

Reviewer 2

Responses shown in italics.

Short Summary:

The paper analyses data from the ROMEX experiment focusing on the three missions that contributed most data in the ROMEX period (September - November 2022). These are Spire, Yunyao, and COSMIC-2. Uncertainties and biases between datasets are addressed and sought understood. There are many interesting results, in particular global maps of uncertainties and biases, that I think deserve publication. However, I have concerns that the data that are analyzed are different from the data that have been provided to NWP users in the ROMEX experiment (if I understand it correctly). And I'm unsure if the data that are analysed are publicly available (or maybe not yet). I also have concerns about the correctness of some of the statements, which I elaborate in my specific comments below.

In my opinion, the paper needs major revision, with an update of some of the figures and a few more added, as well as modifications to many of the statements in the paper. Also more references needs to be included. The description of averaging method needs improvement. Generally the paper is well organized and the study is important.

General response: We thank the reviewer for this careful and thorough review, which has contributed to the improvement of the paper. Some of the comments are complex and to fully respond to them is beyond the scope of this paper. However, we have tried our best to respond and would welcome further discussions with the reviewer.

Specific comments:

L26: Maybe the COSMIC acronym should be spelt out. Or maybe it could be handled by saying "... referred to as COSMIC-2 (C2) ...".

Response: COSMIC-2 is spelled out in the revised version: Constellation Observing System for Meteorology, Ionosphere and Climate-2.

L33-34: "They are similar on the average in the region of overlap (45°S-45°N)". I don't think you can say this. According to Fig. 8, the Yunyao uncertainties are significantly larger (up to a factor of two) than Spire and C2 in the 10-15 km range. Is the sentence needed?

Response: The differences between the uncertainties of the three missions over most of the atmosphere from about 5 to 55 km are much less than the magnitudes themselves (Fig. 8b), except for the 15-20 km layer where the Yunyao uncertainty is larger than the other two. However, this is an artifact of their initial processing and has since been

remedied. This is our qualitative assessment, and we prefer to keep it in the Abstract. The closeness of the uncertainties of these three very different independent missions is important because it means that the data can be treated similarly in model data assimilation.

L37: "The assimilation of ROMEX data caused small degradations in biases in several NWP models". I suggest to remove this sentence from the abstract since it is not part of the study, and it is not mentioned anywhere else in the paper. It may give the impression that the biases studied in this paper was affecting the assimilation experiments, but I think it is now understood that they are likely not the cause of what NWP centers have found (presented at ROMEX workshops). I also question whether the data analysed in this study are similar enough to the data that were assimilated (see later comments).

Response: We agree and have removed this sentence from the abstract.

L43-45: Maybe this sentence in parenthesis is not needed in the abstract. It is explained later in the paper, and the detail is not needed here.

Response: We have deleted the definition of the radius of curvature in the parentheses.

L44: BA is not defined (but see my suggestion above of removing the sentence).

Response: The phrase in the parentheses has been deleted.

L68-69: "The ROMEX data became available at the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) ...". I think you should add here "Radio Occultation Meteorology (ROM) Satellite Application Facility (SAF)". Then in line 123: "EUMETSAT Satellite Application Facility (SAF) on Radio Occultation Meteorology (ROM)" can become EUMETSAT ROM SAF.

Response: Suggestion accepted.

L87-88: "Spire and COSMIC-2 (C2) are relatively well known and have been widely studied". Please provide references.

Response: We have now referenced Schreiner et al. (2020) for C2 and Bowler (2020) for Spire.

L91: "... Germany 17-19 April 2024 (Cheng 2025)". Should it be "(Cheng 2024)"?

Response: The workshop was held in 2024 but the reference to the workshop is 2025.

L106-107: "The original (raw) data were downloaded ... by each data provider". Could you clarify which data providers you mean? It is not clear to me why data providers would need to download their own data.

Response: The data providers are those who process the excess phase of each mission (e.g. COSMIC, Yunyao). We mean downloaded from the satellites and have added this clarification.

L113-118: When was this done? Does this cover all ROMEX data or only a subset of them? Did EUMETSAT process these into refractivity? It appears that these data are different from the data described in the next paragraph (line 122 and forward), but it should be made much more clear up front why you mention these data and if it is those that are analysed in this study (or maybe it is only the UCAR part of them - needs to be more clear).

