1D-Var retrieval of temperature and humidity using GNSS airborne radio occultation data

Paweł Hordyniec[1], Aleksandra Maciejewska[2]

Wrocław University of Environmental and Life Sciences

(1) Institute of Geodesy and Geoinformatics, Wrocław University of Environmental and Life Sciences, Wrocław, Poland
(2) AGH University of Krakow, Krakow, Poland
contact: pawel.hordyniec@upwr.edu.pl

AGH

Abstract

Atmospheric rivers (ARs) are major contributors to extreme precipitation and hydrological hazards, yet their representation in numerical weather prediction remains limited by sparse observations over oceanic regions. The Atmospheric River Reconnaissance (AR Recon) program addresses this gap by deploying targeted aircraft and buoy observations ahead of landfalling ARs along the U.S. West Coast. The campaigns enable simultaneous observations of ARs using dropsondes and complementary profiles from GNSS airborne radio occultation (ARO), both of which can improve the analysis of AR environments. The value of ARO in data assimilation has recently become the subject of extensive study, driven by the development of advanced forward models for ARO observations. This work builds on ongoing efforts to quantify the impact of ARO data on atmospheric analyses through the use of a one-dimensional variational (1D-Var) retrieval. By combining ARO observations with background information, the most probable profiles of temperature and humidity are estimated which otherwise cannot be directly observed with ARO. This approach broadens the applicability of ARO data by providing an independent benchmark for evaluating model background states and conventional observations. Operational systems can utilize 1D-Var for initial impact assessment and quality control screening prior to assimilation with 3D- or 4D-Var schemes. It is shown that background profiles derived from the ECMWF ERA5 reanalysis can be further improved through the inclusion of ARO data in 1D-Var retrieval. The impact on the temperature analysis is quantified to be on the order of 0.5 K in terms of analysis-minus-background statistics. Additional sensitivity experiments are conducted to assess the influence of different processing configurations, including observational error models, error covariances and minimization strategies. Particular attention is given to the ability to capture sharp vertical gradients associated with potential inversion layers identified from retrieved thermodynamic profiles.

1. Key Points

1) 1D-Var retrieval is implemented for refractivity observations from GNSS airborne radio occultation.
2) Various processing scenarios for error covariance options are tested and diagnosed with Desroziers method.
3) Retrievals shows improvements in humidity and temperature which strongly depend on covariance options.

2. Data and methods

The 1dVar retrieval for ARO is implemented in ROPP software and consists of following core modules:

(a) **ropp_fm_bg2ro_1d**: refractivity forward model
(b) **ucar2ropp, grib2bgrasc**: input data pre-processing
(c) **ropp_1dvar_refrac**: 1dVar tool for ARO refractivity

Observations and background data:

(a) **ARO**: ~1200 refractivity profiles, AR Recon 2023
(b) **ECMWF**: ERA5 reanalysis, 137 model levels, 0.25 ×0.25 deg horizontal resolution, hourly

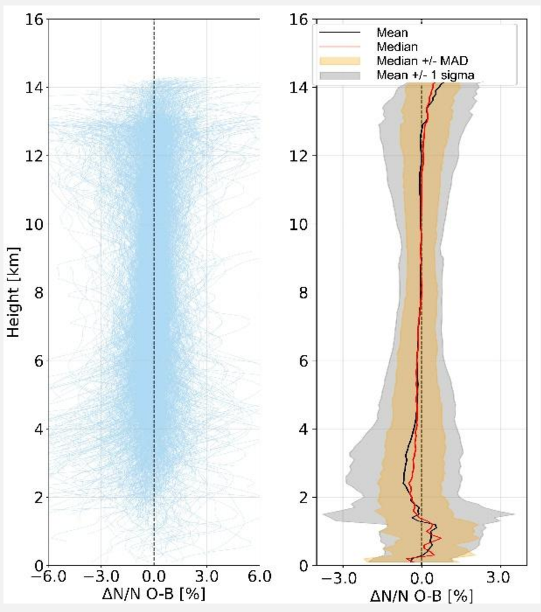

Fig 1. O minus B statistics for ARO refractivity

3. Background errors and correlations

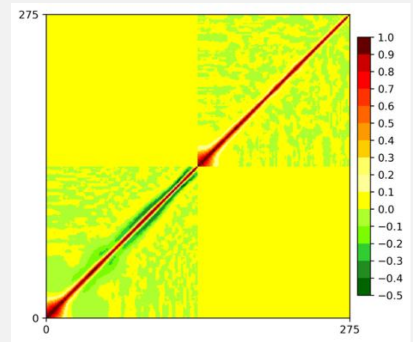

Fig 2. Background error correlations from SES method in block diagonal structure arising from a 3 element state vector: {T, q, p}.*

