Implementation of the Super-Refraction Correction for GNSS RO Data at the NOAA/STAR

Stanislav Kireev[1], Yong Chen[2], Shu-peng Ho[2], and Yuxiang He[3]

[1]Global Science & Technology, Inc.; [2]NOAA/NESDIS/STAR; [3]GAMA-1 Technologies

1. Abstract

With high vertical resolution and all-weather sensing capability, the RO-derived atmospheric variables have been applied widely for weather forecasting, tracking critical atmospheric events, detecting long-term climate signals, and improving atmospheric models. However, the super-refraction (SR) phenomenon, caused by sharp gradients of temperature and moisture in the Planetary Boundary Layer (PBL), is frequently observed in subtropical regions over oceans. Due to the SR, RO refractivities are systematically underestimated in and below the PBL *(Sokolovskiy, 2003)*. It leads to the well-known negative bias of RO retrieved water vapor compared to in-situ radiosondes (RAOB) data and atmospheric profiles derived from microwave and infrared sounders.

In the case of SR, the input refractivity should be corrected before using it in the retrieval. This is a challenging problem because a) there is no information about the refraction index in the SR layer; b) the infinite number of corrected refractivity profiles satisfy the given bending angle; and c) the proper choice of correction among potential candidates is an ambiguous and arguable issue.

We present how these challenges are met in the STAR RO-SR retrieval algorithm. To build a family of potential candidates for refractivity correction under SR conditions, we implemented the approach proposed by *(Xie et al., 2006)* and further developed in *(Wang et al., 2017)*. We use radiosonde measurements from the VOCALS campaign *(Wood et al., 2011), Oct-Dec 2008*, as references to simulate the refractivity and bending angle profiles under SR conditions. We also applied the correction algorithm to actual COSMIC observations, and validated the results with collocated VOCALS RAOB data. Results show that the STAR RO-SR refractivity correction algorithm significantly reduces the negative bias of RO retrieved water vapor.

2. The RO-SR Algorithm Key Steps

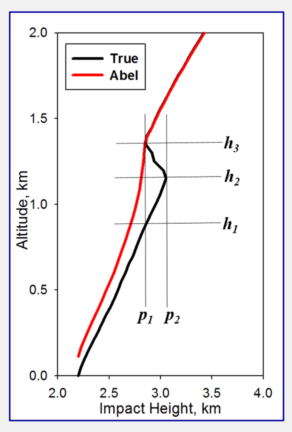
- Obtain refractivity profile $N_{TRUE}(h)$ using VOCALS {P, T, P_W}: $N_{TRUE}(h) = 77.6\frac{P}{T} + 3.73\times 10^5\frac{P_W}{T^2}$
- Get bending angle using STAR RO Forward Model
- Inverse bending angle into refractivity with Abel Transform (filtering out unstable levels leads to degraded $N_{ABEL}(h)$ refractivity).
- Build a family of corrected refractivity $N_{CORR}(h)$ *(Xie et al., 2006)* by varying SR parameters $\{h_1, h_2, h_3, p_1, p_2\}$:

$$h(p) = h_3 - \frac{h_3-h_2}{p_2-p_1}(p-p_1),\quad h_2 \le h \le h_3 \text{ (SR Layer)}$$

$$h(p) = h_1 + \frac{h_2-h_1}{p_2-p_1}(p-p_1),\quad h_1 \le h \le h_2 \text{ (Shadow Layer)}$$

$$h(p) = h_{Abel}(p) + \frac{2}{\pi}(h_3-h_1)\left[\varphi - (1+\varphi^2)\tan^{-1}(1/\varphi)\right],\quad h < h_1 \text{ (Mixing Layer)}$$