Response: EUMETSAT relayed all the ROMEX excess phase data that it received from the providers to UCAR and STAR for further processing into bending angles, refractivities, and other products. This sentence has been modified for clarity. As described in L122-141 of the original paper, the data analyzed in this paper are the ROMEX data processed by UCAR. The bias and uncertainty statistics differ in some minor ways from the data processed by EUMETSAT. Most of the NWP modeling centers so far have used the EUMETSAT-processed data, which are being analyzed in detail by EUMETSAT. However, the UCAR-processed data also include a parameter that is related to the uncertainty of the observations in the troposphere, the local spectral width (LSW), which can be useful in data assimilation to estimate the RO error model of individual observation (Sjoberg et al. 2023) and a few centers are also using the UCAR-processed data.

L116-118: "EUMETSAT, UCAR, and STAR processed the excess phase data into bending angles, refractivities, and other products, as described by Kuo et al. (2004) and Steiner et al. (2020)". But these references did not describe the processing of ROMEX data. Text needs modification to be clear. Perhaps mentioning EUMETSAT and NOAA STAR here just adds confusion.

Response: These references describe in general terms how the processing of RO data is done, not the full description of the individual centers' processing algorithms, which are much too lengthy and detailed to be presented in this paper. The reader interested in these details may obtain them from the documentation provided by the processing center. We have added "as described generally by Kuo....." in the revised paper. We also added a reference to the details of the UCAR processing in the revised paper (Sokolovskiy, S.: Standard RO Inversions in the Neutral Atmosphere 2013 - 2020 (Processing Steps and Explanation of Data). [2020, Copyright 2021 UCAR 1 Standard RO Inversions in the Neutral Atmosphere 2013, 2021](#)).

We think it is important to mention that two other centers also process the same ROMEX data, because these independently processed data may be useful for structural uncertainty and other studies.

L130-135: I think you should move the citation in line 135 to line 130 as "Aparicio (2024)" instead of saying "Josep Aparicio (Environment Canada)". It is a problem that

this work is not publicly available. Did you check with Josep Aparicio if a publication is forthcoming?

Response: We accepted this suggestion. We did check with Josep Aparicio, and he said he would include his work in a paper to be submitted to the ROMEX special issue of AMT. For now, it is a personal communication.

L138-141: "... data that were originally provided to EUMETSAT and then processed by UCAR ...". Is this the data mentioned earlier (I think so, but it is not clear)? Are these data available anywhere (I could not find them)? In line 140 you say that UCAR-processed data and EUMETSAT-processed data are similar, but couldn't there be important differences larger than the differences between some missions? Three potential examples comes to mind after reading the whole paper:

- 1) Is there a different penetration for Metop in Fig. 4. than what was provided to NWP centres?
- 2) What is the influence of different definitions of the occultation point?
- 3) Could refractivity biases be significantly different at high altitudes due to different approaches in statistical optimization?

Response: Yes, all the data analyzed in this paper are the data processed by UCAR, after receiving the excess phase data from EUMETSAT. We agree that some differences between the UCAR and EUMETSAT processing have been discovered recently and have qualified this statement. The refractivity biases at high levels (above 40 km) may be different due to the different statistical optimizations, but we do not discuss the high-level refractivities in this paper.

The UCAR-processed ROMEX data were just recently added to the ROM SAF ROMEX server, but have always been available from UCAR upon request.

L139: "In sensitivity studies to investigate structural uncertainty (Steiner et al. 2020), we find ...". I think you should skip the citation as it is not directly related to the data analysed here. Or phrase things differently.

Response: Although this is not a paper about comparing UCAR- and EUMETSAT-processed ROMEX data, we thought we should say something about what we have found so far about the differences between the two datasets. We have reworded the sentence to: "Performing structural uncertainty analyses similar to Steiner et al. (2020), in limited comparisons we find that the UCAR-processed data and the EUMETSAT-processed data are similar in most respects; examples are shown in the Supplement (S9)."

L141: "... processed data are similar. Examples are shown in the Supplement.". Please provide the figure numbers?

Response: We show examples of UCAR vs EUMETSAT processed data in S9 of the Supplement as noted in the revised sentence above.

L144-146: "The penetration rate is defined as the percentage of successful occultations reaching different levels ...". Is it one number? or several numbers? It is not clearly defined here or anywhere else. Maybe it should not be called "rate".

Response: We have changed the sentence to “The penetration depth is defined as the percentage of profiles of a sample of RO observations reaching different levels above the ground.” It is a number (%) for each level of a sample of RO profiles. For example, a penetration depth of 80% at 2 km for a sample of RO profiles means that 80% of the profiles in this sample reach 2 km. It is a single number for each sample and each level.

L160-166: "The root mean square error is ... RMS" Why mention it if it isn't used?

Response: Many papers use RMS differences, and so we thought that was useful to distinguish RMS from STD. However, we agree it is unnecessary and have deleted it.

L172: "RO biases are therefore assimilated in NWP models without bias corrections". Do you mean "RO observations are therefore assimilated ..."?