Background error correlations:

a) **ropp_bg_ef_ei_error_corr_sigma_PsBias_LatB5d_L137**

Derived from ERA-Interim forecast/analysis statistics using the Desroziers-Fisher diagnostic (DF) method resolved on 5 deg latitude bins. Pressure standard deviation has been inflated to compensate for bias of ERA-I forecast with respect to ERA-I analysis. Suitable for bg covar method **FSFC**.

b) **ropp_bg_ses_ecmwf_error_corr_L137**

Scaled Ensemble Standard Deviation (SES) method (Holm and Kral, 2012) to be run with bg covar method **RSFC**. The standard deviation of q is calculated profile-by-profile, using the background q multiplied by a fixed <dq/q>. These standard deviations are then used to calculate the covariances using the given correlation matrix as $ECM = \sigma \cdot Corr \cdot \sigma^T$

Desroziers diagnostics in Fig. 3 show the agreement of the combined background and observation errors with the correspoding O-B statistics. The applied background covariance is based on SES method (b). While the agreement in the troposphere is reasonable, further optimization is required above 9 km.

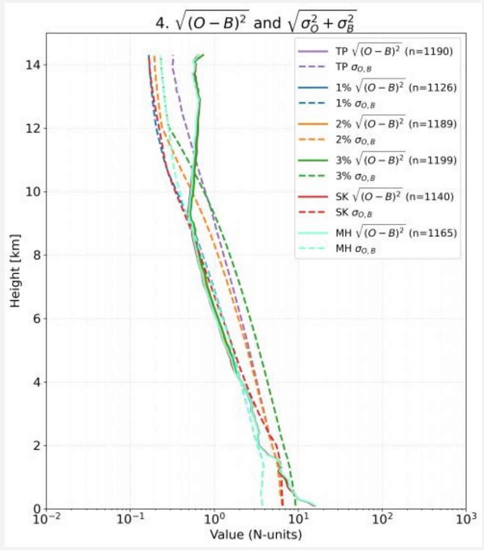

Fig 3. Desroziers diagnostics for assumed background (SES) and obs errors

4. Observation errors and correlations

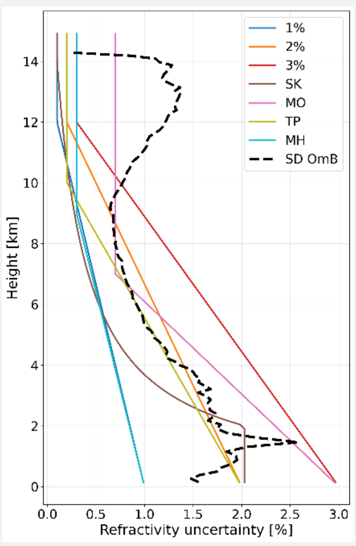

Fig 4. observation error models for refractivity

Existing RO refractivity error models are tested:

1 % from 1 % at the surface to 0.1 % above 12 km
2 % from 2 % at the surface to 0.2 % above 12 km
3 % from 3 % at the surface to 0.3 % above 12 km
TP 2 % with dynamically estimated tropopause
MO Met Office operational error model
SK based on Steiner & Kirchengast (2005).

Proposed error model for airborne RO:

MH from 1 % at the surface to 0.3 % above 9 km,

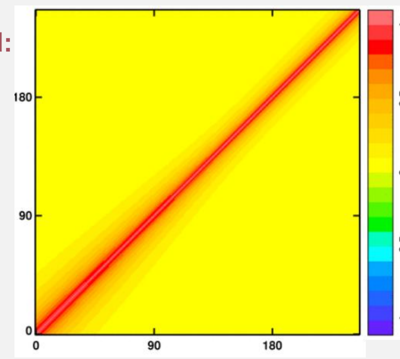

Fig 5. Error correlations on standard 247 refractivity levels

The advantage of a dedicated observation error model for ARO refractivity is demonstrated using Desroziers diagnostics in Fig. 6. Diagnostics are based on 1dVar configuration RSFC for background and VSDC for obs data. A better fit to the vertical distribution is achieved by adjusting the transition height (9 km from 12 km), followed by an inflation of errors above this level.

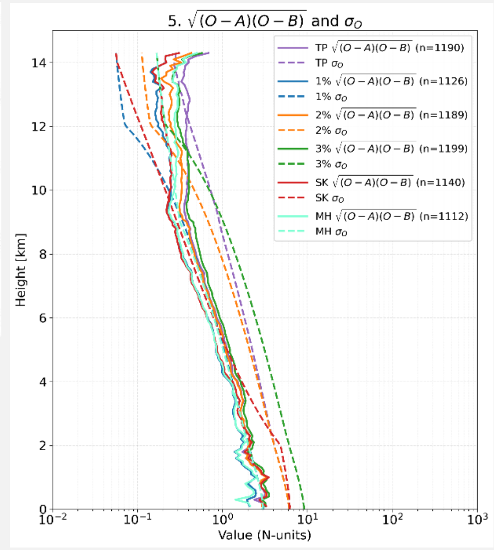

Fig 6. Desroziers diagnostics for tested obs error models

5. 1dVar results

Following 1dVar scenarios are evaluated to assess impact of different background and error covariance options on the analysis.

