NSF Annual Report
Grant # 1642650
PI: Jennifer S. Haase
2022-02-17
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)
Janelle Wargo, Undergraduate (Wake Forest University)
Brandon Bourassa, Undergraduate (UCSD)

*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
Glen Offield, Engineer (SIO/UCSD)

## 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*

ROC Receivers
Five ROC2 receivers were prepared and tested. The individual units were tested on aircraft in 2020 and 2021 during the ARRecon field campaign. ROC2.4 successfully recorded data on two channels from a horizontally and vertically linearly polarized antenna in 2020 and 2021. ROC2.5 and ROC2.6 successfully recorded data from the Air Force C-130 aircraft in 2020. ROC2.7 and ROC2.8 successfully recorded data from Air Force C-130 aircraft in 2021.

An additional ROC3.1 receiver was prepared and tested, based on the XEOS Resolute receiver developed for the NSF UNAVCO facility for deployment in extreme environments. The receiver has the capability to transmit data using its own Iridium modem. The ROC3.1 receiver system was developed in 2021 and was tested on the ground in the Seychelles in 2021 during the Strateole2 flight campaign.

2021 Field campaign
The 5 units were integrated onto the balloon gondolas in Seychelles in October-December 2021. During ground testing we found that interference from the Iridium modems and the MC2 power supply that furnished power to all science instruments prevented the ROC receivers from tracking continuous signals. For further details see the

accompanying field report. Three balloons were launched in an attempt to record signals in a different environment (away from the airport and other interfering instrumentation) despite the known issues, and did not return data of sufficiently good quality to analyze. The remaining two gondolas did not launch because the early unexpected rupture of many balloons prevented CNES from continuing launches.

Publications
We completed a publication on the high quality results from the 2019 technology demonstration campaign. It is in the final stages for submission.

Dissemination of results
We presented results at scientific meetings including AMS 2021, IROWG-8 2021, AMS 2022. Preparations are underway for presentations at SPARC 2022.

Datasets
The ROC2 dataset has been made openly available at https://agsweb.ucsd.edu/strateole2/data/ and also on our French collaborator's open web site along with other data from the STR1 balloons carrying ROC:
https://data.ipsl.fr/catalog/strateole2/
https://observations.ipsl.fr/aeris/strateole2/data/C0/ROC/
https://thredds-x.ipsl.fr/thredds/catalog/C0/BECOOL/catalog.html
https://thredds-x.ipsl.fr/thredds/catalog/C0/TSEN/catalog.html

Promoting Diversity
We provided summer research opportunities to two women of which one is Latina, and one first-generation college student. We hired Julianna Cativo as an assistant for the field campaign in 2021. Ms. Cativo is Latina and was a former student intern from the SIO summer undergraduate research program. She was a highly valuable participant in the ROC deployment effort in the campaign. She has since gone on to a permanent job with a geotechnical consulting firm.

## 2.3 Specific Objectives

*Data Processing and Archiving*

A second release of the retrieved refractivity and dry temperature profiles from the 2019 technology validation campaign has been made available. The second release includes profiles from the full dataset that was retrieved for 2019.340-356, 2021.001, 2021.009-013, for all constellations that were recorded. It is not continuous because of unforeseen limitations in data rate of the data transmission system, but all possible profiles have been retrieved.

Additional flights of opportunity were carried out, which greatly contributed to the reliability of the ROC2 instruments performance in real atmospheric conditions, and further development of the analysis software. We processed the data from the deployment on the NOAA G-IV during the AR-Recon 2021 Campaign from January 19, 2021, through March 30, 2021. Multiple receivers were flow for intercomparison purposes. ROC2.4 was deployed on the NOAA-GIV. 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 provided valuable functional tests for two additional receivers. This confirmed that all ROC2 instruments that were planned to fly in the C1 Campaign were flight tested and that the data was high quality for performing occultations according to expectations.

The dataset from 21 aircraft flights in 2021 has been collected and processed, and is in the process of being analyzed. This has led to several advances in the processing especially with respect to processing data in near real time. It also gave an opportunity for undergraduate summer research students to get involved in analyzing and reporting on their own dataset.

