Tropical waves observed by balloon-borne GPS Radio Occultation during the equatorial Strateole-2 super-pressure balloon campaign

Bing Cao[1], Jennifer S. Haase[1], M. Joan Alexander[2], Martina Bramberger[2], Michael J. Murphy[1], Albert Hertzog[3]

1. Scripps Institution of Oceanography, University of California at San Diego, CA
2. Northwest Research Associates, Boulder, CO **3.** Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure, IPSL, Paris, France

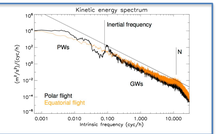
bic020@ucsd.edu Bing Cao,
jhaase@ucsd.edu Jennifer Haase

IROWG-8
2021 Apr 7-9

1. Science Objectives

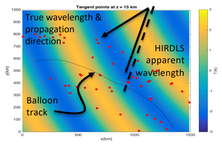
Dynamics of the Equatorial Stratosphere

Observations of gravity wave (GW) momentum fluxes in the tropics are needed for waves of all scales as well as the intermittency of their occurrence. Momentum fluxes will be retrieved from in-situ 30s balloon observations (u', v', p', and z') based on the GW polarization relationship.



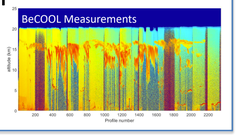
Investigation of Tropical Waves in 3D Space

Current methods, for example using the satellite HIRDLS temperature profiler, sample apparent wavelength and phase speed in 2D, so the derived momentum flux is biased. The Radio Occultation (ROC2) profiler attempts to sample large horizontal scale, fine vertical scale waves in 3D by sampling profiles to the sides of the flight track as well as along the flight track and is expected to provide a more representative measure of momentum fluxes.



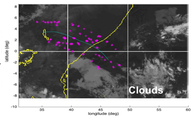
Wave Influences on CPT, Dehydration, Cirrus Formation

ROC2 profiles capture vertical wave structures very accurately and their correspondence with the Cold-point Tropopause (CPT) height, that is representative of large spatial scales. The LATMOS BeCOOL backscatter lidar on the same platform, detects cirrus below the balloon trajectory and provide valuable data for investigating cirrus formation.



Relation between Gravity Waves and Convection

Parameterization schemes for GWs generated from convection require momentum flux phase speed spectra at cloud tops which depends on convective latent heating. Observations of waves and clouds are needed for these schemes to behave realistically both in present day and future climate simulations, especially in the poorly sampled equatorial region.



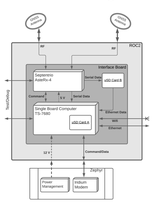
3. Strateole-2 Super-pressure Balloon Campaign

Spherical Helium Super Pressure Balloons, 11 and 13 -m diameter, fly at 18 and 20 km altitude, respectively.

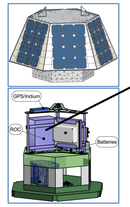
One STR-2 flight carried ROC2 as well as the BeCOOL backscatter LIDAR for detecting cirrus.

Radio OCcultation V2 (ROC2) Instrumentation

ROC2 Block Diagram



Zephyr Gondola



ROC2 Receiver

ROC2 in Zephyr

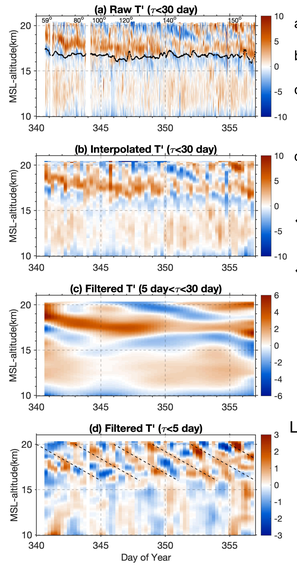
- ROC2 contains a multi-GNSS OEM board with two side-looking avionics GNSS antennas.
- ROC2 interfaces with the new Zephyr gondola designed by the Laboratoire de Météorologie Dynamique (LMD), which manages data transfer/comands via Iridium communication to the LMD Mission Control Center.
- The receiver tracks all GNSS signals (GPS, GLONASS, Galileo, Beidou), however only GPS signals were recorded continuously in 2019-2020. Faster satellite data rates in the upcoming 2021-2022 campaign will enable transmission of occultations from all constellations, with at least doubling of the number of profiles.