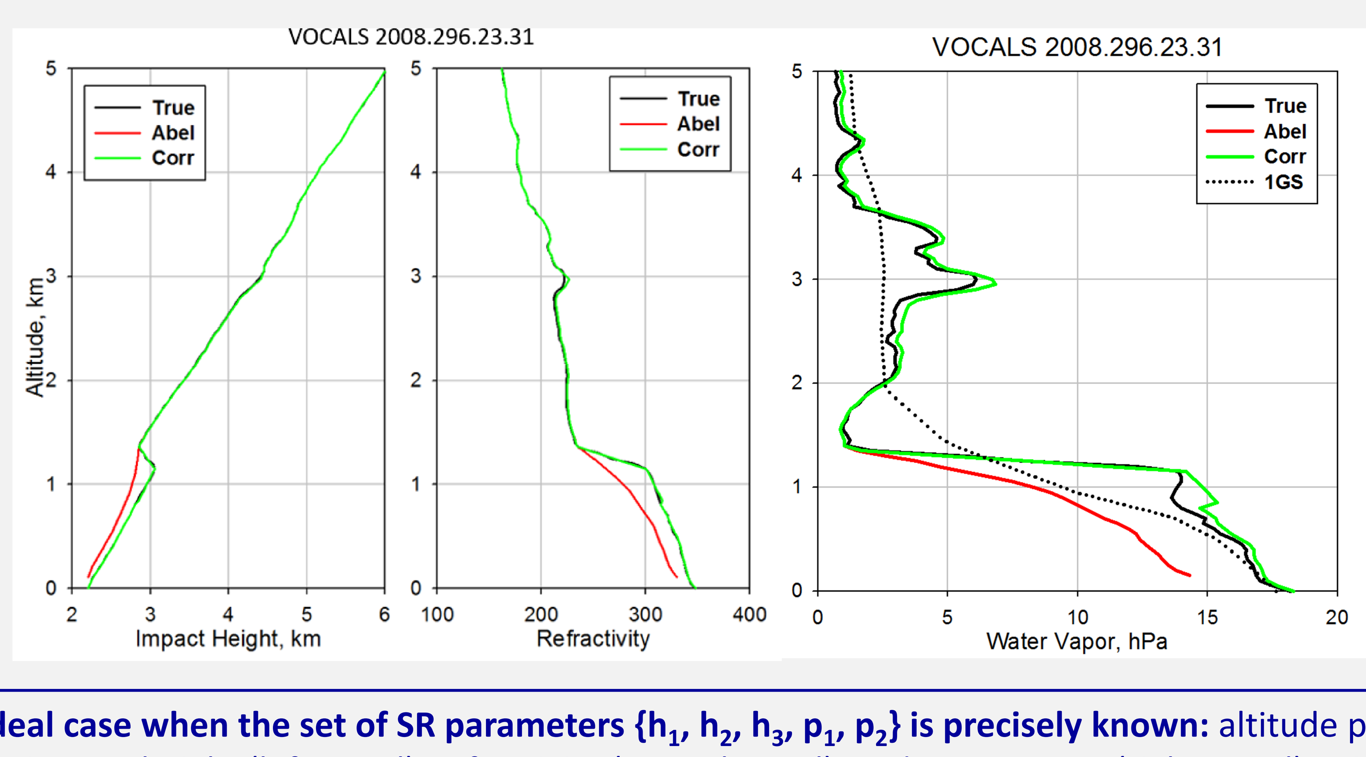
$$\varphi = \sqrt{p_2-p}/\sqrt{p_2-p_1}$$



- The initial estimation of h_3 and p_1 SR parameters is obtained from the condition $min\frac{\partial N}{\partial h}$ <-79 N/km; the rest of SR parameters is determined by brute force.
- Retrieve {P, T, P_W} from $N_{ABEL}(h)$ and each $N_{CORR}(h)$.
- Select the best N-correction which provides $min|\Delta TPW|$ difference between retrieved moisture and the First Guess (GFS-6-Hours-Forecast).
- Compare water vapor profiles, retrieved from N_{ABEL} and N_{CORR}, with actual VOCALS RAOB.