*Wave analysis*
We collaborated with Joan Alexander at NWRA to refine our analysis of long period atmospheric equatorial waves, using more refined incorporation of background information from COSMIC-2 spaceborne radio occultation. We began an analysis comparing the properties of profile transects observed in different orientations to explore the 3D variations of the wave field. We began discussions with the Joint Center for Satellite Data Assimilation on the prospect of using data assimilation to provide model analyses fields that incorporate the variations due to waves. We are planning for joint work on that approach as well as observation based approaches.

***2021 Science Campaign***

*Instrument performance*
The deployment and performance of the ROC2 instruments in the 2021 science campaign are described in the accompanying field report. As stated above, interference prevented retrieval of any profiles.

*Payload testing for future deployments*
We have created a test plan for determining the cause and viable solutions for the interference experienced during the campaign, with our engineering staff at SIO. We engaged with engineering staff at LMD and CNES to move forward with a test plan, with the intention of being prepared for the Campaign planned for 2024.

## 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. (2022). 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.

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

We expanded our summer intern research fellowship efforts to introduce three new undergraduates to radio occultation science using the ROC2 datasets from flights of opportunity. Janelle Wargo, is an  undergraduate from Wake Forest University, without access to the same type of research opportunities as are available at an R1 university. She explored machine learning techniques to explore and compare refractivity profile properties between airborne RO and dropsondes. Apollonia Arellano, an undergraduate from Cal Poly Pomona San Luis Obispo, is a Latina interested in climate science who had the opportunity to investigate the feasibility of RO observations from research aircraft in Antarctica. Brandon Bourassa is a first generation college student from UCSD who investigated the possibility of using GNSS-INS systems to more rapidly postprocess the positioning data with enough precision to enable near-real time airborne RO observations. All three undergraduates prepared AMS talks from their research, although their ability to participate in AMS was limited by COVID.

We hired Julianna Cativo as an assistant for the field campaign in 2021. Ms. Cativo is Latina and was a former student intern from the SIO summer undergraduate research program the previous year. In her summer research project she explored making RO observations from the Loon balloons. She was a highly valuable participant in the ROC deployment effort in the campaign, carrying out all levels of testing and operations in the field. She has since gone on to a permanent job with a geotechnical consulting firm.

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 to 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. Dr. Sepulveda, a Latino, 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. We have a journal article ready for submission on this case study.

Sepulveda, I., B. Cao, J. S. Haase, and M. J. Murphy, Jr. (2021), Optimizing simultaneous water level and wave measurements from multi-GNSS interferometric reflectometry over one year at an exposed coastal site, Journal of Geophysical Research-Oceans, to be submitted.

**How have the research activities been disseminated to communities of interest**

We have presented the results at the following conferences:

Hertzog, A., R. Plougonven, A. Podglajen, M. Corcos, M. J. Alexander, M. Bramberger, J. S. Haase, B. Cao, L. Kalnajs, D. Goetz, S. Davis, F. Ravetta, and S. Venel (2022), Strateole-2: long-duration balloon observations of gravity waves in the tropical lower stratospher, in 2022 SPARC Gravity Wave Symposium, edited, Frankfurt, Germany. (to be presented)

Alexander, M. J., M. Bramberger, J. S. Haase, B. Cao, A. Podglajen, and A. Hertzog (2022), Identification of fine-vertical-scale tropical wave modes in Strateole-2 balloon observations: Implications for QBO forces in the lowermost stratosphere, in 2022 SPARC Gravity Wave Symposium, edited, Frankfurt, Germany.

Cao, B., J. S. Haase, M. J. Alexander, M. Bramberger, M. J. Murphy, Jr., and A. Hertzog (2022), Equatorial waves observed by balloon-borne GNSS Radio Occultation during the Strateole-2 super-pressure balloon campaign in American Meteorological Society Annual Meeting, edited, virtual.

Apollonia Arellano, J. S. H., Jamin Greenbaum, Bing Cao, Michael J. Murphy, Matthew Mazloff, Rui Sun (2021), Potential Contributions to Observing Ice-Ocean-Atmosphere

Interactions of the Antarctic Atmospheric Boundary Layer

with Airborne Radio Occultation, paper presented at Summer Undergraduate Research Fellowship Conference, Scripps Institution of Oceanography, La Jolla, CA, 13 August 2021.

