NSF Annual Report
Grant # 1642650
PI: Jennifer S. Haase
2021-08-20
Collaborative Research: Tropical waves and their effects on circulation from 3D GPS radio occultation sampling from stratospheric balloons in Strateole-2

1 Participants

1.1 Scripps Institution of Oceanography

Jennifer S. Haase, PI, Scripps Institution of Oceanography (SIO/UCSD)
Bing Cao, Postdoc, (SIO/UCSD)
Michael Murphy, Postdoc, (SIO/UCSD)
Emma Robertson, Undergraduate (Amherst)
Julianna Cativo, Undergraduate (UCLA)
Apollonia Arellano, Undergraduate (Cal State San Luis Obispo)

Supporting personnel (current and over the course of the project)
Steven Liang, Graduate Student (UCSD)
Eric Wang, Postdoc (SIO/UCSD)
Frankie Martinez, Undergraduate (UCSD)
John Souder, Engineer (SIO/UCSD)
Sean McPeak, Engineer (SIO/UCSD)
Jessie Saunders, Graduate Student, (SIO/UCSD)
Margaret Morris, Graduate Student, (SIO/UCSD)
Jimmy Lozano, Undergraduate (UCSD)
Dave Jabson, Engineer (Brainstorm Engineering)
Hong Liang, Visiting Scholar (SIO, CMA)
Stephanie Mumma, Staff Research Associate (SIO/UCSD)
Allen Nance, Embedded Micro Systems

1.2 Collaborators

M. Joan Alexander, and Martina Bramberger, 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;
Francois Ravetta, LATMOS, Guyancourt, France

2 Accomplishments

2.1 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 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 are derived on either side of the balloon trajectory that sample the equatorial wave field in three dimensions. This will provide an unbiased view of 3D versus 2D wave properties at fine vertical scales and large horizontal scales.

2.2 What was accomplished under these goals?

2.2.1 Major activities

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, recording data on board continuously with only a few data gaps. We transmitted and received a total of 24 days of data of which 17 days were consecutive, approximately the 3 weeks that we had targeted to be able to capture signals from large horizontal scale fine vertical scale waves.

Data processing
The data analysis techniques were refined for the processing chain from raw observations to dry temperature retrievals. We analyzed the accuracy of the observations. We optimized the techniques for highest resolution.

Data analysis
We analyzed the temperature variations in the profiles to detect waves at different periods and attribute the likely wave types. We compared and contrasted the results with similar analyses from spaceborne RO and radiosondes.

Dissemination of results
We presented results at scientific meetings and drafted a publication on the results, AGU 2020, AMS 2021, and IROWG-8 2021. We convened a scientific review of the overall campaign progress with international partners on 2020-03-17 (Virtual).

Campaign preparation for 2021

We worked with LMD to revise the communications to assure we can overcome the limited transmission rates experienced in the last campaign. We flight tested all units.

Outreach
We hosted three undergraduate students from underrepresented groups (African American and Latina) to work on summer projects related to long duration balloon observations. Emma Robertson and Julianna Cativo presented their results at the December 2020 Meeting. We recruited another student from underrepresented groups for a summer research project in June-August 2021 related to airborne radio occultation observations for climate studies in Antarctica. We have hired Julianna Cativo on as an assistant for the field campaign in 2021-2022.

2.3 Specific Objectives

Data Processing and 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 adds to the three deployments on flights of opportunity, in AR Recon 2018 and the 2019 Grav-D mission and AR Recon 2020, 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 extra flight data has not kept pace. However, 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. A first release of the Strateole2 ROC2 dataset has been made available to the public at Scripps Institution of Oceanography.

Campaign Preparation for 2021

Instrument development
The construction of all four ROC2 units plus one spare has been completed. 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). In year 3, 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 was flown in the Strateole2 technology validation campaign and has

been lost (retired). In year 4, two additional receivers were built with the same design, ROC2.7 and ROC2.8. Four receivers plus one spare are now available for flight during the science campaign planned for October 2021 (ROC2.4, ROC2.5, ROC2.6, ROC2.7, ROC2.8). ROC2.1 is an additional spare, and ROC2.2 remains the breadboard model for testing in the lab.

On board software
The software has been upgraded to be robust to any communication errors between the ROC2 instrument and the Zephyr

Seychelles campaign preparation
The campaign has been confirmed for Fall 2021 despite the setbacks associated with COVID as all teams have confirmed that they will be able to travel to Seychelles.