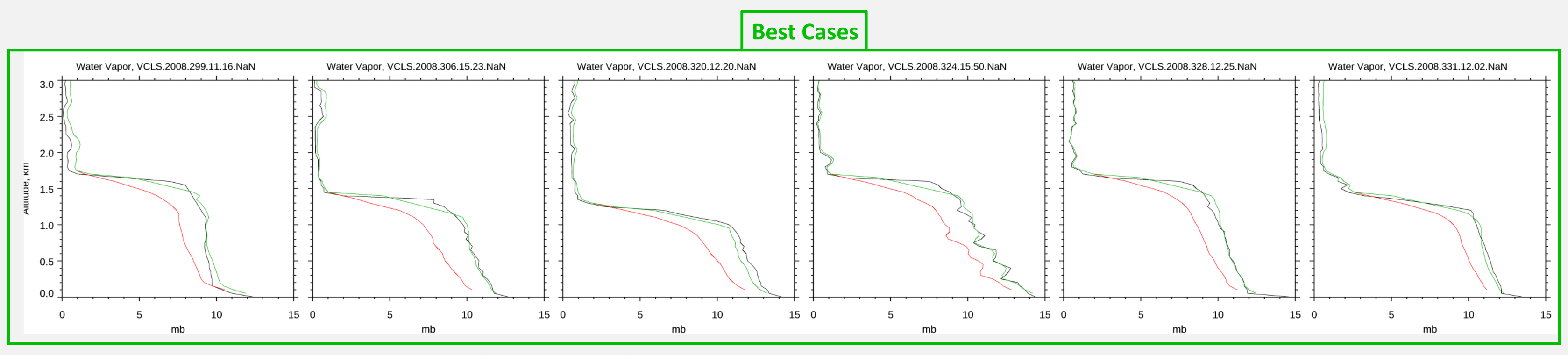
In processing actual RO observations (COSMIC1), first two steps are omitted.

3. VOCALS Simulations Results of N-Correction

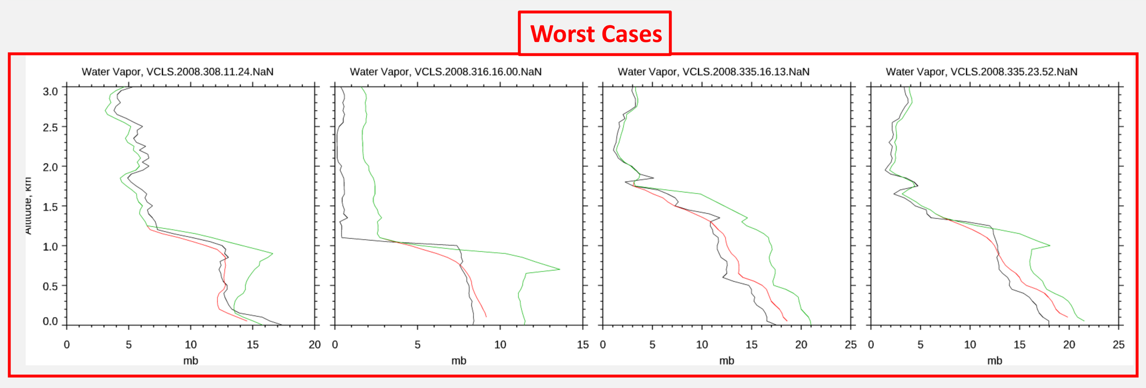


An ideal case when the set of SR parameters $\{h_1, h_2, h_3, p_1, p_2\}$ is precisely known: altitude profiles of the impact height (left panel), refractivity (central panel), and water vapor (right panel). VOCALS RAOB profiles (black), before N-correction (red), and after N-correction (green) profiles are shown. The black dotted line at the right panel is the first guess profile used in the STAR RO 1D-Var.

