NSF Annual Report

Grant # 1642650
PI: Jennifer S. Haase
2018-01-31

1 Participants

Jennifer S. Haase, PI, Scripps Institution of Oceanography (SIO)
Bing Cao, Postdoc, (SIO)
Michael Murphy, Postdoc, (SIO)
Hong Liang, Visiting Scholar (SIO, CMA)
Eric Wang, Postdoc (SIO)
Jessie Saunders, Graduate Student, (SIO)
Margaret Morris, Graduate Student (SIO)
Stephanie Mumma, Technician (SIO)
Dave Jabson, Engineer (Brainstorm Engineering)
Allen Nance, Embedded Micro Systems

Other Organizations:

Collaborators:
M. Joan Alexander, NorthWest Research Associates, Boulder, CO;
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;

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 designed, built and tested the ROC2 radio occultation receiver

We simulated observations by raytracing through an atmospheric model containing wave perturbations in order to design a method for retrieving wave properties from the observations. The results were presented at the COSMIC Data Users' Workshop and International Radio Occultation Working Group Meeting (COSMIC-IROWG) as well as the American Geophysical Union Annual meeting in December 2017.

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

We installed the ROC2 receiver onboard the NOAA GIV research aircraft for a field campaign to be executed 26 January 2018 through 3 February 2018 out of Seattle. The main objective is to describe the observation quality and make an accurate estimate of data rates for low elevation angle data that is difficult to do from the ground. The data that is collected is expected to be of use after post-processing for research investigating the impact of upper level temperature and potential vorticity structure on the evolution of atmospheric river storms.

Specific Objectives

Significant Results

ROC2 receiver demonstration data

The ROC2 receiver hardware rev0 was developed and tested at Laboratoire de Metéorologie Dynamique in Palaiseau France to verify that there was no significant interference from the Iridium communication antenna and to verify that it produced high quality low elevation angle data. The figure below shows carrier phase data from a GPS satellite as elevation angle decreases. The data has high signal to noise ratio and tracks continuously. As expected for a station on the ground, the elevation angle does not descend below zero degrees. The receiver is ready to be tested on an aircraft where we should be able to demonstrate tracking below the horizon.