Tests with the standalone XEOS Resolute receiver

We confirmed that our request to LMD and CNES to fly a standalone Resolute receiver on one of the 6 CNES EUROS gondolas that does not carry any other instrument payload has been approved. They have confirmed we will fly one standalone Resolute on one STR1 balloon configuration in 2021, and they will consider 6 resolute receivers for the 2023 Second Science Campaign, C2.

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 2021 Campaign from January 19, 2021, through March 30, 2021. It was once again 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 2021 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 two additional receivers.

This confirms that all ROC2 instruments that will fly in the C1 Campaign have been flight tested and perform according to expectations.

Significant Results

The Strateole2 technology validation campaign

We have completed an article draft on the analysis of the ROC2 data that is provided with this report, and the significant results from the analysis are summarized below:

This work is the culmination of efforts to design and deploy next generation Global Navigation Satellite System (GNSS) receivers for Radio OCcultation (ROC2) on board equatorial long-duration stratospheric balloons. The Strateole-2 technology demonstration campaign in 2019-2020 was the first time that balloon-borne GNSS RO (BRO) has been used to derive high vertical resolution equatorial wave observations.
About 45 temperature profiles were retrieved daily over a period of 17 days, from ~20 km down to a median altitude of 8 km. The BRO technique samples the atmosphere an orthogonal pattern over a broad area +/- 400-500 km along both sides of the flight track, which will be useful in the future for examining horizontal variations in wave propagation characteristics.

For verification, retrieved refractivity and dry temperature profiles were compared with colocated radiosonde observations over Indonesia and southeast Asia within 300 km and 1 hour of the observation time. The BRO refractivity profiles show good agreement with radiosondes, given the large horizontal drift of the profile tangent points, within 2% refractivity and 1% temperature from flight level to 10 km altitude. Most importantly, the BRO profiles, with vertical resolution better than 500 m, show the same vertical wave structure in the temperature and cold point tropopause as is seen in the radiosonde profiles.

Over the duration of the flight over the maritime continent, the mean difference with the ERA5 reanalysis is less than 0.2% refractivity above 7 km and the standard deviation is less than 1%. A systematic bias in the comparison with ERA5 from 15 to 20 km is explained by a large scale Kelvin wave observed in the data that is not resolved or underrepresented in the ERA5 reanalysis.

We computed the daily regional mean from the much sparser COSMIC-2 RO profiles to compare to the daily mean BRO profiles and found excellent agreement from balloon flight level down to 8 km altitude, with an RMS difference less than 0.1% refractivity.
Slightly larger differences at 17--18 km are a possible indication that wave variations with less than 3 km wavelength are not resolved as well in the sparser spaceborne RO dataset.

The most dominant signal in the individual BRO profile transects, made visible by the consecutive sampling in time and space, was a large-scale Kelvin wave with ~4-6 km vertical wavelength, which is also visible in the binned COSMIC-2 data. However, the BRO observations with slightly higher vertical resolution and denser sampling retrieved a higher amplitude temperature variation associated with the wave. The BRO observations present the advantage that the waves are measured in the intrinsic reference frame.
After removing the large scale signal of the Kelvin wave, the BRO observations show wave variations with 2-3 km vertical wavelength, that are interpreted to be westward propagating

inertia-gravity waves with 3-4 day period. These results demonstrate the ability to extract fine-vertical scale wave properties continuously in time and space in poorly sampled regions of the globe. The results are promising and indicate the data will be useful for distinguishing contributions of waves of different scales to momentum forces for wave driving of the QBO that is expected to lead to improved QBO representation in models.

We retrieved a short dataset from the Galileo and GLONASS constellations with comparable accuracy to GPS, which demonstrates the feasibility to nearly double the sampling density in the 2021--2022 Strateole-2 science campaign, which will have Iridium data rates high enough to support continuous transmission of all constellations throughout the entire flights.

Five balloons carrying the ROC2 receiver will be deployed to perform RO observations in that follow-on campaign. Exploiting the full data set, and the information available from the directional sampling of the profiles on the north and south sides of the balloon paths, will provide opportunities to capture waves over an even broader range of scales.
BRO observations contribute to the larger objectives of the Strateole-2 campaigns that include multiple types of instruments to be flown on a total of 21 balloons.