The super-pressure balloon carrying ROC2 was launched the night of 2019/12/06

8 balloon trajectories of the 2019-2020 Strateole-2 campaign

- A technology-validation campaign was carried out beginning in November 2019 from the Seychelles in the South Indian Ocean.
- Eight balloons carrying different instruments that measured atmospheric temperature, water vapor, aerosol, etc., were launched.
- A science campaign with 20-balloon flights in boreal fall-winter 2021-2022 is in preparation.
- A final 20-balloon campaign in 2023-2024 is planned for the opposite phase of the QBO.
- Real time balloon trajectories here: https://webstr2.lmd.polytechnique.fr/#/

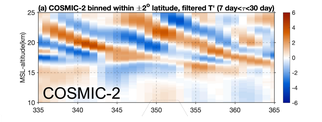
5. Tropical Waves Captured by Balloon-borne RO



a) Temperature perturbations for all individual STR-2 RO profiles, after removing a background 30-day mean determined from COSMIC-2.
b) Temperature perturbations are binned and averaged in even 6-hr intervals, then interpolated over one missing data gap.
c) Low-pass filtered temperature perturbations, with periods longer than 5-days. The perturbation amplitude reaches ±4 K and shows a slow downward phase progression with a period characteristic of a Kelvin wave (~20 days).
d) Temperature residuals after subtracting the long period variation show a fast downward phase progression, likely from westward propagating inertia-gravity wave, with 3-4 day period not captured by COSMIC-2.

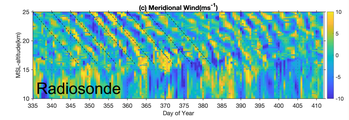
- (lower right a) COSMIC-2 temperature perturbations binned within ±2° latitude of the equator and within 120-140° longitude, filtered for periods between 7-30 days.
- (lower right b) Radiosonde meridional wind perturbations from one site with monthly mean removed.

20-day vs 17-day



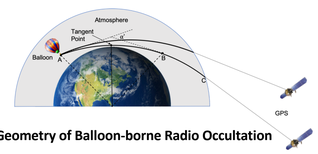
Lagrangian vs Eulerian

3-4-day vs 5-day



- The Kelvin wave amplitude determined by STR-2 RO, averaged within +/- 6 degrees of the balloon latitude, is comparable to the peak amplitude determined by COSMIC-2 within ±2° latitude of the equator.
- Balloons determine the intrinsic periods of the waves from the Lagrangian measurement platform, as opposed to the Eulerian measurements from COSMIC-2 and radiosondes.

2. Balloon-borne Radio Occultation (RO)



Geometry of Balloon-borne Radio Occultation

- The ROC2 receives GPS signals traveling nearly horizontally through the atmosphere which sample the atmospheric refractivity profile with high vertical resolution.

$$N = (n-1)\times 10^6 = 77.6\frac{P}{T} + 37.3\times 10^5 \frac{P_w}{T^2}$$

- The bending is an integral along the ray path from the receiver to the tangent point altitude, then to the GPS satellite. The asymmetric geometry requires additional corrections for the in-situ refractivity and the refractivity above the receiver.

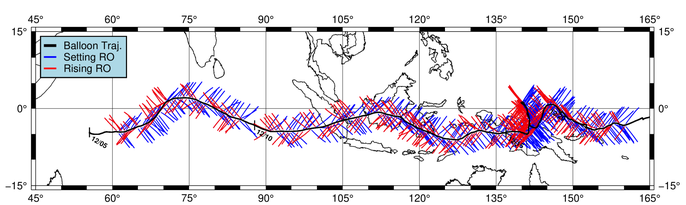
$$\alpha(a) = -2a\int_{r_t}^{r_R}\frac{1}{n}\frac{dn}{dr}\frac{dr}{\sqrt{n^2r^2-a^2}} - a\int_{r_R}^{r_T}\frac{1}{n}\frac{dn}{dr}\frac{dr}{\sqrt{n^2r^2-a^2}}$$

- The partial bending angle corresponds to the accumulated bending from the segment of the ray path below the altitude of the receiver. The partial bending angle (difference between positive and negative elevation angle bending) is inverted using the Abel transform to retrieve the refractive index.

$$n(a) = n_R\cdot\exp\left(\frac{1}{\pi}\int_a^{n_R r_R}\frac{\alpha'(x)dx}{\sqrt{x^2-a^2}}\right)$$

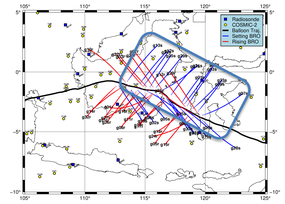
- The dry temperature and pressure as a function of height is retrieved using the refractivity equation, assuming negligible moisture above 10 km.
- For profiles near the equator, the orbital geometry for a relatively slow-moving balloon receiver produces slanted tangent point profiles, where the tangent point drifts horizontally 400-500 km as the satellite sets.

