Reviewer #1

There is no discussion on the impact of horizontal refractivity gradients errors on the retrieval performance. It would be useful for the authors to consider the recent Zeng et al (2016, Appendix A) paper (http://www.atmos-meas-tech.net/9/335/2016/) that show that horizontal gradients in the ionosphere can lead to features being assigned the wrong height. More generally, if atmospheric and ionospheric horizontal gradients are causing an impact parameter error, da, the resulting radius or height error, dr, is dr = da/(n+r.(dn/dr)) where n is the refractive index, and r is the radius. The key point here is that impact parameter errors are amplified when mapped to radius, and this is particularly problematic for ducting conditions where r.(dn/dr)_1. How does this affect your interpretation?

Page 12, last line: I suggest that the 200 m difference between estimated x_b and the corresponding radiosonde information could be caused by the variation of n.r.sin(phi)(=a) along the ray path. This a well known consequence of horizontal gradients. Have you investigated this by looking at gradients in the analysis fields along the ray paths?

<Response>

Thank you very much for this valuable comment. Indeed, the horizontal refractivity gradient is an issue which could cause erroneous ducting layer height estimation. We are now including a note that mentions these sources of error.

Ducting can affect the RO retrieval process in two independent ways: bending angle error due to horizontal refractivity gradient and the ill-posed problem in refractivity determination. In this article, we focus on solving the effects of ducting in retrieving refractivity profiles, rather than addressing the other issues in the bending angle calculation. To the best of our knowledge, all currently used bending angle and refractivity retrieval processes do not address the violation of spherically symmetric refractivity distribution in the ionosphere, and the retrieved results will contain certain degree of error caused by horizontal refractivity gradients. This error should have the same order of impact on the refractivity profiles retrieved by classical Abel-inversion and the proposed reconstruction method.

On the other hand, we strongly agree that horizontal refractivity gradient is an important factor and should be stated in the main text. Therefore, we added the potential effect in P13 L28:

Another possible cause of x_b discrepancy is the error in GNSS-RO measurement due to horizontal inhomogeneity in the atmosphere and the ionosphere (Zeng et al., 2016). In ducting conditions, this error can be amplified and shift the impact parameter of boundary layer top for more than 100 m. While addressing the horizontal inhomogeneity is beyond the scope of this article, the impact of horizontal refractivity gradient on the reconstruction method can be further investigated in future work.

Secondly, in the context of NWP assimilation, if an NWP system is assimilating refractivity/bending angles down close to the ducting later, and is also assimilating other radiances like AMSR-E and, would the retrieved refractivity profiles below the ducting layer provide any extra information? If the authors argue that the retrieved refractivity is not intended for NWP assimilation, that is reasonable but it should be stated in the text.

<Response>

While NWP assimilation can incorporate both measurements, the results cannot accurately model the PBL. One example is the systematic low bias of the ECMWF PBL height [Xie et al., 2012], which can also be observed in many cases when compared to the RAOB results as shown in Figure 5 and Figure 10. It appears that the observations of GPS-RO and AMSR-E were not optimally assimilated into the model below the ducting layer, and this could have impacts on cloud evolution simulations. Therefore, we argue that it is valuable to develop an independent refractivity retrieval process outside of NWP data assimilation.

To better explain this reasoning, we added the following sentences at P11 L17:

The statistically low PBL heights in ECMWF, which were extensively observed in the region, implies an erroneous refractivity profile below the ducting layer. This difference has been attributed to the model physics and assimilation process limitations (Xie et al., 2012). Even though ECMWF and other NWP system assimilate both GNSS-RO bending angles and AMSR-E radiances, it is not clear that the full vertical resolution of the measurements can be taken into account. Thus an independent, unbiased, refractivity retrieval outside of NWP data assimilation systems remains extremely valuable.

Specific comments

Page 4, Line 28, "Able" should be "Abel".

<Response>
Thank you for your comment, the change has been made.

Page 8, The AMSR-E PW values are not "measurements". They are retrieved quantities that will depend on a-priori information. Please correct this throughout the paper. What a-priori is used in the AMSR-E retrievals? EG, do they have to assume a temperature profile?

<Response>

Thank you for the comment, we corrected them in the article. The details of the PW retrieval algorithm from AMSR-E can be reviewed in the following technical report:

Yoshiaki Takeuchi (2002), Algorithm theoretical basis document (ATBD) of the algorithm to derive total water vapor content from ADEOS-II/AMSR, EORC Bulletin/Technical Report -- Special Issue on AMSR Retrieval Algorithms

This report has also been added in the reference list of the article. According to this report, no temperature profile is needed for the retrieval. However, the temperature at 850hpa and sea surface level from global analysis is required.

Page 8, ECMWF analysis information. Are you using the 137 vertical levels, horizontal resolution, etc? Please give details.

