



## Retrieval of humidity based on refractivity profiles from GNSS airborne radio occultations

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### Abstract

Global Navigation Satellite Systems (GNSS) radio occultation from airborne platform (ARO) provides unique approach in atmosphere profiling that originated from more mature spaceborne missions. A total of 1,212 GNSS-ARO files from the 2023 California coastal campaign (AR2023) were processed using Radio Occultation Processing Package (ROPP) 1-dimensional vertical profile (1D-Var) retrieval. This processing yielded 42 deep occultations, with a penetration depth of 1 kilometer or better. Retrieval diagnostics demonstrate that 1D-Var effectively mitigates ERA5 background errors, as evidenced by tight OmA residuals clustering near zero ( $|\Delta N/N| \lesssim 0.015$  mean/median, std < 0.08) across 1–12 km altitudes. This is in contrast to the wider observation-minus-background (OmB) spread of  $\pm 0.10$  N-units (which has been reduced by 72%). ARO uniquely resolves moisture in the troposphere associated with atmospheric rivers not fully captured by ERA5. Spaghetti plots confirm robust retrieval across full altitude range. GNSS-ARO emerges as complementary regional observing system for complex coastal meteorology, enabling high-resolution profiling and Numerical Weather Prediction validation.

### 1. Introduction

Atmospheric refractivity is a fundamental parameter for understanding the structure of the atmosphere and its impact on electromagnetic wave propagation. The predominant factors influencing this phenomenon are temperature, pressure, and the water vapor content. Accurate refractivity profiles are imperative for enhancing the precision of weather prediction models, facilitating the monitoring of climate variability, and supporting aviation and communication systems. This is particularly evident in the context of enabling high-resolution moisture and temperature retrievals in atmospheric rivers (ARs), which contributes to the refinement of landfall forecasts, the enhancement of integrated vapor transport (IVT) accuracy, and the mitigation of flood risk along the U.S. West Coast. Airborne GNSS ARO observations from AR Reconnaissance campaigns provide dense, cloud-penetrating profiles that directly improve NWP assimilation and precipitation forecasting during extreme events [1,2]. Radio occultation (RO) techniques provide a highly precise and independent means of remotely sensing the atmosphere. In spaceborne RO, signals from Global

Navigation Satellite Systems (GNSS) are recorded by Low Earth Orbit (LEO) satellites as they pass behind the Earth's limb. Although the majority of RO observations are derived from space platforms, the airborne radio occultation (ARO) technique provides a complementary capability for regional studies. In ARO, GNSS receivers mounted on aircraft record refracted signals along the flight trajectory, enabling detailed investigation of the lower and middle troposphere. This method provides greater spatial flexibility and can capture small-scale refractivity variations that are often unresolved in satellite-based observations [3,4]. The Pacific region adjacent to the Californian coastline functions as an optimal natural laboratory for refractivity studies due to its pronounced temperature/humidity gradients, dynamic marine boundary layer, and frequent inversions, enabling sharp vertical refractivity variations. This study utilizes GNSS-ARO refractivity profiles from Atmospheric River Reconnaissance (AR Recon) campaigns—winter missions (November to March) employing NOAA G-IV/USAF WC-130J aircraft over the eastern Pacific to enhance AR forecasts and West Coast flood predictions [5]. The application of 1D-Var retrievals (ROPP framework) against ERA5 backgrounds is employed to generate OmA diagnostics, with the objective of characterizing retrieval errors, vertical variability, and consistency across AR conditions. The analysis corroborates the efficacy of aircraft-based ARO refractivity as a high-resolution profiling instrument.

### 2. Data and Methods

The study utilizes GNSS-ARO observations collected during research aircraft campaigns over the Pacific Ocean near the Californian coastline. GNSS receivers installed on the aircraft successfully recorded L1/L2 signals from GPS satellites, thereby yielding high-resolution atmospheric soundings in the lower and middle troposphere. A total of 42 profiles from 2023 campaigns were selected after quality control, with cases lacking minimal height below 1 km excluded.

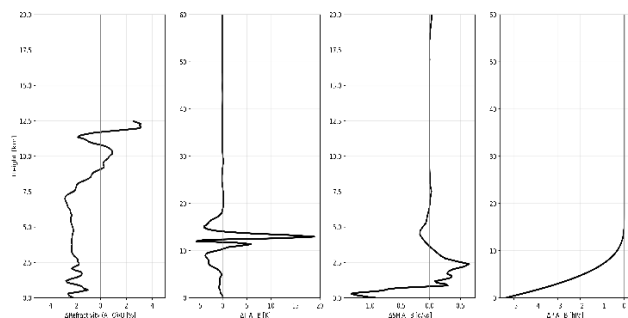
Atmospheric refractivity profiles were retrieved using the one-dimensional variational (1D-Var) method for temperature and humidity assimilation, implemented in the Radio Occultation Processing Package (ROPP) software suite (version 11.0) developed by the EUMETSAT Radio Occultation Meteorology Satellite Application Facility (ROM SAF). The 1D-Var process is a data assimilation

technique that minimizes the cost function between observed and modeled refractivity. It uses a background covariance matrix consistent with ERA5 reanalysis data, which has a spatial resolution of  $0.25^\circ \times 0.25^\circ$  and an hourly temporal resolution. The ECMWF ERA5 reanalysis fields (T, q, and P on 137 hybrid levels) were utilized to provide the a priori background state. The observation vector was utilized to calculate model-equivalent refractivity from background profiles via the forward model, a process that is independent of geometry. The 1% observation error model was employed, with the objective of optimizing refractivity directly.

