Response to Review#2

General Comments

1. This paper presents a new residual ionospheric errors (RIE) in bending angles based on the GNSS RO excess phase measurement for each RO event. The excess phase gradient method, is self-sufficient and based on the vertical derivative of the RO excess phase profile. Specifically, a linear fit was applied to the excess phase data at heights above 65 km, then calculate the RIE using the vertical derivative of the linear fit excess phase profile, finally the derived RIE is extrapolated to the RO measurements at the lower heights by assuming that $\Delta\alpha$ has the same impact on the entire α profile.

If I understand correctly, in this method the RIEs in bending angle are considered as the slopes of the linear fit excess phase profiles (as the red lines shown in the sub-figure (c) of figures 1-4). Then use this slopes as the RIE values for the entire bending angle profiles.

Your understanding is correct.

According to the sections "*2.1 Atmospheric Bending Angle (α) and Excess Phase (ϕex)*" and "*2.2 RIE and Detection Method*" this mothed has 3 assumptions:

- "*For a rising/setting occultation, $V\perp$ is the ascending/descending rate of RO sampling with respect to ht, or the GNSS–LEO straight line height (SLH), which yields $V\perp \cong dht/dt$. The get equation (6).*" **Which uses the $V\perp$ of the LEO satellite as the tangent point velocity. In the GNSS-LEO RO, this assumption will induce errors.**

This assumption works well at ht > 30 km where the $\boldsymbol{V\perp}$ is close to a constant and the error is small compared to RIE. In the lower atmosphere where the bending is severe, $\boldsymbol{V\perp}$ is no longer constant with respect to ht and an inversion is required to determine the bending.

From the review comments, we feel that one of the key points in this paper was not well communicated. Therefore, we added Appendix A to discuss how RIEs can arise in the case without bending. It’s a misconception to attribute RIEs solely to the bending effect.

Appendix A provide more discussions on ‘bending delay and phase advance’ from radio wave propagation in plasma. Especially, the phase advance due to the faster-than-light phase velocity from propagation in plasma can be mistakenly interpreted as a bending. In fact, it is an independent effect from bending (due to group velocity) in the GNSS-RO excess phase measurement. This is also the major reason that this study argues to analyze the excess phase data, rather the bending data, of which the latter would mislead what might cause the RIE. In Appendix A, we discuss the situation that RIEs can occur even without bending.

- “*In the upper atmosphere where there is little atmospheric bending (i.e., $\alpha_c \approx 0$), a significant value that is not zero in $d\phi/dh_t$ (indicates the existence of α_{RIE}, which can be both positive and negative.*” **Define the α calculated by equations (4) and (6) as bending angle RIEs. Actually, the equations (4) and (6) calculate the ionospheric bending angles above ~80 km, physically this variable is different from the bending angle RIEs defined in the previous studies.**

See the above for explanation. We believe that RIEs contain errors other than those from the bending effect. Therefore, it is more appropriate to characterize RIEs using the excess phase measurements, rather the bending angle.

Because the bending angle has been used to compare the amplitudes of RIE derived from different methods, here in this study we adopt the equation of bending angle expression but do not fully agree with the bending as the sole contribution to RIEs.

- The equation (6) is used for the linear fit excess phase profiles (as the red lines shown in the sub-figure (c) of figures 1-4). Then use this slopes as the RIE values for the entire bending angle profiles. **As discussed in the manuscript, the fit excess phase profiles depend on the local time, season, solar cycle, solar activity, and RO receiver type, RO top height. Maybe also geomagnetic field, the RO plane direction and so on. While this method only use equation (6) to calculate the ionospheric bending angles as bending angle RIE. This will induce problems in the application.**

The fitting does not require any knowledge about local time, season, solar cycle, solar activity, etc. The results from the fitting do, which is called the RIE in this study.

Also in the revised manuscript we made it clear that interpreting the vertical gradient of excess phase profile as a bending would be misleading since a RIE can occur even without bending.