Response: Yes, we have corrected the sentence.

L180-183: "... commonly used verification charts ... often plotted together on a scale of -20% to +20%". Please provide references.

Response: We have added Schreiner et al. (2020) and Ho et al. (2023) as examples.

L184-189: Please provide specific references to support the statements here (I suppose from the ROMEX workshops).

Response: Yes, the ROMEX workshops. We have noted this in the revised paper and provided a link to the IROWG website that has all the ROMEX workshop presentations: irowg.org/romex-events-meetings/.

L194: "sometimes called the RO core region, golden zone, or sweet spot" Please provide references.

Response: We don't know of any reference that uses all three of these terms. These are colloquial terms often used in the community and we define them here. We have revised the text slightly to “sometimes colloquially called....”.

L200-204: It would be good to mention here that the analyses and forecast data are forward modelled to BA and N.

Response: This is an important point; we agree and have added this to the appropriate sentence and also described how errors in the forward model could contribute to the perceived model RO biases.

L210: "Nielson" should be "Nielsen".

Response: Corrected.

L269: "We compare bias and uncertainty profiles...". I suggest to say instead: "We compare bending angle observations ...". It is only the BA observations that are compared on impact heights, not the refractivity.

Response: Suggestion accepted.

L269-272: Would it be more correct to say that the BA observations depend on five parameters: time, impact height, latitude, longitude, and azimuth? The dependency on azimuth is ignored in the comparisons, but not the dependency on the other four parameters.

Response: Although the BA observations depend on these five parameters, only the small difference in azimuth angles of different missions make the plotting of BA vs. impact height not strictly physically meaningful (because of representativeness differences), so that is why it is mentioned here. We have modified the text to read "... in some of our results. The influence of the occultation plane's azimuth angle is not considered in these comparisons and will be further discussed in Section 5."

L276: "The issues ... are much smaller than 0.15% ..." Issues are not quantitative (the representativeness differences are). Please modify text.

L278: "comparing RO missions on impact height ...". I suggest: "comparing RO missions ignoring the azimuth dependency ..."

L280: "However, they likely ...". Now 'they' refer only to issues, not to the representativeness differences. Please modify text.

Response to previous three comments: We have rewritten this text and combined it with the previous paragraph:

"In some of our results, we compare bending angle bias and uncertainty profiles of the ROMEX missions as a function of impact height, which is related to the geometric height by the refractivity and local radius of curvature of the Earth (Sokolovskiy et al. 2010). The influence of the occultation plane's azimuth angle is not considered in these comparisons and will be further discussed in Section 5. These are representativeness differences and not differences in the quality of the retrievals. The magnitude of these differences (less than 0.15%) is much smaller than the 3CH uncertainty estimates, which are 1.5% or higher. However, they may have an impact on the comparison of bending angle biases, which are of the same order of magnitude between 10 and 30 km."

L321: ... "in the 40-45°NS bands". I suggest to note here what NS means.

Response: We have defined NS the first time it appears, i.e. 40-45°NS (40-45° north and 40-45° south).

Figure 1: The first five figures span four pages, but are numbered 1a to 1e, with separate captions and without any direct relation. I suggest to number them 1 to 5. Similar could be said about Figure 10a and 10b,c. (They could be two separate figures).

Response: Since these two figures are all related, we prefer to group them as done in the paper. This does not affect the length of the paper.

Figure 1a: It could be mentioned in the figure caption that the underlying world map is for 12 UTC, but that it is not important. The x-axes could be labelled "local time [hr]".

Response: We have added to the caption: "The x-axes are local time in hours."

Figure 1e: This plot gives the impression that there are very few occultations at high latitudes for the polar missions. It would be more interesting to see the density per unit area (divide by $\cos(\text{lat})$), which I think would be more relevant.

Response: We have added a panel to Fig. 1e showing the number of occultations per 10000 km² as a function of latitude. Indeed, this does present a different perspective.

Figures in general: There is often information in the titles above figures which should be in the captions, e.g., "20 km" in Fig. 2 should probably be mentioned in the figure caption. Please check all figures and modify captions as needed.

Response: We agree and have checked all figures and modified captions appropriately.

L374: "Fig. 2 shows the daily BA profile counts (after UCAR CDAAC QC but before the 3CH QC)". What is the 3CH QC?

Response: It is the QC (quality control) described in the first paragraph of Section 2.3. We have modified the text to say "after UCAR CDAAC QC but before the 3CH QC as described in Section 2.3."