1dVar configuration options for background

RSFC Relative Sigmas Fixed Correlations
FSFC Fixed Sigmas Fixed Correlations

1dVar configuration options for observations

FSFC Fixed Sigmas Fixed Correlations.
FSDC Fixed Sigmas Diagonal Correlations
VSDC Variable Sigmas Diagonal Correlations

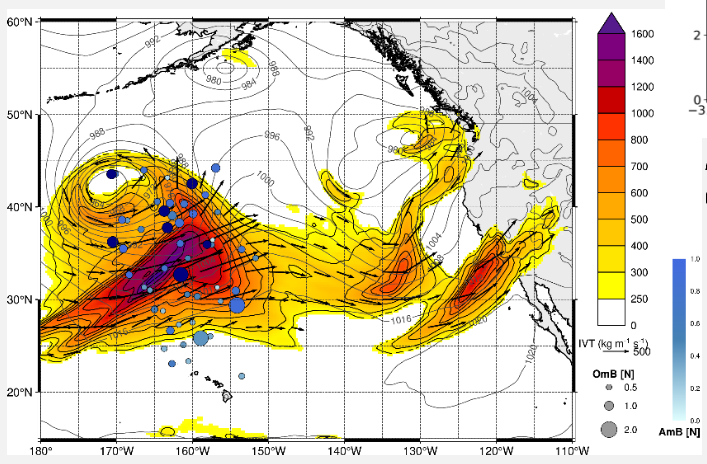

Fig 7. Contour map of IVT (2300 UTC Oct 1) for IOP 10 with innovations (dots) and analysis increments (blue) for ARO profiles. 1dVar option: RSFC_VSDC with MH obs errors

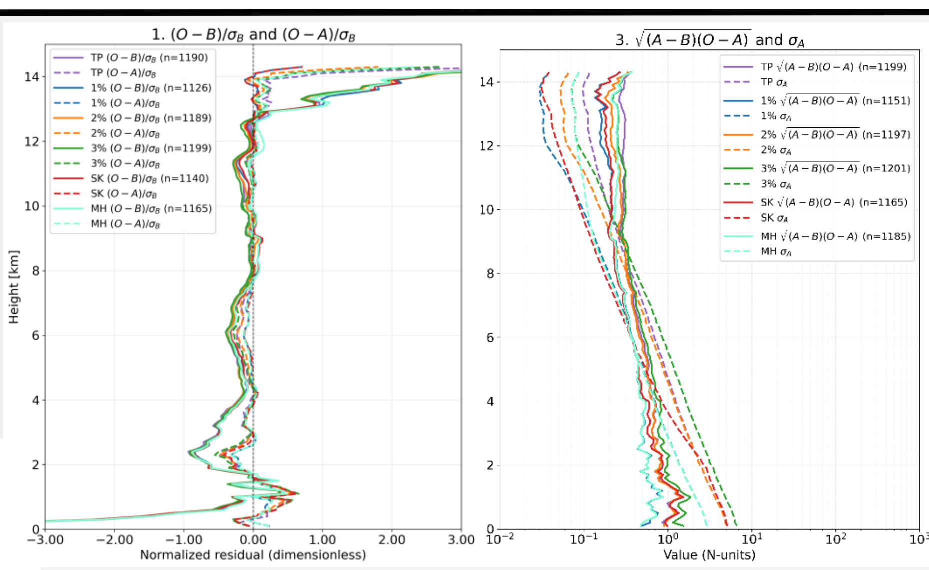

Fig 8. Desroziers diagnostics: (left) background and analysis departures, (right) uncertainty of the analysis (RSFC_VSDC with MH obs errors).

The 1D-Var results suggest that ARO refractivity observations improve the analysis (Fig. 8, left); however, further tuning of the background error correlations is likely required to achieve an optimal solution (Fig. 8, right). Sensitivity tests show that the vertical distribution of analysis increments strongly depends on the treatment of background error covariances. The configuration based on relative sigmas (RSFC) leads to a smaller impact of ARO observations in the lower troposphere, resulting in more conservative increments than the configuration based on fixed sigmas (FSFC). This is reflected in specific-humidity increments of 0.3 g/kg versus 0.6 g/kg for RSFC and FSFC, respectively (Fig. 10).