<Response>

Thank you for your suggestion, we added the ECMWF information at P8 L24:

The high resolution ECMWF analysis data (TL799L91) used in this research have 91 vertical levels from the surface to 0.01 hPa and 0.25^{o} horizontal resolution. The data is modeled at every 6 hours and unevenly sampled in vertical space which has higher resolution near surface (~40 m).

Page 8, equation 9. The temperatures in this equation should be virtual temperatures? Typo or bug in the retrieval? More generally, are you using virtual temperatures when you compute the height of the ECMWF levels?

<Response>

There was no equation (9) on page 8. We assume that you are referring to equation (15). In that case, T is the temperature instead of the virtual temperature [Kursinski and Hajj, 2001]. In this equation $\overline{m}$ is the mean molecular mass taking both dry air and vapor into account:

$$\overline{m} = m_d \frac{p - e}{p} + m_v \frac{e}{p}$$

And in the direct method we have to calculate $\overline{m}$ at each step of iteration using this equation along with the evolving p and e information. To clarify this we added this equation to the manuscript and more description of the direct method:

$\bar{\mathrm{m}}$ is the mean molecular mass of atmosphere which takes both dry air and vapor into account:

$$\bar{m} = m_d \frac{p-e}{p} + m_v \frac{e}{p} \tag{16}$$

where m_v and m_d are the molecular mass of dry air (~28.97 g/mol) and water vapor (~18.02 g/mol), respectively. Using the equation (15) along with the refractivity equation (5) one can solve the water vapor pressure profile e iteratively by updating $\bar{\mathrm{m}}$ at each step and the convergence at each height interval can be reached in one or two iterations.

In addition, the ECMWF height is also not computed with virtual temperatures.

Page 9, C_y in equation should include a forward model error term. EG, caused by assuming ECMWF temperatures are "true" in eq.8, assuming the q(z) is constant etc. Have you estimated it?

<Response>

We plan to perform a more detailed error analysis in a follow-on study. However, a simple test is provided to show the rough estimate of the variation in calculated PW results.

A case of RAOB specific humidity (q) profile is used for simulation (Figure R1). In [Kursinski and Hajj 2001], the 1-σ error of the retrieved q using direct method is estimated as 0.2 g/kg. While these errors cannot be easily modeled, we simulate the sum of the forward model error as the non-biased random noise of 0.5 g/kg. The profile with the noise added is shown in Figure R2. We generated 50 noisy q profiles and calculate PW for each of them. The resulting PW standard deviation of these 50 cases is ~0.11mm. Since we conservatively set our PW σ margin as 1 mm in C_y (including the AMSR-E retrieval $\sigma = 0.6\mathrm{mm}$), the forward modeling error should already been well-considered.

The reason that PW can contain such a small error is because it is calculated by integration, which can be viewed as a low-pass filter to block complex humidity features and uncertainties. However, since simulating the error as a Gaussian noise may not be accurate enough in practice, a more detailed error analysis has to be further investigated in the future. In this article, we also added the forward model error in the sentence of C-y calculation:

The AMSR-E PW retrieval contains an error of ~0.6 mm, but additional errors could rise from RO - AMSR-E collocation distances and forward modeling. Therefore, the conservative PW margin of 1 mm is used as the uncertainty of the PW observation in the C_y matrix.

