

Summary:

This paper assesses the impact of heavy precipitation on GPS radio occultation measurements through comparison of RO profiles within the precipitation and without precipitation as indicated by the satellite radar observations. Systematic positive refractivity errors (or N -biases) above ~2.5 km are shown in GPS RO soundings in the presence of precipitation, when comparing to two analyses (ECMWF, GFS) and one reanalysis (ERA-I). The results are consistent with multiple previous studies by Lin et al. (2010), Yang and Zou (2012), Xou et al., (2012) and Yang and Zou (2016). However, these previous studies attribute such positive N -bias to the GPS RO sounding retrievals for neglecting the RO refractivity contribution from liquid and ice water contents. In contrast, this paper attributes the N -biases to the possible deficiency in global analyses/reanalysis under high specific humidity condition (including both rain and no-rain). The simulation studies were carried out to investigate the contribution of the liquid/ice water content by ray tracing through a 3-D atmosphere with realistic liquid/ice water content estimated from TRMM. The particle size distribution $N(D)$ are adapted from the one used in TRMM radar precipitation retrieval. The simulation study of 65 cases confirms that the liquid/ice water content do not introduce significant bias to the RO retrieval. Further analysis of the N -bias with respect to the specific humidity shows good correlation with the high specific humidity instead of the precipitation.

Overall, the paper is well written. The science of the paper is significant and it advances our understanding of the liquid/ice water content on the GPS RO measurements, which has puzzled the RO community for quite some time. The discovery of positive N -bias (i.e., negative temperature bias, and/or positive moisture bias) likely attributed to the global analyses/reanalysis in the high specific humidity condition will be worth further investigation. Note some more details related to the simulation of liquid/ice water content are needed in the manuscript, and some text and a few figures can be improved.

I would recommend publication of the paper after “minor revision”. The comments are listed below:

Major comments:

- (1) Section 4 missed some details of the ray-tracing simulation.
 - a. The typical range of the liquid and ice water content (along the ray path) derived from TRMM radar reflection measurement (e.g., at different altitude in Fig. 1) should be shown or at least discussed in the manuscript.
 - b. The size distribution of the particles, $N(D)$ was not shown.
 - c. How typical are those precipitation cases observed by TRMM? For example, the size, rain rate, etc, should be discussed.

- (2) The *N*-bias study (e.g., Fig. 6) focused on the high specific humidity based on COSMIC RO wet retrieval. Could the authors use the analyses/reanalysis specific humidity instead, and see whether the *N*-bias pattern will remain the same? Or is there any references that compare the RO specific humidity with the global analyses/reanalyses, which confirm the consistency?
- (3) Figure 3:
- Add latitude/longitude labels
 - Add the title for each row with the precipitation rate “<R>”
 - Maybe put side labels for “ERA-I, ECMWF_An, GFS”
- (4) Figure 4:
- Why the impact height goes all the way down to 0 km, which will likely be ~2km below the earth surface. Should that be “geometric height” instead, especially for the refractivity error plot? Please verify and make sure it is consistent with the manuscript description in L3 in Section 4.1.
- (5) Figure 6:
- Add latitude/longitude labels
 - Add labels after each column title: “no rain low q (<0.5 g/kg)” etc.
 - Maybe put side labels for “ERA-I, ECMWF_An, GFS”

Technical comments:

The line numbers were messy and not consistent. The following is the best I can do to point to the text in the manuscript.

“liquid and solid water content” → liquid and ice water content

Page-1 – Sec. 1 (right column)

L20: remove “of the”

Page-3 – Sec.2.1

L01: change to “the global surface precipitation every 30 minutes with a horizontal resolution of 0.1° latitude x 0.1° longitude.

L10: “compared against” → “collocated with” ;

L11: remove “looking for coincident ... resulted from such comparison.” → “A total of 16,881 COSMIC RO soundings are identified to be within the swath of the TRMM precipitation measurements (250 km), and within +/- 15 minutes.”

It’s confusing whether the collocation threshold “250 km” (i.e., swath size of TRMM) or “100km” as seen in L19 (Section 2.1)? Please clarify.