The retrieved 1D-Var profiles (analysis, denoted as A) were then validated against the corresponding ERA5 background profiles (prior, denoted as B). Standard diagnostics included OmB (Observation minus Background), which is defined as the difference between GNSS-RO observed refractivity and refractivity computed from ECMWF background via the forward model and OmA (Observation minus Analysis), the residual after 1D-Var.

### 3. Results

The 2023 GNSS-ARO dataset yielded 1,212 processed files, encompassing 42 high-quality profiles that penetrated below 1 kilometer, thereby facilitating meticulous sampling of the lower troposphere over the California coastal Pacific. These deep occultations resolved fine-scale refractivity variations associated with humidity gradients and coastal moisture structures that were unresolved by standard models. The 1D-Var retrievals have been shown to enhance the ERA5 background, underscoring the importance of humidity information and the assimilation potential of aircraft observations. For the 42 deepest profiles, the mean temperature bias is -3.5 Kelvin (RMSE  $\approx$  12 Kelvin), with specific humidity and pressure RMSEs of 2.5 g/kg and 7.8 hPa, respectively. The median refractivity residuals are found to be nearly zero, with a few cases displaying greater variability. Diagnostics confirm retrieval convergence and physical consistency across the ensemble (Figure 1).



**Figure 1.** Four-panel diagnostics of a representative profile from the 42-profile dataset.

As illustrated in Figure 1, a four-panel horizontal comparison is presented between GNSS-ARO observations and the 1D-Var retrieval for the deepest profile. The refractivity index exhibits a strong correlation

with post-assimilation observations, with residuals remaining below 3.13%. Temperature demonstrates significant corrections (approximately 5–20 K), while specific humidity adjustments remain modest (1.2 to 0.6 g/kg) relative to ERA5. Surface pressure has been significantly enhanced, although residual pressures of approximately 5 hPa remain.

OmB diagnostics indicate substantial pre-assimilation ERA5 deficiencies, with residuals reaching  $\pm 0.10$  below 10 km, driven by unresolved coastal refractivity gradients and a systematic dry bias. OmA residuals across 42 deep profiles exhibit a tight clustering around zero from the surface to the upper troposphere, with mean and median envelopes near zero and limited spread. This finding confirms robust convergence and physical consistency of the retrievals.

### 4. Conslusions

A thorough analysis of 1,212 GNSS-ARO files from the 2023 California coastal campaign reveals that a mere 42 occultations (3.5%) penetrated below 1 kilometer. This finding underscores the geometric limitations inherent to airborne platforms in comparison to spaceborne radio occultation.

The 1D-Var retrievals demonstrate robust assimilation performance. OmA residuals demonstrate a high degree of concentration around zero between 1 and 12 km, while OmB residuals exhibit a  $\pm 0.10$  N-unit spread that is reduced by 72% following retrieval. The resulting four-parameter corrections are physically consistent, characterized by enhanced surface refractivity, mid-tropospheric temperature warming, modest lower-tropospheric humidity adjustments (ranging from -1.2 to +0.6 g/kg), and surface pressure corrections of approximately 5 hPa.

Aircraft-based GNSS-ARO offers several distinct advantages, including the capacity for high boundary layer penetration, which yields the deepest profiles (92%), the capability for regional targeting with repeated sampling of complex coastal meteorology, and high temporal resolution during intensive campaigns. Notwithstanding, limitations persist, including the low success rate of deep occultations, shorter ray paths relative to satellite geometry, and sensitivity to platform motion, necessitating precise trajectory integration.

A comprehensive evaluation of the results indicates that GNSS-ARO is a valuable complementary observing system for regional atmospheric profiling in coastal and semi-enclosed marine environments. In such environments, fine-scale vertical structure exerts a significant influence on weather prediction and air quality modeling. Subsequent endeavors should prioritize the development of ensemble-based background error covariances and multi-instrument assimilation approaches to further enhance retrieval accuracy.

## 5. Acknowledgements

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## References

- [1] B. Cao, J. S. Haase, M. J. Murphy Jr., and A. M. Wilson, "Observing atmospheric rivers using multi-GNSS airborne radio occultation: system description and data evaluation", *Atmospheric Measurement Techniques*, **18**, 6, June 2025, pp. 3361-3392, doi: 10.5194/amt-18-3361-2025.
- [2] P. Do, J. S. Haase, I. H. Baños, P. Hordyniec, and B. Cao, "Impact of airborne radio occultation observations on short term precipitation forecasts of an atmospheric river", *Geophysical Research Letters*, **52**, 13, July 2025, doi: 10.1029/2025GL115639.
- [3] B. J. Murphy, J. S. Haase, P. Muradyan, J. L. Garrison, and K. Wang, "Airborne GPS radio occultation refractivity profiles observed in tropical storm environments", *Journal of Geophysical Research Atmospheres*, **120**, 5, March 2015, pp. 1690-1709, doi: 10.1002/2014JD022931.
- [4] F. Xie, K. J. Nelson, B. C. Chan, A. Goel, J. Kosh, and M. Vergalla, "First results of airborne GNSS radio occultation sounding from Airbus commercial aircraft", *Geophysical Research Letters*, **51**, September 2024, doi: 10.1029/2024GL110194.
- [5] T. E. Winning Jr., F. Xie, and K. J. Nelson, "Assessing the ducting phenomenon and its potential impact on Global Navigation Satellite System (GNSS) radio occultation refractivity retrievals over the northeast Pacific Ocean using radiosondes and global reanalysis", *Atmospheric Measurement Techniques*, **17**, 12, December 2024, pp. 6851-6863, doi: 10.5194/amt-17-6851-2024.