L433: "penetration rates are noticeably less for Metop-C (green), ...". And Metop-B too, it seems (I would say that the colors for Metop-B and Metop-C are olive green and/or dark cyan, but maybe there are more precise color names provided by the plotting software that could be used here). Why is the penetration so poor for Metop? Is it the same in the ROMEX core data that can be found at the ROMEX data server, or is this an artefact of the CDAAC processing?

Response: The penetration depth profiles of Metop-B and Metop-C here are noticeably poorer than the other ROMEX missions. Although not shown here, they are also poorer than the EUMETSAT-processed Metop data. Thus, this is probably an artifact of the

CDAAC processing and is undergoing investigation. We have inserted a sentence to this effect in the revised paper.

L436: "These results confirm that radio occultation is a useful method of obtaining global information on the planetary boundary layer." Please provide references (or maybe the sentence is not needed here).

Response: We have added a reference here: Ao, C. O., D. E. Waliser, S. K. Chan, J.-L. Li, B. Tian, F. Xie, and A. J. Mannucci (2012), Planetary boundary layer heights from GPS radio occultation refractivity and humidity profiles, J. Geophys. Res., 117, D16117, doi:10.1029/2012JD017598.

L448: "In this section we present an overview of the bias and uncertainty statistics of all the ROMEX data. Many additional detailed results are presented in the Supplement." But the supplement only contains details about the three missions that are the focus in the next sections, not the rest of the ROMEX data that are discussed in this section (Section 3). Maybe the last sentence is not needed.

Response: We have revised the last sentence to read: "Many additional figures showing statistics for the three largest ROMEX datasets are presented in the Supplement."

L451-455: Say "MSL altitude" instead of "MSL height" (altitude is commonly used with reference to MSL). It would be good to mention here that it is the MSL altitude of the tangent points (I suppose).

Response: Suggestion accepted. We have added that it is the altitude of the RO tangent points.

L457: "... having the smallest uncertainties because of their more accurate clocks (Padovan et al. 2024)". Padovan et al. only looked at Sentinel-6 and COSMIC-2 and did not compare to other missions. Could the CDAAC processing also here have an influence?

Response: We have added a reference on the more accurate Metop data because of their more accurate clocks (Bonnedal et al. 2010). We are not sure why the CDAAC reference is relevant here, since CDAAC starts with the excess phases and all the datasets being processed use consistent algorithms.

Figure 5: Are all the missions processed by CDAAC with the same software version? If not, I suggest to add a table which shows processing versions and/or origin of the processing (e.g., if the low level processing was done by another data provider).

Response: All the missions shown in Fig. 5 (as well as other figures) were processed with the same software version after the excess phase data were received from EUMETSAT. The excess phase data were obtained from EUMETSAT, which in turn received them from each data provider as described in Section 1.1.

L458: "Fengyun-3 shows higher uncertainties between 10-30 km than the other missions. Yunyao has a peak in uncertainties between 10-15 km ...". Should it be "uncertainty" (singular)? I don't think it is correct to say "between X-Y km". Either say between X and Y km, or in the X-Y km range (or similar). Please modify all such occurrences throughout the paper.

Response: There are multiple values of uncertainties that are plotted between 10 and 15 km so plural seems appropriate. We have changed the notation for layers from “between X-Y km” to “between X and Y km” throughout the paper.

L468: "... ROMEX missions between 10-35 km (Fig. 6a)". This is the first reference to Fig. 6, but before that, it should be properly introduced in the text (not in a parenthesis). I noticed the same regarding Fig. 15 and Fig. 17.

Response: We have changed the sentence to “ROMEX missions between 10 and 35 km, as shown in Fig. 6a.” This should be sufficient to introduce Fig. 6.

L475: "Fig. 6: Upper left (a) ...". Letters (a,b,c,d) are missing in the Figure. Please add letters to each of the four panels.

Response: The letters have been added to Fig. 6.

Figure 6: There is a confusing background grid with dots over all four panels that doesn't belong here. It needs to be removed. Same can be said of Fig. 4.

Response: Dots have been removed in Figures 4 and 6.

L486-487: Perhaps replace "in these latitudes" with "at these latitudes".

Response: Suggestion accepted.

L489: "figures show the importance of comparing different RO missions using spatial and temporal sampling as similar as possible". Why temporal? At first glance, I don't see any effect of different temporal samplings. Please clarify.

Response: We agree that Fig. 6 shows the importance of similar spatial sampling and not temporal sampling and have removed “temporal” from the sentence.

L503: "... the simple but effective error model used by ECMWF (Ruston and Healy 2022) is shown as a dashed line." I assume you mean "error model for RO observations". The general reader could misunderstand this to be the error of the ECMWF operational model, especially when one looks at the legend in Figure 7. I suggest to use a more precise indication than "ECMWF" in the legend to distinguish the meaning from that of "ERA5" and "JRA3Q".

