Reviewer #2

The subject is interesting, and this exercise may be useful. However, my main concern is that the authors should better explain why it is important to, for instance, try to address this negative bias, rather than to accept that the retrieval of refractivity from bending angle presents limitations and is an ill-posed problem below superrefractive layers. As with other underdetermined problems, adding sufficient information eventually provides a closure. The information that best provides this closure is most likely user dependent. The authors specifically propose the integrated precipitable water (PW) as closure. Although PW may be often available, it is a source external to GNSSRO. The authors should explain why PW is to be preferred over other quantities that may also be equally available, and are also external, or why the retrieval of the refractivity profile is still important, when it can only be carried out requesting external information.

<Response>

Thank you for the valuable comment. These issues are addressed in the following responses.

Specific comments:
P1L16: "that couples", to for instance ", and couples"

<Response>

Thank you for the suggestion, the change is made.

P1L23: "technique precisely" to "technique that precisely"

<Response>

Thank you for the suggestion, the change is made.

P2L14: "transceiver geometry". Current GPSRO does not use transceivers. The transmitter never receives, and the receiver never transmits.

<Response>

Thank you for the suggestion, this sentence has been changed to:

Due to the **transmitter and receiver** geometry of GNSS-RO, the tangent point…

P2L16: “information inside the ducting layer will be missing”. It is not really missing. GNSSRO does not provide it.

<Response>

We agree that the information inside the ducting layer is not “missing”. We meant the ducting information does not exist in bending angle measurement. To avoid the confusion, we modify this sentence to the following at P2 L14:

As a result, the GNSS-RO bending angle measurements will loss the information inside the ducting layer, in which cannot be recovered using solely GNSS-RO observations.

P2L19: “To mitigate the N-bias”. It should be explained why it must be mitigated, rather than accepted.

<Response>

In PBL research, characterizing the vertical structure of the PBL is important because it can be related to different atmospheric processes associated with the PBL [Ao et al., 2012]. However, although the weather analysis incorporated both GNSS-RO and AMSR-E measurements, the systematic low bias of the ECMWF PBL height [Xie et al., 2012] shows that the observations were not optimally assimilated into the model below the ducting layer. Therefore, we argue that developing an independent bias-mitigation retrieval process outside of NWP data assimilation is valuable.

To clarify this idea, we added the following sentences right before the paragraph:

Correcting the N-bias within the PBL is essential towards the use of RO in studying the vertical structure within the PBL. While the weather analyses can assimilate RO bending angles, which are unaffected by the refractivity bias caused by ducting, it is not clear that the analyses can optimally handle these high vertical resolution measurements. In addition, the analyses may be strongly affected by bias in the model, as evidenced by the low PBL height over the stratocumulus regions (Xie et al., 2012). Therefore, it is of great scientific interests to retrieve an unbiased PBL refractivity based on observations only.

P2L30: “Measurements of PW”. There are very few actual measurements of PW available. Information of PW does exist, but most are retrievals, estimations, or background model information. Given that PW is often not the actual source, why should PW be used, rather than the original measurements?

P8L4: “PW meaurements”. I understand that the measurements are brightness temperatures related to PW, not PW itself. Also, ground-based GNSS provides ZTD, with PW being derived only through the approximate subtraction of the hydrostatic delay, which must itself be estimated from further measurements or external information.

P13L28: “PW measurements”. The measured quantity is a brightness temperature. But given that external information must be used, why PW? Why from AMSR-E? Why not from a background model? Why not some other quantity or quantities from a background model?

<Response>

Thank you for this valuable feedback. First, as the other reviewer also pointed out, the PW used in this article is not a “raw measurement” but a “retrieval result”. We agree with your comment and made the changes throughout the article.

Second, there are several reasons to choose PW over other physical quantities:

i) PW is widely available through a variety of measurement techniques.
ii) Most of the PW is concentrated within the PBL.
iii) PW value of a GNSS-RO refractivity profile can be calculated easily.

Indeed, some alternative measurements or retrievals are also appropriate in our optimization scheme. For example, the 3-D water vapor from AIRS and cloud top temperature from MODIS could also be potential candidates to distinguish different refractivity profiles. But in this study, PW is used and proved to be a feasible solution for our purpose.

To emphasize the advantage of using PW, we added the sentences at each paragraphs of P8:

First, most of the water vapor in the atmosphere is located within the PBL so that accurate PW observations can provide extra information below the ducting layer to assist GNSS-RO retrievals.

Second, PW are available globally from a variety of sensors (Millan et al, 2016).

Third, PW value of a candidate refractivity profile can be easily calculated to compare with the PW observations.

Third, although using the quantity estimated by the background models is convenient, we prefer a measurement-based approach when possible. As shown in our results (Figure 5 and Figure 10), the structure of PBL estimated by ECMWF analysis were very different from the ones observed by RAOB. In fact, this systematic low bias of the ECMWF PBL height has been reported (e.g. [Xie et al., 2012]). Therefore, the PW and other quantities provided by the background model may not be accurate enough, and the use of independent sensing sources might be preferred in some cases. The detailed comparison between different PW sources can be found in the discussion between L21 and L26 in P12.

To better illustrate this reason, 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.