4. Characteristics of ROC2 Balloon-borne RO

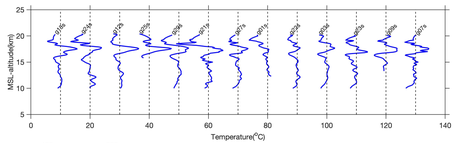


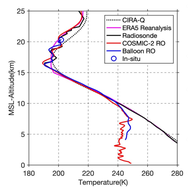
- String-of-Pearls: A continuous sequence of ROC2 balloon-borne RO profiles were retrieved over 17 days from 2019-12-06 to 2019-12-22, producing ~750 profiles in total.
- The profiles are slanted and occur in 4 principal orientations determined by the orbital planes of the rising and setting satellites. The 400-500 km horizontal drift of the tangent points provides 3D sampling.
- Around 45 GPS-only RO profiles were retrieved per day, covering about 800-1000 km per day along the trajectory depending on the wind velocity at flight level.
- Most profiles truncate at about 5-8 km altitude when the receivers lose track of the GPS signal.

- 48 balloon RO profiles shown for one day on 2020-12-12.
- The profiles extend in 4 principal orientations forming a near-orthogonal sampling pattern around the balloon path.
- Less dense COSMIC-2 RO profiles are scattered across the same area on the same day without any temporal ordering.

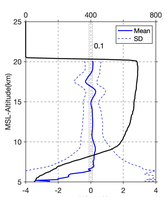


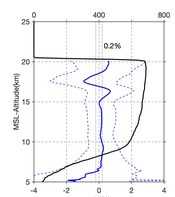
- A transect of multiple near-parallel ROC2 RO profiles, from the box in the above figure, showing a persistent wave pattern, which is the signature of a Kelvin wave.





- Comparison among balloon-borne RO, radiosonde, COSMIC-2 RO and ERA5 reanalysis for a typical profile.
- They are all within a 2-hr time interval and a 300-km distance separation.
- ROC2 dry temperature closely matches the radiosonde and COSMIC-2 above 10 km and resolves the tropopause very well.
- Similar wave pattern can be identified in all observations, but not in the reanalysis.
- Differences below 10 km are due to the simplified dry temperature retrieval process.





- The refractivity of ERA-5 is interpolated to the locations of the RO drifting tangent points.
- There is a difference of 0.2% mean (0.1 N-units) and 1% standard deviation (0.5 N-units) between balloon-borne RO and the ERA-5 model above 10 km.
- The differences show a clear wave pattern above 15-km, that is believed to be a persistent wave throughout the 17-day observation period.
- Further comparisons require ERA-5 products on model levels, since these waves are not captured by ERA-5 product available on pressure levels.

6. Summary

- **The ROC2 data are being used to derive:**
  - **precise positions for Quasi-lagrangian gravity wave measurements that correspond to shorter periods than are possible with TSEN GPS and**
  - **vertical profiles of temperature variations associated with equatorial waves at different scales, continuously along the trajectory of the balloons.**
- **The dense, high vertical resolution STR-2 RO profiles show excellent agreement with collocated radiosonde and spaceborne RO.**
- **Over the 17-day dataset, STR-2 RO and ERA-5 reanalysis show a 0.2% mean and 1% SD percentage difference in refractivity.**
- **The amplitude of Kelvin waves of 4-6 km vertical wavelength was larger than that observed from spaceborne RO, likely due to higher vertical resolution and denser sampling.**
- **Consecutive sampling from STR-2 RO also resolved westward propagating inertia-gravity waves with 3-4 day intrinsic period, and 2-3 km vertical wavelength that are not resolved with the temporal sampling of COSMIC-2.**
- **ROC2 will fly on 5 balloons in the 20-balloon Strateole-2 science campaign in 2021-2022 for a more comprehensive sampling of equatorial waves.**

References

Cao et al., 2021, Tropical waves observed by balloon-borne radio occultation, in preparation.
Haase et al., 2021, Multi-GNSS airborne radio occultation observations as a complemente to dropsondes during Atmospheric River Reconaissance, submitted to J. Geophys. Res.- Atmos.
Haase et al., 2018, Around the world in 84 days – Strateole-2 investigates the tropical atmosphere with long-duration superpressure balloons, Eos, 99, https://doi.org/10.1029/2018EO091907

Acknowledgements

Strateole-2 ROC2 scientific research is supported by National Science Foundation (NSF) grant AGS-1642650. Strateole-2 is an international research project with major funding provided by NSF, the French Space Agency (CNES), and National Center for Scientific Research (CNRS) with collaborators from France, USA, Italy, India, and Australia (https://www.lmd.polytechnique.fr/VORCORE/McMurdo.htm), We thank LMD, CNES, UNAVCO, and Brainstorm Engineering for assistance implementing the ROC2 measurements.