Response: We have revised this line to say “simple but effective RO observation error model used by ECMWF.” We have noted that the label “ECMWF” in the legend refers to the ECMWF RO error model rather than the uncertainties of CSY and ERA5 derived from the 3CH method.

L504: "Considering that it was developed many years ago, the agreement with the CSY data is remarkable." I think this is an overstatement. The ECMWF-used error estimate is significantly larger at high altitudes. Please modify text.

Response: We have modified the text to emphasize that the close agreement between the ECMWF RO error model and the CSY uncertainties is between 10 and 35 km.

L533: "uncertainties and biases below 5 km are related to their cutoff of carrier phase data ..." This is the first mention of a bias in Yunyao data below 5 km, and it is not shown in Fig. 8. Should it be shown?

Response: We have removed “and biases” from the sentence because Fig. 8 shows only the uncertainties. We do not investigate possible biases in the Yunyao data in this paper.

L534: "... too early, as described by Sokolovskiy (2014) and noted by Marquardt et al. (2024)". Sokolovskiy (2014) did not describe Yunyao data, so I don't think you should cite it like this. In the conclusion of (Xu et al. 2025) it says: Larger biases are primarily observed in the lower troposphere, a phenomenon that has been extensively discussed in previous studies (Sokolovskiy et al., 2014; Xie et al., 2010). However, I think that is with reference to the more recent data version that Yunyao has processed. Are you sure that the much larger bias in the Yunyao data in your study can be attributed to the effects described by Sokolovskiy (2014)?

Response: Thank you. As noted above, we did not look at the Yunyao biases. We have removed “biases” from the discussion of the Yunyao data in this sentence and only discuss uncertainties.

L535: I think it should be (Xu et al. 2025).

Response: Yes, we changed it to 2025.

Figure 8: It is very difficult to distinguish solid, dash-dotted, and dashed of the same color. Given the curves in Fig. 7, would it make sense to show differences to these in Fig. 8? Like Fig. 6, this figure also has a confusing background grid that needs to be removed.

Response: We prefer to show the error standard deviations of the three missions. The difficulty in distinguishing the three RO missions emphasizes the important point that all three missions are similar over most of the heights. We have added details about the similarity of the profiles in the Figure caption. We have deleted the background grid from Figs. 4, 6, and 8.

L551: "Larger uncertainties occur over Asia and the Pacific". I see it in many other places in the tropics. Why single out Asia and the Pacific? It is difficult to see that the uncertainty is particularly larger there.

Response: We agree and have deleted this sentence.

L552-554: "... interesting regional feature is the maximum uncertainty over the Weddell Sea at 20 and 30 km, which may be related to the ionospheric Weddell Sea anomaly (Chang et al. 2015)". If it is related to ionospheric disturbance, then why would it not be seen at 50 km? Could there be other explanations? It is indeed very interesting!

Response: The color scale of the uncertainty map is larger by more than an order of magnitude at 50 km than it is at 20 and 30 km; thus, the feature of interest visible at 30 and 40 km does not show up at 50 km.

L564: "Fig. 9: Global distribution of 3CH uncertainties (%) for CSY BA at 3 km (a), 5 km (b), ...". Letters are missing in the figure panels.

Response: Letters have been added.

L570: "Larger versions of the panels are presented in the Supplement." Actually, the Fig. 9 and Fig. 12 maps are a bit more sharp (when zooming in) in the paper than in the Supplement in my pdf viewer (acrobat).

Response: Yes, the figures in the Supplement are not quite as sharp as those in the paper because we had to compress the Supplement in order to meet the AMT size limit. However, we find all of the figures acceptably sharp to show the main features in the uncertainty distributions.

L574-576: "The small negative impact of the ROMEX data on the biases of several NWP models has caused intensive study of possible causes of these small biases, including the possibility of small biases in the ROMEX data." Would a reference to 'this issue' (or similar) be possible here? (I assume that the paper, when it is in its final form, will be included in the special ROMEX issue).

Response: We added a reference to the ROMEX workshops at the beginning of Section 4.2 where these NWP biases are mentioned. Yes, our paper will be included in the ROMEX special issue.

L584-585: "... collocate an RO dataset with a model or another RO dataset, with advantages and limitations discussed in Section 2.". Could you briefly remind the reader what the advantages and limitations are? It is not totally clear to me.

Response: "Section 2" is a typo. We describe the collocation of an RO dataset with either a model or another RO dataset in the last paragraph of Section 1.1. We have clarified

this in the second paragraph of Section 4.2 in the revised paper so that the reader can easily find the advantages and limitations of the two collocation methods.