Brandon Bourassa, Jennifer S. Haase, B. C. Michael J. Murphy, A. M. Wilson, J. Parrish, G. DeFeo, J. Johnson, and J. Dahlberg (2021), Improved Atmospheric River Forecasting using Airborne Radio Occultation, paper presented at Summer Undergraduate Research Fellowship Conference, Scripps Institution of Oceanography, La Jolla, CA, 13 August 2021.

Brandon Bourassa, Jennifer S. Haase, B. C. Michael J. Murphy, A. M. Wilson, J. Parrish, G. DeFeo, J. Johnson, and J. Dahlberg (2022), Improved Atmospheric River Forecasting using Airborne Radio Occultation, paper presented at American Meteorological Society 21st Annual Student Conference, Houston, TX, 22-23 January 2022.

Janelle Wargo, Jennifer S. Haase, Michael J. Murphy, and B. Cao (2022), An Investigation of Spatially Dependent Atmospheric Refractivity Characteristics within Atmospheric Rivers and their Importance for Airborne Radio Occultation Observations, paper presented at American Meteorological Society 21st Annual Student Conference, Houston, TX, 22-23 January 2022.

Janelle Wargo, Jennifer S. Haase, Michael J. Murphy, and B. Cao (2021), An Investigation of Spatially Dependent Atmospheric Refractivity Characteristics within Atmospheric Rivers and their Importance for Airborne Radio Occultation Observations, paper presented at Summer Undergraduate Research Fellowship Conference, Scripps Institution of Oceanography, La Jolla, CA, 13 August 2021.

Cativo, J., E. Robertson, J. S. Haase, M. J. Murphy, Jr., B. Cao, A. M. Wilson, N. Chernyy, and J. zsntifaev (2021), Investigating the Feasibility of  Obtaining RO Measurements of a Meteorological Phenomena Using Loon Balloons, in International Radio Occultation Working Group-8, edited, Taipei, Taiwan (virtual).

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

Alexander, M. J., J. S. Haase, M. Bramberger, B. Cao, A. Hertzog, A. Podglajen, and R. Vincent (2021), Surfing Tropical Waves in the Lower Stratosphere: Inferences on Waves and Winds from Long-Duration Super-Pressure Balloons and Balloon-borne Radio Occultation Profiles, paper presented at International Radio Occultation Working Group-8, Taipei, Taiwan (virtual), 7-9 April 2021.
Alexander, M. J., M. Bramberger, B. Cao, S. Davis, D. Goetz, Jennifer S. Haase, A. Hertzog, L. Kalnajs, A. Podglajen, and R. Vincent (2021), Balloon-borne Observations of Short Vertical Wavelength Tropical Waves and Interactions with Winds in the Lower Stratosphere, paper presented at American Meteorological Society Annual Meeting, New Orleans, LA, USA, 10-14 January 2021.

We have made data available at the following web sites:

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

The next reporting period will be focused on 1) Diagnosing problems with the Strateole2 gondola in preparation for the future science campaign in 2024 2) further wave analysis of the 2019 dataset.

# 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*.
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## 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

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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

## 5.5 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.

# 6 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 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.

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.

**What was the impact on teaching and educational experiences?**

Three undergraduate women from underrepresented communities and one man from a first-generation college student family have been involved in summer research projects.

A research seminar was presented for the faculty, graduate students, and postdocs at Scripps Institution of Oceanography.

**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.

**What percentage of the award's budget was spent in a foreign country?**

0.01 % of the budget was spent in Seychelles for the balloon deployment in 2019.