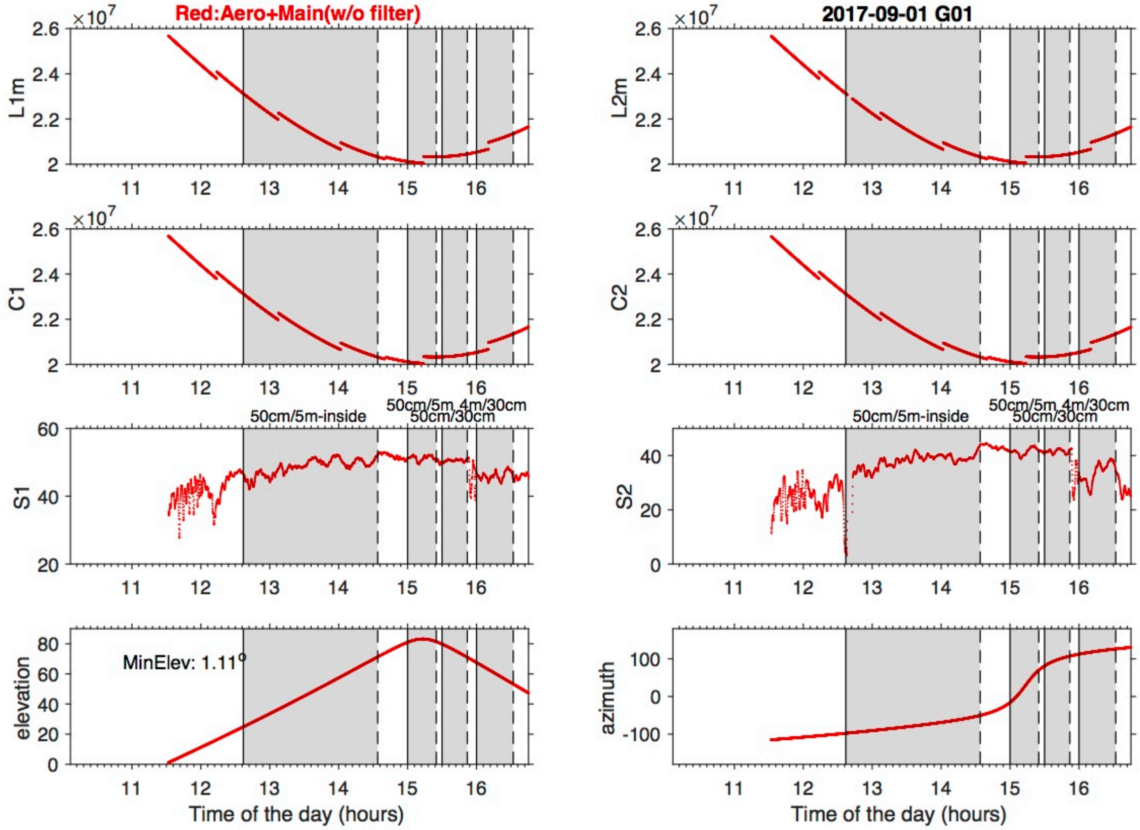

Figure 1 Test recordings from the ROC2 receiver at Palaiseau, France, during EMI testing of the effects of Iridium transmissions. Discontinuities in the L1m and L2m observations are due to millisecond clock offsets and do not affect data quality. High quality recordings extend down to 1 degree elevation angle. Variations in signal to noise ratio are due to local reflection multipath off the nearby structures at the measurement site.

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 and 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.

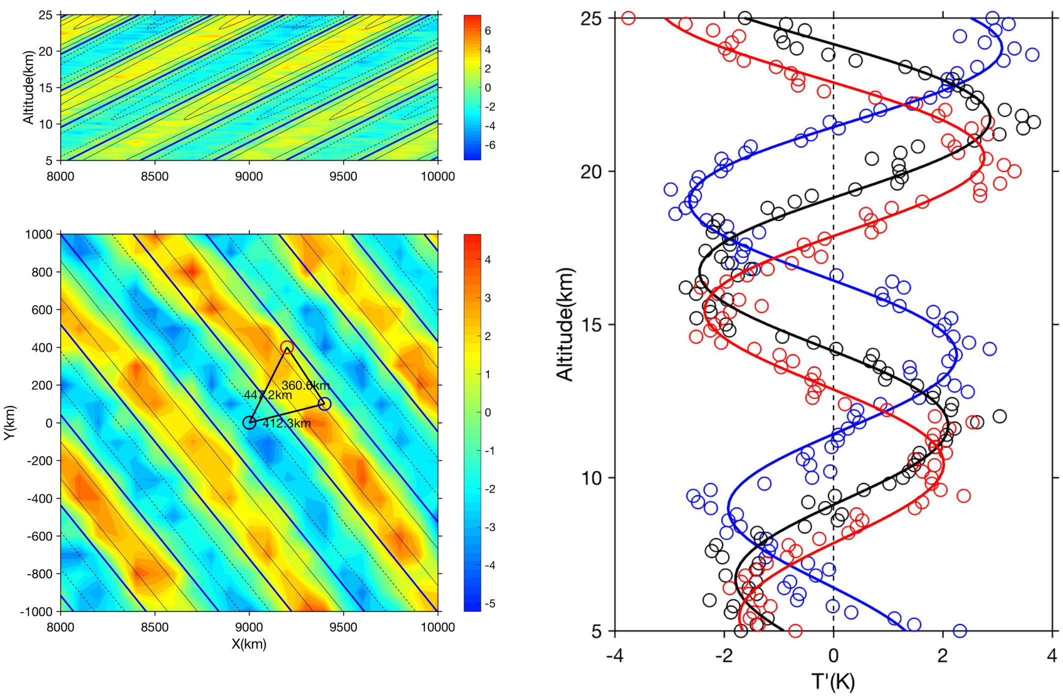

Figure 2 Wave variation of temperature in the vertical (top) and horizontal at 25 km height (lower left). (Rigth) Temperature profiles at the three points shown in the map at left (solid lines) and retrieved temperature profiles from three radio occultation simulations (dots).