L586-587: "... the two RO datasets in latitude-longitude bins and compute the averages over each bin of the difference between the RO and reference data (e.g., ERA5)". This raises a number of questions:

1) How do you handle drifting tangent points? Can one part (say the lower part) be averaged within one bin, and another part (say the upper part) be averaged within another bin? Or is it at a reference location for the whole profile?

2) Is area weighting with a cosine factor taken into account when averaging over latitude?

3) Are sampling errors taken into account?

You need to describe your method in much more detail, possibly with equations, so that others can reproduce it. Gleisner et al. (2020) (<https://doi.org/10.5194/amt-13-3081-2020>) gives a nice description of how one can average in 5 degree latitude bins, including sampling error correction. I suppose your method is slightly different. Please describe it.

Response: We have rewritten this paragraph and added more details of the second way (collocation within latitude-longitude bins and comparison with model data in the bin) in the revised paper. The tangent point of each profile is used to locate the RO observation in the appropriate bin at each level, and so one part of a profile can be in one bin and another part in another bin. There is no area weighting; this is simply an estimate of the mean differences between a sample of RO data and a reference dataset.

L587: "This results in large samples and all RO data can be included.". Do you mean all three months? Please clarify.

Response: This statement is true in general (all RO data in any sample can be included) including the three-month sample studied here.

L602: "propagates into N after the Abel inversion". Since this is the first mention of the Abel inversion, perhaps a reference to the Abel transform would be good here for the general reader.

Response: We added Kursinski (1997) as a reference.

L617: "computed from 5x5° latitude-longitude bin averages over all bins and days of ROMEX." Do small bins at high latitudes contribute with the same weight as large bins at low latitudes?

Response: We are comparing RO vs. ERA5 biases on a per-profile basis (i.e. each RO profile is included in the sample regardless of latitude). There is no latitude weighting

because this bias estimate is only for the entire RO dataset—it is not representative of a latitude-weighted global sample as used for climate studies. Please see also the response above to Comment L586-587.

L618: "bases" should be "biases".

Response: Corrected.

L630-631: "Fig. 11 shows the mean differences between Yunyao and C2 from Spire between 10-40 km impact height." I suggest rephrasing to something like: "Figure 11 shows Yunyao and C2 normalized biases relative to Spire between 10 and 40 km."

Response: Suggestion accepted.

L634-637: "The bulge between 15 and 20 km is likely related to the relatively large horizontal sampling differences in the 5x5° latitude-longitude bins in a layer with large variations of atmospheric densities in the vicinity of the tropopause." I don't understand how that could be a reason. Please elaborate and please clearly describe how the results in Fig. 11 are obtained. Do they come from collocations? What does "2-day Mean" in the title above plots mean?

Response: We have added a more detailed description of how the profiles and maps of the biases and uncertainties are obtained using the 5x5° bins, including the meaning of "2-day mean" near the beginning of Section 4.2 as discussed above. We have also added additional evidence for the cause of the "bulge" between 15 and 20 km being related to the systematic sampling differences in the 5x5° bins—the fact that the "bulge" does not exist when the Spire and C2 observations are collocated very closely (Fig. 13). Finally, we added the Yunyao minus Spire differences with Yunyao restricted to 45°NS in Fig. 11 for better comparison with the C2 differences.

L651-652: "ERA5 biases may be of comparable or larger magnitude at all levels." I don't think ERA5 biases are this large at the lower levels. Would you agree?

Response: This is an important point. The ERA5 (and other model) biases of BA and N are computed from a forward model using the model data (temperature, pressure, and water vapor). Biases may occur from systematic errors in the forward model as well as the model data. Both contribute to what we call "ERA5 biases." We do not think the ERA5 model data biases themselves are necessarily as large as these RO biases would indicate. We have clarified what we mean by ERA5 and other model biases in the revised paper (Section 1.1 L219-221) in the revised manuscript.

L670-672: "The ROM SAF Matched Occultation page presents daily estimates of the biases of RO satellites compared to other RO satellites, with a collocation criteria of 300 km and 3 hours (<https://rom-saf.eumetsat.int/monitoring/index.php>)." I think the collocations are more precisely at <https://rom-saf.eumetsat.int/monitoring/matched.php> .

Response: We agree and have used the more precise link in the revised paper.

L672-674: "This monitoring site shows various combinations of mean and standard deviation of differences between BA and N from different satellites". I don't think the sentence makes sense (Combinations of mean and standard deviation? Combinations of differences between BA and N?). Please rephrase.

Response: We have deleted "various combinations of" from the sentence.

L674-676: Perhaps the paper should not be discussing details in a figure from someone else's website. Is it necessary?