## 7 Conference Presentations

Hertzog, A., R. Plougonven, A. Podglajen, M. Corcos, M. J. Alexander, M. Bramberger, J. S. Haase, B. Cao, L. Kalnajs, D. Goetz, S. Davis, F. Ravetta, and S. Venel (2022), Strateole-2: long-duration balloon observations of gravity waves in the tropical lower stratospher, in 2022 SPARC Gravity Wave Symposium, edited, Frankfurt, Germany. (to be presented)

Alexander, M. J., M. Bramberger, J. S. Haase, B. Cao, A. Podglajen, and A. Hertzog (2022), Identification of fine-vertical-scale tropical wave modes in Strateole-2

balloon observations: Implications for QBO forces in the lowermost stratosphere, in 2022 SPARC Gravity Wave Symposium, edited, Frankfurt, Germany.
Cao, B., J. S. Haase, M. J. Alexander, M. Bramberger, M. J. Murphy, Jr., and A. Hertzog (2022), Equatorial waves observed by balloon-borne GNSS Radio Occultation during the Strateole-2 super-pressure balloon campaign in American Meteorological Society Annual Meeting, edited, virtual.
Apollonia Arellano, J. S. H., Jamin Greenbaum, Bing Cao, Michael J. Murphy, Matthew Mazloff, Rui Sun (2021), Potential Contributions to Observing Ice-Ocean-Atmosphere
Interactions of the Antarctic Atmospheric Boundary Layer
with Airborne Radio Occultation, paper presented at Summer Undergraduate Research Fellowship Conference, Scripps Institution of Oceanography, La Jolla, CA, 13 August 2021.
Brandon Bourassa, Jennifer S. Haase, B. C. Michael J. Murphy, A. M. Wilson, J. Parrish, G. DeFeo, J. Johnson, and J. Dahlberg (2021), Improved Atmospheric River Forecasting using Airborne Radio Occultation, paper presented at Summer Undergraduate Research Fellowship Conference, Scripps Institution of Oceanography, La Jolla, CA, 13 August 2021.
Brandon Bourassa, Jennifer S. Haase, B. C. Michael J. Murphy, A. M. Wilson, J. Parrish, G. DeFeo, J. Johnson, and J. Dahlberg (2022), Improved Atmospheric River Forecasting using Airborne Radio Occultation, paper presented at American Meteorological Society 21st Annual Student Conference, Houston, TX, 22-23 January 2022.
Janelle Wargo, Jennifer S. Haase, Michael J. Murphy, and B. Cao (2022), An Investigation of Spatially Dependent Atmospheric Refractivity Characteristics within Atmospheric Rivers and their Importance for Airborne Radio Occultation Observations, paper presented at American Meteorological Society 21st Annual Student Conference, Houston, TX, 22-23 January 2022.
Janelle Wargo, Jennifer S. Haase, Michael J. Murphy, and B. Cao (2021), An Investigation of Spatially Dependent Atmospheric Refractivity Characteristics within Atmospheric Rivers and their Importance for Airborne Radio Occultation Observations, paper presented at Summer Undergraduate Research Fellowship Conference, Scripps Institution of Oceanography, La Jolla, CA, 13 August 2021.
Cativo, J., E. Robertson, J. S. Haase, M. J. Murphy, Jr., B. Cao, A. M. Wilson, N. Chernyy, and J. zsntifaev (2021), Investigating the Feasibility of Obtaining RO Measurements of a Meteorological Phenomena Using Loon Balloons, in International Radio Occultation Working Group-8, edited, Taipei, Taiwan (virtual).
Cao, B., J. S. Haase, M. J. Alexander, M. Bramberger, M. J. Murphy, Jr., and A. Hertzog (2021), Tropical waves observed by balloon-borne GPS Radio Occultation during the equatorial Strateole-2 super-pressure balloon campaign in International Radio Occultation Working Group-8, edited, Taipei, Taiwan (virtual).
Alexander, M. J., J. S. Haase, M. Bramberger, B. Cao, A. Hertzog, A. Podglajen, and R. Vincent (2021), Surfing Tropical Waves in the Lower Stratosphere: Inferences on Waves and Winds from Long-Duration Super-Pressure Balloons and Balloon-

borne Radio Occultation Profiles, paper presented at International Radio Occultation Working Group-8, Taipei, Taiwan (virtual), 7-9 April 2021.

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

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.

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.

## 8 Acknowledgements

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# 9 Changes / Problems

**Changes in approach and reasons for change**

We are requesting supplemental funds to diagnose engineering issues with the Strateole2 gondola and intereference on the ROC2 receiver

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

**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

# 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.