Key outcomes or other achievements:

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, all four early career scientists (postdocs) from my research group presented research results at the COSMIC-IROWG conference on topics related to GNSS radio occultation. As a group activity it provided in depth training and exposure to observational and modeling studies that span the full range of possibilities of the RO technique. Each postdoc identified areas of collaboration and future research during the meeting. One a interest for Bing Cao that extends from the Strateole2 work was the possibility of collaborative work with the ionospheric physics community in order to derive information about the middle atmosphere through analysis of wave through the middle atmosphere to the ionosphere during Strateole2 and using previous datasets from the NSF Concordiasi 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 COSMIC Data Users' Workshop. We have contributed to presentations by collaborating organizations in the larger Strateole2 project by CU Boulder LASP, the CNES, LMD/LATMOS, and SWRA. We have published an AGU EOS article and have collected an expanding list of researchers interested in the project data as a result of this article targeted at a broad community. We have contributed to presentations at the 2017 US CLIVAR Summit on the atmospheric observation system.

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

We plan to fly the ROC2 receiver on an aircraft to collect test data that will demonstrate the ability to track reliable phase data. We plan to publish our wave simulation results in a short note. We plan to complete the integration and testing with the full balloon configuration at CNES in the 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://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.

Impact on other disciplines
The project educates a large 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 can potentially be used by a broader range of users without such a heavy demand for specialized knowledge.

What is the impact on institutional resources that form infrastructure?

What is the impact on information resources that form infrastructure?

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.

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.

5 Conference Presentations

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 Student Publications

7 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).

8 Changes/Problems

Changes in approach and reasons for change
Nothing to report

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

While the hardware was delivered ahead of schedule, some communications problems with the payload management system provided by the Laboratoire de Meteorologie Dynamique (LMD) is delaying the final steps of integration. These problems are being resolved by brining in additional engineering expertise that can provide help within the required timeline.

Changes that have significant impact on expenditures

Nothing to report

9 Project Outcomes Report for the general public

"Collaborative Research: Investigating the characteristics of lower tropospheric airborne GPS radio occultation observations and their impact in hurricane studies"

Intellectual Merit: A new atmospheric observation system, the GNSS Instrument System for Multistatic and Occultation Sensing (GISMOS), has been developed for observing moisture from aircraft using signals that are transmitted from Global Positioning System (GPS) satellites. The aircraft is equipped with a GPS receiver that measures the time it takes the GPS signal to get from the GPS satellite to the aircraft. In the standard use of GPS data, the signal travel time is divided by the speed of light to calculate the distance to the satellite, and the measurements of distance are used to locate the aircraft precisely. We use the fact that the signals are slowed down by the atmosphere to measure the extra delay of the signal and then derive the amount of moisture along the path that the GPS signal passes through. By making these observations as GPS satellites set, the signal passes lower and lower through the atmosphere, and we can retrieve measurements at each height. This technique is called airborne GPS radio occultation (ARO) [*Haase et al.*, 2014].

The amount of moisture as a function of height in the tropical regions greatly affects how hurricanes develop. We flew the new GISMOS system during the 2010 Atlantic hurricane season over areas where hurricanes had the potential to develop. GISMOS provides high vertical resolution profiles that are insensitive to clouds and precipitation, and provides greater control than spaceborne RO observation systems on the sampling location to be near tropical cyclones, and is therefore useful for targeted regional studies. We developed new techniques for analyzing the GPS ARO data to improve their accuracy and we verified that the system was giving reliable observations by comparing it to the types of dropsonde measurements that the Hurricane Hunters release from their aircraft [*Murphy*, 2015; *Murphy et al.*, 2015; *Wang*, 2015; *Wang et al.*, 2015].

The feasibility of the system was demonstrated with flights carried out during development of an Atlantic tropical storm, before it went on to develop into category 5 hurricane Karl that brought torrential rains and flooding to parts of Mexico.

The GISMOS airborne RO system increased the number of height profiles available for studying development of tropical storms by more than 50% over what was available from dropsondes alone during this campaign. The data are being put into weather models to examine how the measurements could improve hurricane forecasting in the future. The observations suggest that it is important to measure the largest variations of moisture that occur in the range between 4-6 km during the tropical storm genesis stage. This is the first study to publish results showing how airborne RO can be used to study weather systems.