Response: We think this reference to C2 biases with other RO missions from an independent source such as the widely used ROM SAF monitoring site is an important source of independent information supporting the small positive biases of C2 BA, similar to other references included in this paragraph.

L694: "Why are C2 BA positively biased to Spire ...". Maybe say "biased relative to".

Response: Suggestion accepted.

L711: "computed from 5x5° latitude-longitude bin averages over all bins ...". I think there may be a copy-paste mistake here. There are no averages over bins in Fig. 14, right?

Response: Correct. There are averages within each bin and over all days of ROMEX. We have corrected the caption.

L716: "The small positive biases of C2 relative to Spire and other ROMEX missions in BA". Suggestion: "The small positive BA biases of C2 relative to Spire and other ROMEX missions".

Response: Suggestion accepted.

L717: "... between 10 and 35 km result from their different orbits around the non-spherical Earth". I suggest to say "result from their different orbit configurations."

Response: We have revised the sentence to say: "...result from their different orbit configurations around the non-spherical Earth." We think it is important to mention the role of the non-spherical Earth.

L719: "... that best fits the Earth's surface curvature at a given location ...". Ending parenthesis is missing. I would rather say: "... that fits the Earth's surface curvature along the direction of signal propagation ...".

Response: Suggestion accepted.

L722-723: "The effect of this variation of R_c on the BA ...". Perhaps say "the azimuth" instead of "this" to be clear.

L723: "... may be called the anisotropy of Earth's curvature effect.". Do I understand correctly that this covers both the azimuth effect and the sideways sliding effect? Should it be plural (effects)?

Response: We have rewritten the sentence in L722-723 as: "This variation of R_c may be called the anisotropy of Earth's curvature, and it has two effects on the BA, the azimuth effect and the sideways sliding effect."

L724-725: "C2 is in a low-inclination orbit (24°), with all of its observations located within $\pm 45^\circ$ latitude and occultation planes predominantly oriented in an east-west (E-W) direction.". I'm not convinced of this. I suggest to include a figure showing the distribution of occultation plane azimuth angles for C2 and Spire.

L741: "... oriented E-W (as in most C2 occultations) ...". Please show it.

Response: We have included a figure (new Fig. 15) showing the frequency distribution of azimuth angles for C2, Spire, and Yunyao (shown below).

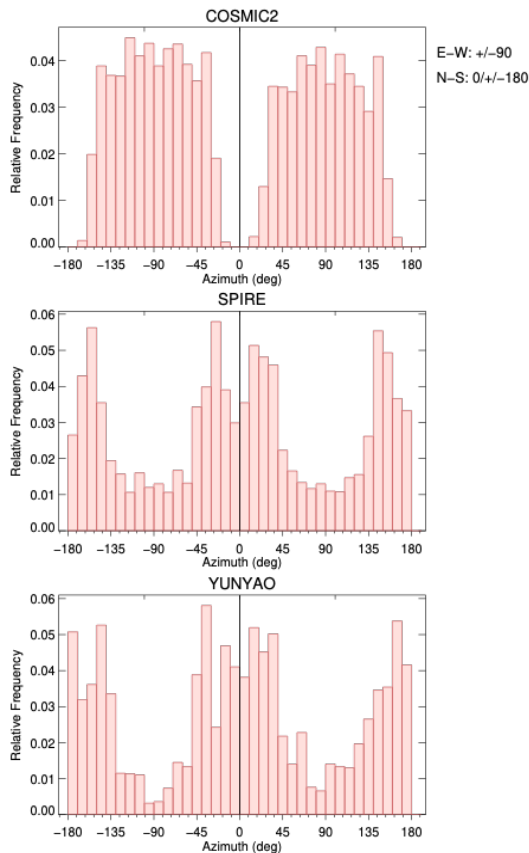


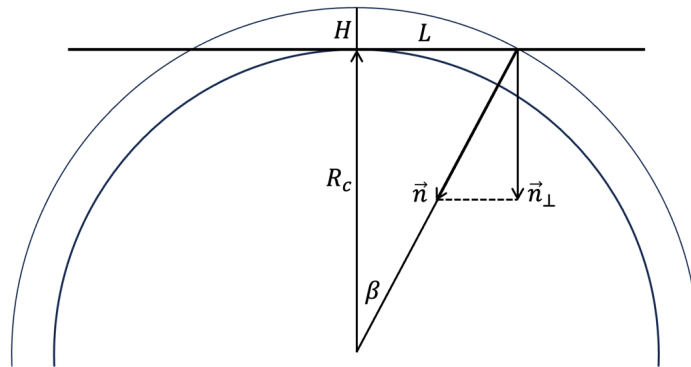
Fig. 15 (new): Frequency distribution of azimuth angles for C2, Spire and Yunyao.