The high vertical resolution provides new knowledge on fine vertical scale waves that are unresolved in global models and provides direct observations of their spatial structure. When combined with other observations such as the Strateole-2 BeCOOL micro-lidar nadir cloud observations, the BRO observations will help determine the relationship of upper troposphere waves to the presence of cirrus clouds that can be used for improving model representations of these clouds. They will help quantify global characteristics of waves that determine tropical cold point temperature variability for use in improving models of stratospheric dehydration. Slow upwelling, rapid transport by penetrating deep convection, thin cirrus precipitation, and horizontal transport and cooling by waves combine to give the observed variability in water vapor on timescales ranging from very short to decadal. Because stratospheric water vapor plays an important role in the radiative budget of the stratosphere as well as in modulating surface warming, quantifying wave properties in the equatorial region is important for improving climate models.

Key outcomes or other achievements:

An article draft has been completed:

Cao, B., Haase, J. S., Murphy, M. J., Jr., Alexander, M. J., Bramberger, M., Hertzog, A., & Zhang, W. (2021). Equatorial waves resolved by balloon-borne Global Navigation Satellite System Radio Occultation in the Strateole-2 Campaign. *Atmospheric Chemistry and Physics, draft to be submitted.*

The dataset of atmospheric temperature and refractivity has been completed for the 2019-2020 campaign C0.

5 ROC2 and 1 ROC3 receiver have been prepared for the 2021-2022 campaign C1.

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

We used the experience to provide an opportunity for two undergraduate summer intern research fellowships for Julianna Cativo, who is a Latina first generation college student, and Emma Robertson, who is an African American. Under these fellowships the two students and our research group collaborated on a project to investigate the feasibility of radio occultation data collection from commercial balloons with Loon, LLC. This company, owned by Google Alphabet, provides internet and data services to remote countries near the equator. The Ms. Cativo presented her work at AGU and the International Radio Occultation Working Group, (IROWG) conference and will be participating in the Strateole-2 Science Campaign C1. Ms. Robertson has gone on to graduate studies at Penn State in climate science.

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 postdoc, Ignacio Sepulveda, used the receiver to measure sea level and investigate the use of reflected signals for calibrating models for storm surge in remote locations. He has expanded his use of the technique and now has a new faculty position at San Diego State University where he is pursuing collaborative research and proposal opportunities with SIO.

How have the research activities been disseminated to communities of interest

We have presented the results at the following conferences:

Alexander, M. J., Bramberger, M., Cao, B., Davis, S., Goetz, D., Jennifer S. Haase, et al. (2021, 10-14 January 2021). *Balloon-borne Observations of Short Vertical Wavelength Tropical Waves and Interactions with Winds in the Lower Stratosphere.* Paper presented at the American Meteorological Society Annual Meeting, New Orleans, LA, USA.

Haase, J. S., Alexander, M. J., Cocquerez, P., Davis, S. M., Deshler, T., Durry, G., et al. (2020, 7-11 December 2020). *The First Fights of the Strateole-2 technology demonstration campaign: Observing the global equatorial tropopause with long-duration balloons.* Paper presented at the American Geophysical Union Annual Meeting, San Franciso, CA, USA.

Cao, B., Haase, J. S., Murphy, M. J., Jr., Alexander, M. J., & Bramberger, M. (2020). *Tropical waves observed by balloon-borne GPS Radio Occultation measurements of Strateole-2 campaign over the equatorial area.* Paper presented at the American Geophysical Union Annual Meeting, San Francisco, CA, USA.

Cao, B., Haase, J. S., Alexander, M. J., Bramberger, M., Murphy, M. J., Jr., & Hertzog, A. (2021). *Tropical waves observed by balloon-borne GPS Radio Occultation during the equatorial Strateole-2 super-pressure balloon campaign* Paper presented at the International Radio Occultation Working Group-8, Taipei, Taiwan (virtual).

Robertson, E. R., Cativo, J., Haase, J. S., Murphy, M. J., Jr., Cao, B., Wilson, A. M., et al. (2020, 7-11 December 2020). *Simulating Observations from Loon Balloons for Atmospheric River Reconnaissance.* Paper presented at the American Geophysical Union Annual Meeting, San Francisco, CA, USA.

Cativo, J., Robertson, E. R., Haase, J. S., Murphy, M. J., Jr., Cao, B., Wilson, A. M., et al. (2020, 7-11 December 2020). *Investigating the Feasibility of Using Loon Long Duration Balloons for Meteorological Studies.* Paper presented at the American Geophysical Union Annual Meeting, San Francisco, CA, USA.

Cativo, J., Robertson, E., Haase, J. S., Murphy, M. J., Jr., Cao, B., Wilson, A. M., et al. (2021). *Investigating the Feasibility of Obtaining RO Measurements of a Meteorological Phenomena Using Loon Balloons*. Paper presented at the International Radio Occultation Working Group-8, Taipei, Taiwan (virtual).