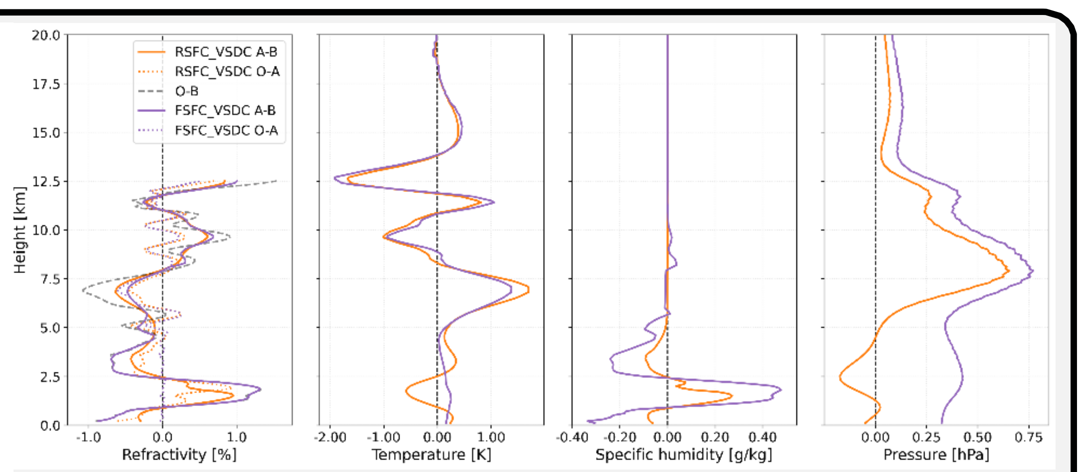

Fig 9. 1dVar solutions based on individual ARO profile

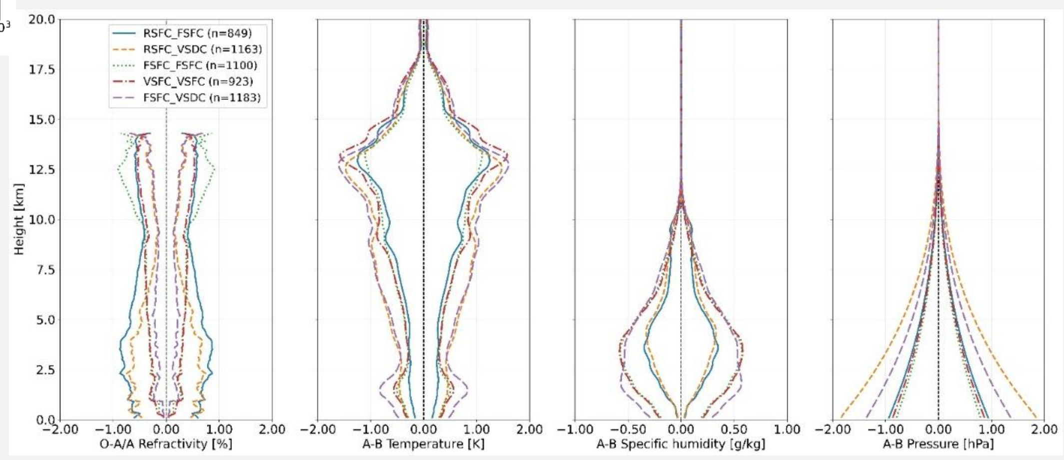

Fig 10. Overall statistics for various 1dVar solutions based on MH obs error model

Summary

A 1D-Var retrieval capability for ARO refractivity observations was implemented within the ROPP software. At present, the software is primarily optimized for spaceborne RO observations, which exhibit error characteristics that differ from those of airborne measurements. Available configuration options were evaluated to assess their suitability and sensitivity for 1D-Var retrievals based on ARO refractivity. First, a dedicated observation error model for ARO refractivity was developed and shown to satisfy consistency requirements based on Desroziers diagnostics. Second, two background error covariance configurations provided by ROM SAF were tested and found to produce distinct 1D-Var retrievals, both yielding substantial analysis increments. However, Desroziers diagnostics applied to both configurations indicate that further adjustments to the background-error correlations are required. These correlations were originally developed for spaceborne RO observations and may not be fully appropriate for airborne measurements that are characterized by a different observation geometry. This study was conducted with the aim of supporting ongoing data assimilation experiments involving ARO observations in 3D-Var and 4D-Var configurations, which currently employ a more advanced observation operator for bending angle profiles. The results presented here are expected to be complemented by future 1D-Var experiments based on bending angle observations, which are anticipated to outperform retrievals based on refractivity. Achieving this objective, however, will require further refinement of the error covariance specifications to obtain an optimal solution.

Acknowledgements:

This study was carried out within the project funded by the National Science Centre, Poland (grant 2024/55/D/ST10/00661).
Author P. Hordyniec acknowledges funding support from the Wroclaw University of Environmental and Life Sciences, Poland (grant N060/0001/24).