.

Cao, B., J. S. Haase, and W. Zhang (2017), Deployment of GPS radio occultation instruments in the upcoming Strateole-2 equatorial superpressure balloon campaign to investigate tropical waves and their effects on circulation, paper presented at Joint COSMIC Tenth Data Users' Workshop and IROWG-6 Meeting, Estes Park, CO, USA, 21-27 September 2017.

Serra, Y., M. J. Alexander, J. S. Haase, G. Huffman, G. Jackson, N. Nalli, B. Nelson, L. Oreopoulos, M. Ralph, and D. Waliser (2017), Health of the atmospheric observing system, paper presented at 2017 US CLIVAR Summit, Baltimore, MD, USA, 8-10 August 2017.

6 Acknowledgements

Major funding for the Stratéole 2 campaign is provided by the French Space Agency (CNES), the French National Center for Scientific Research (CNRS), and the U.S. National Science Foundation (NSF). Resources for flight tests and aircraft facilities are provided by NOAA and the Center for Western Weather and Water Extremes.

7 Changes / Problems

Changes in approach and reasons for change

N/A

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

The flight tests were also critical for testing some of the operational elements of the instrument. In particular we discovered a problem with the serial port transfer of data from the GPS board to the internal linux single board computer which resulted in small gaps of less than 0.1% in the data. Unfortunately, this is enough to seriously degrade the position calculation necessary prior to calculating the excess phase due to the atmospheric effects. Because we had redundant receivers deployed, we were able to provide the position through other receivers. We have found a solution that eliminates the recording problems by using slower data transfer rates, and reduces risk by storing data internally on the GNSS receiver as a backup. We are currently researching an alternative linux single board computer for a future hardware revision.
Because of delays in the development of the CNES power management system for the balloons, the balloon gondola was not ready for use in time to have the validation field campaign in Nov 2018-Jan 2019. The campaign has been delayed by one year, as well as the first 20-balloon science campaign. The power management systems are now operational and ready for deployment as planned.

The CNES has a team working very hard to gain authorization for flight over all the countries necessary for the equatorial flights. Replies from the relevant embassies have been slower than expected. The French team, with supporting material provided from the US scientific team, has met with the French Minister of State to present arguments for proceeding with the campaign as long as the countries do not respond negatively. It is expected that a majority of countries will send explicit authorization so that the French Minister of State will approve the flights.

Changes that have significant impact on expenditures.

The delay in the field campaign will have an impact on expenditures by requiring personnel to be engaged in the project over a longer time period. A supplemental grant will be written if it is not possible to manage that with a no cost extension in a future year.

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

8 References

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Villamil-Otero, G., R. Meiszberg, J. S. Haase, K.-H. Min, M. Jury, and J. J. Braun (2015), Topographic - thermal circulations and associated GPS-measured moisture variability at Mayaguez, Puerto Rico, *Earth Interactions*, *19*(1), 1-16.

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