A first release of the Strateole2 ROC2 dataset has been made available to the public at Scripps Institution of Oceanography:
https://agsweb.ucsd.edu/strateole2/data/2019-12-05_str2/data_release_2021-06-25/
And at the US Strateole-2 project web site:
https://strat2.org

Data from the complete suite of instruments is also through IPSL:
https://data.ipsl.fr/catalog/strateole2/eng/catalog.search#/search?from=1&to=30
https://thredds-x.ipsl.fr/thredds/catalog/C0/ROC/catalog.html
https://observations.ipsl.fr/aeris/strateole2/data/C0/ROC/

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

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

The next reporting period will be focused on 1) deployment and data analysis for the 2021-2022 Strateole-2 Science Campaign C1.

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 following COVID-19. (Hopefully).

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*.

An article draft has been completed:

Cao, B., Haase, J. S., Murphy, M. J., Jr., Alexander, M. J., Bramberger, M., Hertzog, A., & Zhang, W. (2021). Equatorial waves resolved by balloon-borne Global Navigation Satellite System Radio Occultation in the Strateole-2 Campaign. *Atmospheric Chemistry and Physics, draft to be submitted*.

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:

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.

A first release of the Strateole2 ROC2 dataset has been made available to the public at Scripps Institution of Oceanography:
https://agsweb.ucsd.edu/strateole2/data/2019-12-05_str2/data_release_2021-06-25/

The US Strateole-2 project web site provides a link to the data:
https://strat2.org

Data from the complete suite of instruments is also through IPSL:

https://data.ipsl.fr/catalog/strateole2/eng/catalog.search#/search?from=1&to=30
https://thredds-x.ipsl.fr/thredds/catalog/C0/ROC/catalog.html
https://observations.ipsl.fr/aeris/strateole2/data/C0/ROC/

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

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

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

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, strat2.org. 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 undergraduate 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. Three undergraduate women from underrepresented communities have been involved in summer research projects.

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.

The technology was tested and found to be feasible on the commercial Loon, LLC, stratospheric balloons. Unfortunately a management decision by Google Alphabet was made to discontinue the balloon program.

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 tested the concept with Google Loon balloons, and completed a collaborative preliminary study fall 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., Haase, J. S., Alexander, M. J., Bramberger, M., Murphy, M. J., Jr., & Hertzog, A. (2021). *Tropical waves observed by balloon-borne GPS Radio Occultation during the equatorial Strateole-2 super-pressure balloon campaign* Paper presented at the International Radio Occultation Working Group-8, Taipei, Taiwan (virtual).

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Haase, J. S., Alexander, M. J., Cocquerez, P., Davis, S. M., Deshler, T., Durry, G., et al. (2020, 7-11 December 2020). *The First Fights of the Strateole-2 technology*

demonstration campaign: Observing the global equatorial tropopause with long-duration balloons.* Paper presented at the American Geophysical Union Annual Meeting, San Franciso, CA, USA.

Cao, B., Haase, J. S., Murphy, M. J., Jr., Alexander, M. J., & Bramberger, M. (2020). *Tropical waves observed by balloon-borne GPS Radio Occultation measurements of Strateole-2 campaign over the equatorial area.* Paper presented at the American Geophysical Union Annual Meeting, San Francisco, CA, USA.

Robertson, E. R., Cativo, J., Haase, J. S., Murphy, M. J., Jr., Cao, B., Wilson, A. M., et al. (2020, 7-11 December 2020). *Simulating Observations from Loon Balloons for Atmospheric River Reconnaissance.* Paper presented at the American Geophysical Union Annual Meeting, San Francisco, CA, USA.

Cativo, J., Robertson, E. R., Haase, J. S., Murphy, M. J., Jr., Cao, B., Wilson, A. M., et al. (2020, 7-11 December 2020). *Investigating the Feasibility of Using Loon Long Duration Balloons for Meteorological Studies.* Paper presented at the American Geophysical Union Annual Meeting, San Francisco, CA, USA.

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.

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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.

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7 Changes / Problems

Changes in approach and reasons for change

We are requesting supplemental funds to support near-real time analysis of the ROC2 data for potential data assimilation studies with the Joint Center for Satellite Data Assimilation.

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

COVID-19 and the extension of international travel restrictions that prohibit a team member from traveling to Seychelles has caused major problems.

Changes that have significant impact on expenditures.

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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