Reply to Reviewer #1:

This discussion paper summarises the use of GPS-RO data in an LETKF system. Details of forward-modelling are provided along with quality control procedures. The LETKF methodology is described and the effect of RO on the ensemble is demonstrated, both compared to a 'control' run, assimilating conventional observations only, and also ERA-interim reanalysis fields, both showing improvements.

Thank you very much for your kind recognition of our effort on the manuscript. We have done our best to improve the manuscript based on your constructive comments.

1. General comments

The quality control step is described clearly, and the statistics following this step are improved, but the number of observations that pass/fail the QC at different heights should be plotted, with an approximate percentage noted in the body text.

Thank you for your constructive comments. We added the number of observations before/after the quality control at different heights in Figure 3(a, b) and Figure 5(a, b). Following the modification of the Figure 3, we revised the caption in Figure 3. As the reviewers suggests, we also added explanation of the number of observations before/after the quality control at different height in the body text as follows:

In Section 2.4;

"The number of observations reduced by 1.07 % of the total number of observations for the entire vertical range after the quality control. The mean value of observation rejection for 10 km vertical intervals range from 0.65 % as minimum to 1.61 % as maximum and such a difference depends on the height. The relatively large number of observations are rejected under ~ 20 km."

In Section 3.2;

"About 13 % of the total number of observation is rejected during the data processing. The number of rejected observations widely ranges from 2.9 % to 32 % in the vertical profile. Note that the number of observations around ~33 km (impact height) was considerably reduced (~75 %

of the total number of observations for the vertical range of 32 ~ 33 km) compared to other levels. This is mainly due to the large difference of bending angle between observation and background for that vertical range before the data processing. This could be affected by the bending angle calculation using one-dimensional observation operator described in Section 2.2 around the model top with a large vertical spacing of the CAM-SE. Another possible reason can be ascribed to a quality of the CAM-SE background for those vertical levels. CAM-SE is a climate model that may not be optimal to be used for the purpose of NWP although we chose it for a test model due to the same grid structure as KIM-SH. Therefore, we expect that replacing the forecast model by KIM-SH would solve this issue greatly."

"Also, the number of observation is significantly reduced compared to results from use of KMA forecast after the data processing."

In the LETKF experiment, the top of the model is at 40km. This is very low for the assimilation of bending angles (though the text clarifies that the model will be extended). A description of the (presumably extrapolated) background data used to integrate Equation 1 above the model top is required, which should explain the large bias above 30km in Figure 5a.

Thank you for your helpful comment. As we mentioned in the manuscript, we adopted a one-dimensional bending angle operator, which is included in the Radio Occultation Processing Package (ROPP) developed by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Radio Occultation Meteorology Satellite Application Facility (ROM SAF). In the one-dimensional bending angle operator of the ROPP, ray bending above the model top is accounted for by extrapolating the most upper model parameters. We added equations and detailed explanation of this in Section 2.2 as follows:

Assuming that refractivity varies exponentially with x between model levels j and $j+1$, and $\sqrt{x^2-a^2} \approx \sqrt{2a}\sqrt{x-a}$, the bending angle calculation at a single layer is given by

$$\Delta\alpha_j = 10^{-6}\sqrt{2\pi a k_j}N_j \exp\left(k_j(x_j-a)\right)\left[erf\left(\sqrt{k_j(x_{j+1}-a)}\right)-erf\left(\sqrt{k_j(x_j-a)}\right)\right] \qquad (2)$$

where k_j and the error function erf are defined respectively as

$$k_j = \frac{\ln(\frac{N_j}{N_{j+1}})}{x_{j+1} - x_j} \quad (3)$$

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dx \quad (4)$$

Ray bending above the model top is accounted for by extrapolating the most upper model parameters and evaluating

$$\Delta\alpha_{top} = 10^{-6}\sqrt{2\pi a k_j} N_j \exp\left(k_j(x_j - a)\right)\left[1 - erf\left(\sqrt{k_j(x_j - a)}\right)\right] \quad (5)$$

Although the model is already constrained by radiosondes in the NH, it is surprising that the RO has almost no effect in the NH (Figures 7 and 8), given that RO observations exist over oceans, where sondes do not. A brief discussion of this should be included.

We agree that there is little impact of RO in the NH, shown in Figures 7 and 8. In the ensemble Kalman filter data assimilation, background error covariance is updated every analysis time. Repetition of forecast-analysis cycle makes the areas with frequent observations have smaller error covariance, which indicates the reduction of uncertainty in the analysis against the background. Since the experiment of EXP_RO starts from the background state of CNTRL_SONDE after two weeks of conventional data assimilation, it may not have enough spread for RO data to correct the background states. Because we have performed EXP_RO only for two weeks, impact of additional RO data can look dominant where there had been no sonde data. Recall that the spinup period usually shows significant analysis increment where observations are newly assimilated. That is why Figures 7 and 8 show little increment over the NH. Therefore, we added the following sentences as Reviewer #1 suggests.