Page-3 – Sec.2.2

L03: spatial ... between +/-60 deg and every 30 min → every 30 minute with spatial coverage between 60°S and 60°N

L12: remove “(IMERG data is ... 30 min)”, which is redundant.

Page-3 – Sec.3

L10: for the two analyses and one reanalysis

L18: The hexagon with a diameter of ~30 deg is used in Figure 3. What is the sampling looks like? What the minimum/maximum and average sampling number of the collocation within the hexagon?

If the sampling plot will not be shown, it needs to be mentioned/discussed in the text, to justify the choice of “30 deg”.

I would expect it is primarily restricted by the sampling, but could it be possible to reduce the size of hexagon and show better spatial pattern?

L22: Revise sentence: “This figure shows the global distribution of the positive refractivity bias under heavy precipitation. The regional difference of the N-bias is evident and the difference among analyses and reanalysis is also shown.”

Page-4

Figure 2 caption: The compared profiles are ...” → The RO profiles are classified into no-rain (solid) and heavy rain (dashed) based on the collocated GPM IMERG precipitation measurements.

The time range should be mentioned in the caption.

Page-4 – Sec.3

L10: “The results have shown no ...” → “The results (not shown) reveal no significant changes to the positive *N*-bias, and confirms that the RO observation geometry is not a contributing factor to the positive bias.

Page-4 – Sec.4

L21: For the case in this study

L22: sum of the effects of all the raindrops

L33: Reference needed for “Raindrops fall following gravity and are flattened ... oblate-shape”.

L04: What is the subscript 1, 2 refer to? Simply corresponding to “h, and v”? Need to be explained.

L06: that is complex → that is a complex number

Page-5 – Sec.4

L35: The REFERENCE is needed for “The *N*(*D*) is obtained ... TRMM products...”

L36: provide → retrieve

Page-6 – Sec.4 – Sec. 4.1

L20: It is a bit odd to see the sentence here. “In the left panel of Figure 4, ...induced phase delay.”

It should be moved and integrated into the discussion of Figure 4 in Section 4.1, possibly after L04.

Figure 4: I would suggest to use (a, b, c) to identify the three panels, which make it easier to discuss in the manuscript.

Figure 4 deserves more discussion on each panel, especially the Fig. 4a (SNR plot). For example, what is the precipitation rate of the selected case, where, when, and how big is the precipitation feature? How typical is that compare to the other 62 cases?

Could the author(s) also add the excess phase delay without rain to be compared to the result (blue shaded) under heavy precipitation?

L08: effect into RO → effect on RO

L432: “The effect that liquid and solid water content has into the RO ... is to induce small errors such as those .. Figure 4.” → “the effect of liquid/ice water content on RO refractivity retrieval results **in small errors (??%, need numbers)**, which does not introduce obvious biases in both bending angle and refractivity (Figure 4b, c).

L435: “Thus, the fact that ...scenarios.” → “Thus the scattering terms in Equation 1 should not be the cause for the positive N-bias in the presence of the heavy precipitation.”

Page-6 – Sec.5

L439 – L457: The two paragraph were not well written and require some revision to improve the points.

Note the author(s) like to use the first person in the manuscript.

L449: “We have done it for the three analyses/reanalyses” → the two analyses and one reanalysis.

L458: “This classification allows us to further .. scenarios:” → “We further classify the collocated COSMIC RO profiles into four different categories:”

L462: the criteria → the threshold

Page-7 – Sec.5

L474: I assume that using coarse resolution of “45 deg” instead of “30 deg” was due to the limited sampling? Please offer the description of the map of sampling after separating into four categories. Will the possibly low and un-even sampling affect the results?

L502: “the bias is larger in ~~the case of~~ ERA-interim ...but smaller in ~~the case of~~ ECMWF ... analysis, showing the different performance of model in characterizing precipitation.

Not sure that is a correct interpretation. The physical model used in ERA-I reanalysis and ECMWF analysis should be pretty much the same. The major difference is the spatial resolution as well as the data assimilated. I would argue the resolution might be the major reason behind the difference. Please discuss and justify your reasoning.