1. Regarding the quality control (QC) on the excess phase data as shown in Table 1, how to determine the QC flags and thresholds? It does not according to the previous bending angle RIE definition and characteristics. To "Retain only realistic $\Delta\alpha$ values", set $|\Delta\alpha| < 2000$ µrad, this threshold is too large. (As shown in your figures, most of the $|\Delta\alpha|$ are less than 2 µrad).

It was a typo. It should be 2 µrad and has been corrected in the revision.

1. Regarding the $\Delta\alpha$ statistics with the latitude: Figures 5-9 show that most of the $\Delta\alpha$ values for day and night from Jan 2013 are positive, while Figure 19 shows most of the $\Delta\alpha$ values for day and night MetOp RO data from 2020 are negative. Why?

Thank you for catching this. It was a plotting error in Fig.19 and has been corrected in the revision.

It also shows that this mothed is very sensitive with the RO top height. When the height increases the ionospheric bending angle will become larger and non-linear, this may be a reason.

It is sensitive to the RO top height up to a certain altitude, which is largely due to sporadic-E (Es) related perturbations. Es often induces a large oscillation at 80-100 km, which can influence the fitting substantially. There is essentially little way to get around these perturbations if the RO profile is cut off around 85 km. Above 110km, fortunately, Es-induced oscillations are small, allowing the fitting method to establish a more robust estimate of the RIE.

In the revised manuscript we also pointed out that Es tends to have a tailing effect below 80km. But it reduces sharply with height as the RO sounding goes below the Es layer. As revealed in other studies, the Es effect is evident in the iono-free bending angle profile as well.

The new method proposed in this study aims to capture the RIEs induced by the F-region ionosphere and above, not by the Es layers, since those errors may have an extended impact on the RO sounding of the atmosphere.

1. Regarding the $\Delta\alpha$ statistics with the local time: As shown in figure 10, the $\Delta\alpha$ statistical behaviors are very strange (not reasonable). (1) from -60 to 60 latitude degree, at local time 8 and 20, where the ionosphere has large horizontal

gradient since the morning and dusk change, and the magnitude of the RIEs are very large, however in figure 10 in this area the $\Delta\alpha$ is around zero. (2) the $\Delta\alpha$ magnitudes at night time are larger than the daytime. (3) generally, the night time RIEs are near zero, however in figure 10 they relatively larger than that in the daytime and with positive sign, which indicated that the positive $\Delta\alpha$ values in Figures 5-9 mainly come from the night time data.

Again, we would not consider that every RIE be induced by the bending effect. We believe that RIEs can come from the radio wave propagation without bending. Appendix A illustrates a simplistic scenario for no bending propagation. In reality, the L1 and L2 bands may split their propagating paths at a location with small-scale inhomogeneous structures and continue with their journey different through the ionosphere. This type of ionospheric propagation could have a small or little bending, but producing a large amplitude of RIE in excess phase from the phase advance differences.

1. As this is a new method and can be used for each individual RO profile, therefore it's better to show the profile-by-profile RIEs and their vertical statistical variables of biases and stdev, which is easier for readers to understand the results, also easier for comparing with previous studies.

In Figs.1-4 (panel c), we provided the fitted slope for each profile example. These examples also highlight the challenges to infer the slope in the presence of large oscillations in the excess phase measurements. Therefore, the inferred slopes are expected to have a large standard deviation that is mainly due to the oscillatory nature of excess phase data. The PDF plots in Figs.5-9 were intended to show the spread of RIEs from the fitting. Fig.10 provided the values of RIE standard deviation as a function of latitude and local time.

Specific comments:

Please update the figures by providing proper units, using uniform color bars in one figure. It's better to combine the same layout figures like figures 1-4 into one figure, since there are so many figures in this paper.

There are lots of typos in the manuscript, please revise them, for examples:

L27: “RIF”

L141: “wehre”

L406: “(2),”

We have corrected these typos among others in the revised manuscript.