"Since the initial ensembles of EXP_RO have already constrained by conventional data for two weeks of CNTRL_SONDE, analysis increments look dominant where the conventional data does not exist especially for two-week analysis period of EXP_RO. Recall that the spinup period usually shows significant analysis increments where observations are newly assimilated. We expect that the system will show more comparable increments even in Northern Hemisphere as the forecast-analysis cycles are repeated."

Thank you so much for your careful comment.

Figures 8, 9 and 10 are plotted for a single height (100hPa), where RO is known to improve analyses in other systems, but this paper would greatly benefit from vertical profiles of the reduction in ensemble spread, and fit to ERA-interim (perhaps separated by NH,TR,SH). Though it is appreciated that this is a system in development, such details are worth including.

We really appreciate the constructive comment of Reviewer #1. As the reviewer suggests, we added Figures 11 and 12 at the end, which shows better fit of EXP_RO to ERA interim data in the vertical after averaging the error reduction in a zonal direction. It clearly shows that our first analysis of GPS-RO bending angle data helps have smaller difference from ERA interim mainly over the tropopause and over the Polar region of lower troposphere. We added the explanation of additional Figures as follows:

"We also took a look at the vertical profiles of analysis improvement in a comparison with ERA interim data in Figure 11. It shows significant error reduction introduced by adding GPS-RO bending angle data overall for two weeks of EXP_RO. There are considerable corrections of errors in upper level wind and temperature. In addition, we could apparently find positive impact of RO data even in the lower troposphere, especially over Polar region where there exists forecast imperfection due to inactivated sea-ice model. Figure 12 shows much greater improvement caused by GPS-RO bending angle data at the level of 20 hPa than the level of 100 hPa, and the global mean of error reduction looks remarkable for both variables of U and T.**"**

2 Specific details

p11929 l4: mention rising occultations as well.

Thank you for your comment. We modified the sentence including description of rising occultation.

p11932 l7: ECMWF have plans to implement a 2D operator in the next model cycle.

Thank you for your comments. We added this information in the manuscript.

p11932 l16: the GRAS SAF is now called the ROM SAF.

Thank you for your correction. We revised it.

p11932 l21: state 'horizontal location' for clarity

Thank you for your comment. We modified it.

p11932 l23: "refractive index" not "refractivity index"

Thank you for your correction. We revised it.

p11932 l24: 'r' only takes this definition for spherical symmetry. In a 1D operator it is strictly the distance from the local centre of curvature.

Thank you for your comment. We revised it.

p11933 l10: Which constants?

We described constant values in the manuscript.

p11933 l11: "impact parameter" should be "x=nr"

We are sorry to make you confused. When we calculate the n (refractive index) for the calculation of impact parameter (x=nr), refractivity value N is used for the calculation of n ($n = 1 + 10^{-6}N$). We tried to explain it, but now we recognized it may can easily cause confusion. We revised it.

p11933 l26: Define "impact height"

Thank you for your comment. We described definition of impact height in the manuscript.

p11935 l17: Use "larger" rather than "inflated"

Thank you for your comment. We revised it.

p11935 l20: Repeated word: "bending".

Thank you for your correction. We revised it.

p11936 l4: Why does tangent point drift reduce the number of observations passing QC? This is counter-intuitive.

Thank you for your opinion. We also agree with your opinion that this is counter-intuitive. Although the difference of remained observation number between "wh_TPD" and "wo_TPD" after the data processing is very small, "wo_TPD" results shows more number of observations than the other after the data processing. We found that the most of difference of observation number comes from the C/NOFS data processing under 10 km altitude. We think that further investigations are needed to better understand it.

p11937 l2: "an every 6 h" -> "a 6-hourly"

Thank you for your correction. We revised it.

p11939 l21: "increment"->"increments"

Thank you. We corrected it.

Figure 1: Should be "TerraSAR-X", "SAC-C" and "C/NOFS" (CORISS is the instrument not the satellite).

Thank you for your correction. We revised it.

Figure 3: Requires counts (see above). Are the zonal plots for all satellites?

Thank you for your comment.

- We revised the figure.
- The zonal plots are for all satellites. We added description of it in the caption.

Figure 4: What is subtracted from what? TPD-noTPD?

“no_TPD” is subtracted from “TPD”. We revised the caption.

Figure 5: Add season to caption.

Thank you for your comment. We revised it.

Figure 6: "Ensenble"->"Ensemble" in title. Specify units of colour scale (radians?).

Thank you for your correction and comment. We revised it.