Broader Impacts:

After these results were achieved, the system was deployed on the NOAA Gulfstream IV jet used for storm reconnaissance over the northwest Pacific Ocean. If a smaller automated version of the system is developed, it could potentially also be deployed on commercial aircraft in the future to help improve aviation weather forecasting.

The project provided support for four graduate students for their PhD Theses [*Muradyan*, 2012; *Murphy*, 2015; *Wang*, 2015] (two female), and two undergraduate student interns. The project provided support for three graduate students (two female) to participate with the PI in the field data collection, which trained them in state of the art instrumentation operation, gave them forecasting experience in collaboration with National Hurricane Center staff, and introduced them to many members of the hurricane research community in the context of the Tri-Agency cooperation among NSF PREDICT, NASA GRIP, and NOAA IFEX campaigns. These graduate students along with the other early career scientists participating in this campaign published an independent journal article on their contribution and learning experience [*Evans et al.*, 2012].

A large group of undergraduates have been involved with the project in the context of a Research Experience for Undergraduates. Prof. Haase organized an undergraduate course "Atmospheric Field Projects" where students learned how to use meteorological instrumentation and GPS equipment to make ground based integrated water vapor measurements. The students planned their own research field campaign in Puerto Rico over spring break, in collaboration with students and faculty from the University of Puerto Rico, Mayaguez. Eleven undergraduates from Purdue and four undergraduates from Puerto Rico participated in the project and completed a presentation and class paper by the end of the semester. One local undergraduate student and two students from UPRM participates in undergraduate student research internships with Dr. Haase. The undergraduates were supported under this grant to attend the American Meteorological Society Annual Meeting to present their project results. This gave them the opportunity to interact with scientists in the field, and explore possibilities for graduate school. A research paper on the project has been published with undergraduate first and second authors [*Villamil-Otero et al.*, 2015].

10 References

Adhikari, L., F. Xie, and J. S. Haase (2015), Application of the Full Spectrum Inversion Algorithm for Airborne GPS Radio Occultation Measurements, *Atmospheric Measurement Technology*, *Submitted*, 24.

Evans, C., H. M. Archambault, J. M. Cordeira, C. Fritz, T. J. Galarneau Jr., S. Gjorjievska, K. S. Griffin, A. Johnson, W. A. Komaromi, S. Monette, P. Muradyan, B. Murphy, M. Riemer, J. Sears, D. Stern, B. Tang, and S. Thompson (2012), The Pre-Depression Investigation of Cloud-systems in the Tropics (PREDICT) field campaign: Perspectives of early career scientists, *Bulletin of the American Meteorological Society*, *92*(9), 173-187.

Haase, J. S., B. J. Murphy, P. Muradyan, F. Nievinski, K. M. Larson, J. L. Garrison, and K.-N. Wang (2014), First Results from an Airborne GPS Radio Occultation System for Atmospheric Profiling, *Geophysical Research Letters*, *41*(5), 1759-1765.

Muradyan, P. (2012), Profiling the atmosphere with the airborne GPS radio occultation technique using open-loop tracking, PhD thesis, 196 pp, Purdue University, West Lafayette, IN, USA.

Murphy, B. (2015), Profiling the moisture environment of developing tropical storms using airborne radio occultation, PhD thesis, 284 pp, Purdue University, West Lafayette, IN, USA.

Murphy, B. J., J. S. Haase, P. Muradyan, J. L. Garrison, and K.-N. Wang (2015), Airborne GPS radio occultation refractivity profiles observed in tropical storm environments, *Journal of Geophysical Research-Atmospheres*, *120*(5), 1690-1790.

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.

Wang, K.-N. (2015), Signal analysis and radioholographic methods for airborne radio occultations, PhD thesis, 149 pp, Purdue University, West Lafayette, IN, USA.

Wang, K.-N., J. L. Garrison, J. S. Haase, and B. J. Murphy (2015), Implementation of the phase matching (PM) method for the GPS airborne radio occultation (ARO) system, *Journal of Geophysical Research*, *to be submitted*, 47.