Best Cases



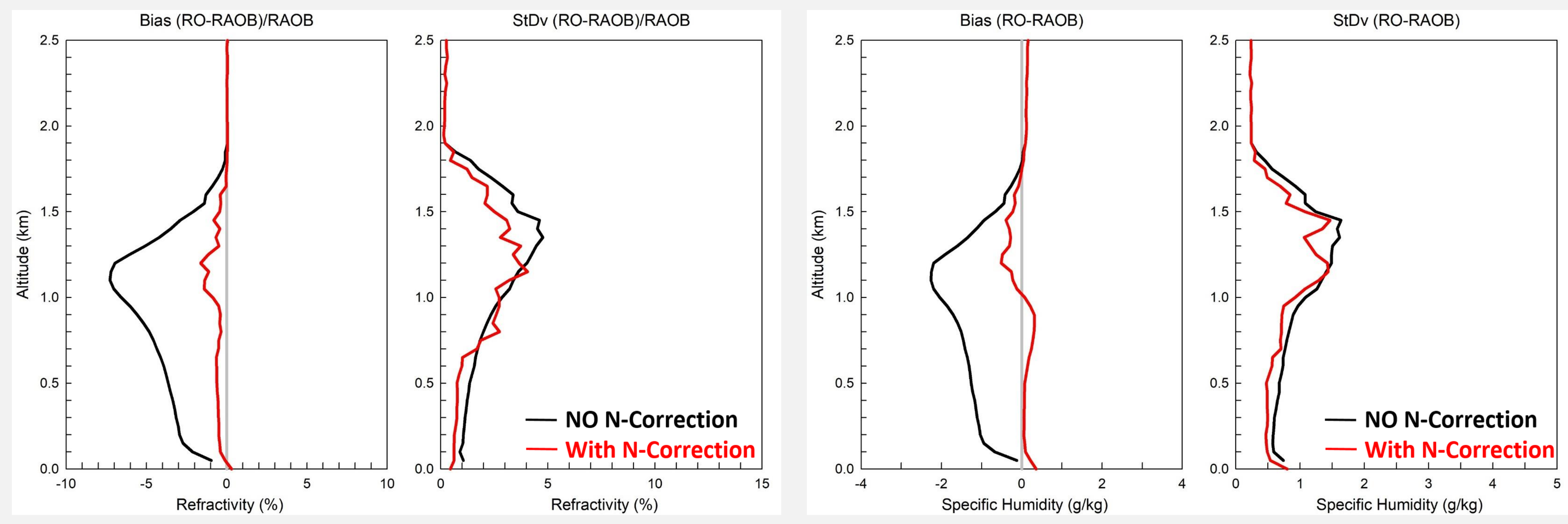
Worst Cases



Individual water vapor profiles:
- VOCALS RAOB
- from non-corrected N
- from corrected N

$Min|\Delta TPW|$ is used to pick the best correction. Main reason of the failed N-correction (worst cases) is a wrong evaluation of the SR parameters.