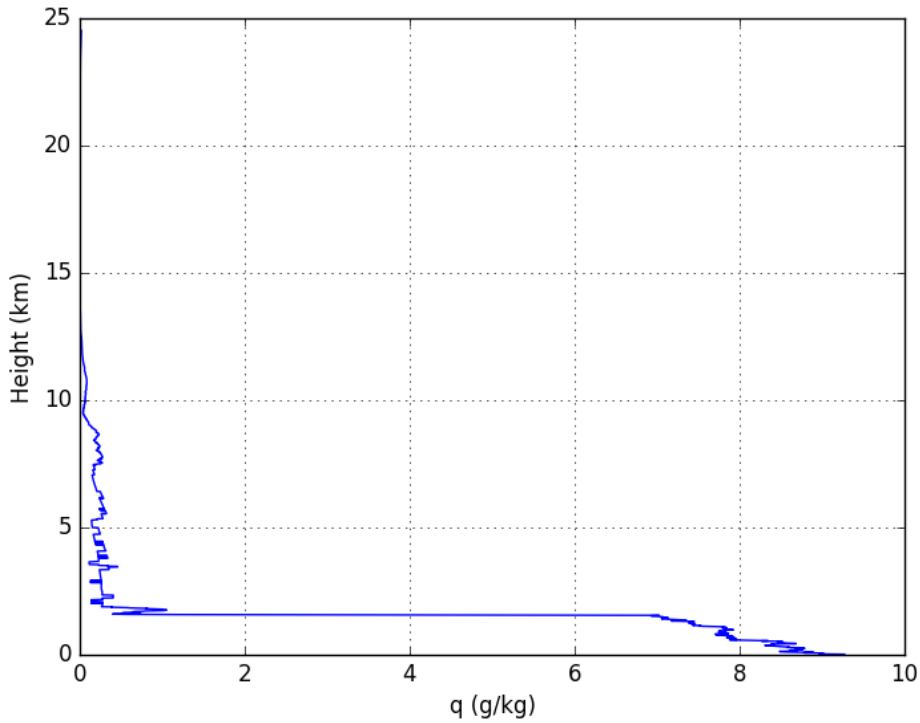

Figure R1. The specific humidity profile from one of VOCALS RAOB cases

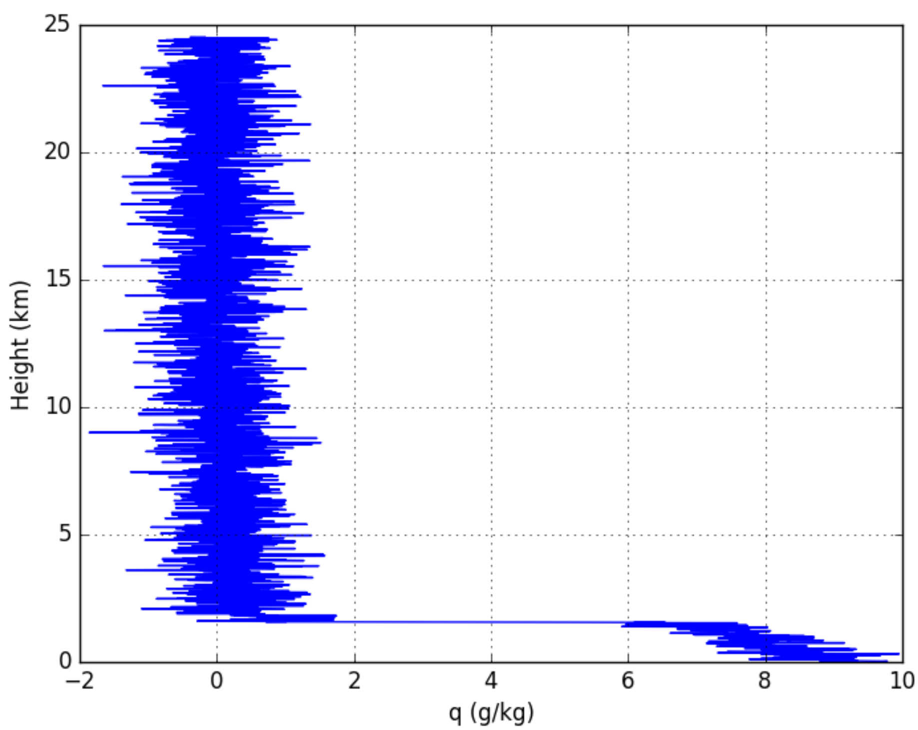

Figure R2. The noisy ($\sigma = 0.5$) specific humidity profile from the same case of Figure R1

Section 3.
When generating the observed bending angle from the raob, I assume you integrate eq.2 or 3? Please state this, and give more details. It should be emphasized that horizontal gradient errors are neglected in simulations in this section.

<Response>

Thank you for the suggestion, we added more details in the following sentences at P11 L8:

While x is not monotonically increasing in the RAOB refractivity profiles, the forward calculation of equation (2) should be used in here to generate the RO bending angle. Note that the potential errors caused by horizontal refractivity gradient are neglected in the bending angle simulation.

Have the raobs been assimilated at ECMWF - ie, the raobs and analysis could be correlated? It might be interesting to see if the ECMWF forecasts at the raob locations look very different.

<Response>

No, the radiosonde data from VOCALS campaign were not assimilated at ECMWF. They should be regarded as two independent information sources. To clarify this, we added the following sentence at P11 L17:

Since VOCALS results were not assimilated in ECMWF analysis, these two data sources can be regarded as independent.

Section 4
Page 12. Line 19. "no double or complex structure inside the trapping layer". Please explain what is being screened out here, and how often it happens.

<Response>

To clarify this condition we added a more complete description as follows at P13 L7:

Three criteria are utilized for choosing these cases: a spatial distance of less than 300 km, a temporal difference of less than 3 hours, the lowest height of the GPS-RO refractivity profile reaches below 1 km to ensure the trapping layer is included. We also exclude the cases with complex x-h structure inside the trapping layer which can heavily violate the bilinear assumption, and the cases with multiple ducting layers which makes the equation (9)

inapplicable. Approximately 15% of the total number of cases are ruled out by these two additional requirements.

Figure 12. Suggest rename it Fig. A1, because its only referenced in the appendix.

<Response>

Thank you for the suggestion; the change has been made.