P3L3: “For a single ray path: : :”: This is ok only in a spherically symmetric refractivity field.

<Response>

Thank you for your comment. We modified this sentence to:

Under the assumption of a spherically symmetric atmosphere, the impact parameter ‘a’ of a single ray path can be defined as:

P3L5: “n is the refractivity index”. It is the refraction index.

<Response>

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

P3L6: “assumption of a spherically symmetric”: The assumption is already necessary above.

<Response>

Thank you for your comment. We removed this assumption in this line:

~~**Under the assumption of a spherically symmetric atmosphere,**~~ the accumulated bending angle of a GNSS-RO ray path can be calculated…

P3L17: “measured bending angle”. Should be “measured bending angle profile”.

<Response>

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

P4L18: “signal with a tangent point inside the trapping layer cannot be received”. I would not say that. There is no signal whose TP is inside the trapping layer, not an existing signal that cannot be received. Tangent points are either above or below.

<Response>

We agree with this comment. Therefore, we modified the following sentence as:

Because of the geometry of GNSS RO, in which both the transmitter and the receiver are located outside the Earth atmosphere, **the tangent points of the received signals will not appear inside the trapping layer.**

P4L21: “multiple values”. This is not a numerical problem, and there is nothing unphysical. Eq (2) represents a function that is not defined for all r_t. This is related to, but not caused by, the existence of multiple heights with the same x.

<Response>

In this paragraph we planned to use Eq (2) to illustrate the idea of “locating the tangent points inside the trapping layer is unphysical”. If we try to calculate the non-existing bending angle inside the trapping layer, which is the range of not defined as pointed out, the integrand value of Eq (2) becomes invalid (complex). This invalidity is mathematically caused by the existence of multiple heights with the same x.

To clarify, we modify this paragraph as follows:

This gap can be noticed by examining equation (2). When evaluating the bending angle with (2) inside the trapping layer, hb < rt-re < ht, the term n(r)r above the height rt becomes less than n(rt)rt because of the negative gradient of x between hm and ht. It would lead to a negative value inside the square root in equation (2) and the solution is a complex number for the bending angle inside the trapping layer which is unphysical.

P4L22: “retrieved”. Bending angle is not being retrieved here. It is being evaluated.

<Response>

Thank you for the suggestion; we changed the word “retrieved” to “evaluated”.

P4L23: “bending angle of these rays can still be retrieved through the regular Abel inversion”. The bending angle can be evaluated if we know the refractivity profile. But the Abel inversion (Eq 4) retrieves the refractivity. And this cannot be retrieved once below the superrefractive layer.

<Response>

Thank you for pointing this out; we accidentally combined two sentences in a wrong way. This sentence has been updated to:

bending angle of these rays can still be calculated by GNSS-RO

P5L3: “Information loss”. It is not lost. It is not being gained. Also later in P13L18.

<Response>

We deleted this phrase in P5L3 and changed the “information loss inside the trapping layer” to “**the lack of bending angle information in the trapping layer** ” in P13L18.

P5L4: “the most significant negative bias”. Please clarify the sentence.

<Response>

We rewrote this sentence as follows at P5 L8:

Among all the refractivity solutions corresponding to the same bending angle profile, the one retrieved by the standard Abel introduces the largest negative bias.

P5L23: “error parameter” should be “error in the parameter”.

<Response>

Thank you for the suggestion, the change is made.

P7L10: “sensitive to the mis-modeling of”. If this is true, then the procedure is weak. The meaning of the rest of the paragraph is unclear. Please rewrite.

<Response>

In this paragraph we meant to explain the “top” of h1(x) calculated by equation (9), rather than the whole profile, is sensitive to the mis-modeling. To clarify the idea, we rewrite the whole paragraph as follows at P7 L19:

First, the highest 100 m of h1(x) will be replaced by the linear extrapolation from below, its slope is determined by linear regression between 100 m and 200 m below the height hb. The reason is that the top of the analytical solution calculated by equation (9) is sensitive to the mis-modeling of h2(x) and h3(x), which are assumed to be bi-linear segments between hb and ht. Spurious spikes and fluctuations are found at the top 100 m of the function h1(x) if the straight line assumption inside the critical layer is violated by the data, or the parameters, e.g. hb, are not appropriately estimated from Equation (12). While these fluctuations in h1(x) are usually small (<20 m) and typically occurred within 100 m below hb, they can significantly change the slope at hb, which makes the h2(x) value obtained from assumption (A3) inconsistent with having one refractivity for each impact parameter below hb. Therefore, we replaced the top portion of h1(x) with a linear extension of the curve below to remove the fluctuation. Note that the variable hb changes when the top of h1(x) is replaced. To avoid the inconsistency between the new hb and the originally specified hb, xm is chosen over hb as the "free" variable to construct a profile inside and below the critical layer

P13L19: Profiles of retrieved bending and retrieved refractivity still have a 1-1 correspondence. The lost 1-1 is between the atmospheric refractivity and the retrieved bending.

<Response>

Thank you for the suggestion; we updated the following sentence:
As the retrieved bending angle loses its one-to-one relationship with the atmospheric refractivity, the standard Abel inversion will give the refractivity solution with the largest negative bias.