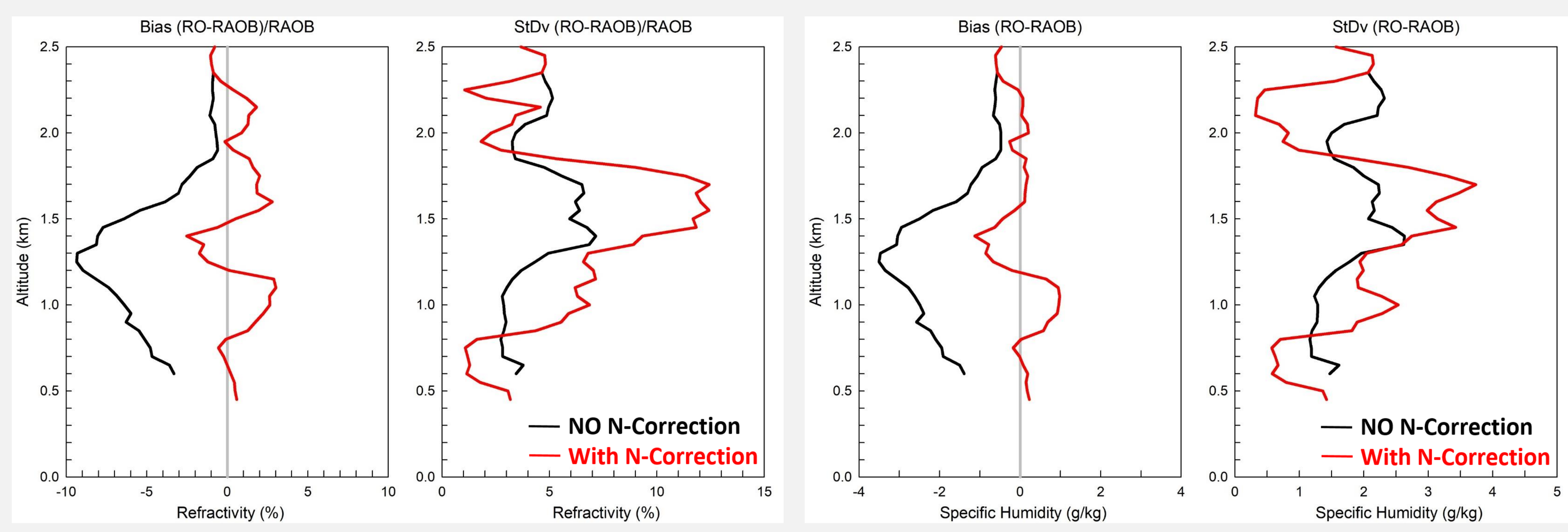
4. VOCALS Simulations Statistics



Bias and standard deviation for fractional N-residual and water vapor, retrieved from non-corrected (black) and corrected (red) refractivity for VOCALS simulations.

The averaging is done over 119 VOCALS observations qualified as SR cases. The bias of water vapor, retrieved from corrected refractivity, does not exceed 0.5 g/kg in absolute value for altitudes below 1.5 km. The best agreement between retrieved water vapor profiles and RAOB data for VOCALS simulations is less than 0.1 g/kg and below 0.6 km. The water vapor profiles, derived from non-corrected refractivity, are biased from -2 to -1 g/kg respectively.

5. COSMIC1 vs VOCALS RAOB Statistics



Bias and standard deviation for fractional N-residual and water vapor, retrieved from non-corrected (black) and corrected (red) refractivity for COSMIC1 vs VOCALS validation.

The averaging is done over 11 COSMIC1 observations, matched with VOCALS RAOB and qualified as SR cases. Match-up criteria are <300km spatial and <2 hours temporal difference between COSMIC1 and VOCALS measurements. The bias of the specific humidity, retrieved from corrected refractivity, is less than 1.0 g/kg in absolute value in the altitude range of SR N-correction, while it is in the range from -4 to -2 g/kg for retrievals from non-corrected refractivity. The wiggling shape of the statistical profiles is caused by the small volume of the averaged data.

6. Conclusions

We cover the approach for RO refractivity correction under SR conditions and its impact on water vapor retrieval. The negative bias of water vapor is significantly reduced, as shown by the validation from the simulation study and the actual COSMIC1 measurements versus the VOCALS campaign RAOB data.

We have used the vertical gradient of the refractivity dN/dh<-79 N-units/km (half of the critical value) as an indicator of the potential SR case. To pick the best correction, the TPW minimum absolute difference rule with the first guess has been applied. Both criteria are workable but arguable in terms of their robustness. The dN/dh rule may lead to the wrong evaluation of the initial SR parameters. The $min|\Delta TPW|$ rule not always results in the perfect shape of the retrieved water vapor profile because it only compares scalar values, integrated over the altitude range of SR correction. Since the TPW difference is computed with the first guess, the quality of retrieval depends on the quality of the first guess.

Despite these apparent limitations, both criteria used in the refractivity correction seem to be two reasonable options available in processing actual RO data. Note that in the case of a water vapor/temperature complex structure, such as multiple inversion layers in one profile, this approach may not be applicable for refractivity correction due to the wrong estimation of the SR top altitude.

Since brute force trials are used to determine the set of SR parameters $\{h_1, h_2, h_3, p_1, p_2\}$, it significantly increases (about an order) the computing time needed for processing the SR case. Further improvements of this approach in the operational processing of RO measurements under SR conditions are required.

7. References

1. **Sokolovskiy**, S. Effect of Superrefraction on Inversions of Radio Occultation Signals in the Lower Troposphere. *Radio Sci., 38,* 2003.
2. **Xie**, F., E.R. Kursinski, and B.M. Herman: An Approach for Retrieving Marine Boundary Layer Refractivity from GPS Occultation Data in the Presence of Superrefraction. *J. of Atmos. And Ocean Technology*, 23, 2006.
3. **Wang**, K.-N., M. T. Juarez, C. O. Ao, F. Xie: Correcting Negatively Biased Refractivity Below Ducts in GNSS Radio Occultation: an Optimal Estimation Approach Towards Improving Planetary Boundary Layer (PBL) Characterization, *Atmos. Meas. Tech.*, 10, 2017.
4. **Wood**, R., C.R. Mechoso, et al.: The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-Rex): Goals, Platforms, and Field Operations. *Atmos. Chem. Phys.*, 11, 2011.

Disclaimer