L746: "larger R_c will accumulate a slightly larger bending angle, due to traversing a slightly longer path." My understanding is different: A signal is being affected by slightly more perpendicular gradients (due to the slightly larger curvature) on its path in the vicinity of the tangent point (vertical refractivity gradients are precisely perpendicular at the tangent point, but gradually less perpendicular away from the tangent point because of the Earth's curvature), thus accumulating more bending. The path length may in principle be the same. Would you agree with this?

Response: Thanks for this question. The explanation in the paper "slightly longer path" was used for brevity.

Considering a thin atmospheric shell of thickness H ($H \ll R_c$) over a sphere of radius R_c . The GNSS signal can be approximated as a straight line through this layer. The horizontal half-path inside the layer is $L \approx \sqrt{2R_c H}$. This is an effective length, which is proportional to $\sqrt{R_c}$. An increase ΔR_c results in a fractional change $\Delta L/L \approx (\Delta R_c/R_c)/2$. The angle between the perpendicular to the ray and local radius vector on exit from the layer is $\beta \approx L/R_c \approx \sqrt{2H/R_c}$. Accordingly, the perpendicular component of the unit vector (associated with the refractivity gradient, which is another contributor to the bending angle noted by the reviewer) is $n_{\perp} = \cos\beta \approx 1 - \beta^2/2 \approx 1 - H/R_c$. An increase ΔR_c causes a fractional increase $\Delta n_{\perp}/n_{\perp} \approx (\Delta R_c/R_c)(H/R_c)$.

Thus, both factors i) the increase of the effective propagation length L and ii) the increase of the perpendicular component of the refractivity gradient proportional to n_{\perp} contribute to the increase of bending angle. But the contribution of second factor (mentioned by the reviewer) is much smaller due to the additional small parameter $H/R_c \ll 1$ and thus it was neglected.



L747-749: "Although this effect is small, it can still cause a difference up to about 0.3% in the bending angles measured at the same impact height along the equator between the N-S and E-W directions". Where does the number 0.3% come from? How did you calculate it?

Response: This estimate is based on two ROs located at Equator, one observing in E-W direction and the other in the N-S direction. This represents approximately the maximum possible difference in BA that can be achieved due to azimuth angle difference. We have added this explanation to the text.

L748: Perhaps "at" instead of "along".

Response: Suggestion accepted.

L750: Better to say "as a function of impact parameter" instead of "as the function of the impact parameter".

Response: Suggestion accepted.

L760: "The azimuth angle effect can be corrected ...". I suppose you mean when comparing collocated BAs on impact heights. Please make that clear in the text.

Response: We have rewritten the sentence: "In general, direct comparisons of BA from different RO missions are not physically meaningful unless the effect of azimuth angle is accounted for, typically through a model-based DD correction."

L760-761: "... through double differencing (DD) using a model." I suggest to call it sampling error correction, not DD. Schreiner et al. (2019) used the term "sampling correction". The term DD in RO has been used for something else (to eliminate clock errors in the phase data by simultaneously observing two GPS satellites and using ground station data).

Response: We agree that "double differencing" can mean more than one thing, We are following Tradosky et. al. (2017) and Gilpin et al. (2019), who used the term to correct for biases between two datasets using a model, which is valid under the assumption that the biases in the model at one observation are the same as those collocated with the other observation. We have modified the sentence to read "The azimuth effect can be corrected through a type of sampling correction termed double differencing (DD) using a model."

L784-785: "In RO data retrieval, it is commonly assumed that the occultation plane remains fixed throughout an occultation event and is anchored at the assigned occultation point, ...". My understanding is different: The centre of curvature and radius of curvature remains fixed, but the occultation plane is not assumed to be fixed. For each sample during an occultation a new occultation plane is calculated based on the fixed centre of curvature and the varying satellite positions. Thus, the occultation plane is assumed to change during the occultation, and the tangent point locations are different for each sample. We say that the tangent points are drifting. What is commonly assumed is that the surface of the Earth locally coincides with the surface of the sphere whose origin is at the centre of curvature. That is the assumption which does not hold exactly. It only holds in the direction of signal propagation at one instant during the occultation, the one that

defines the occultation point which is then fixed. It doesn't generally hold in any other direction or at another instant. Would you agree with this?

Response: Thanks for pointing this out. We have revised the text as follows: "In RO data retrieval, a single reference sphere, defined by a fixed center and radius of curvature anchored at the occultation point, is typically used to approximate the Earth's surface throughout the entire RO profile. However, when the tangent point drifts horizontally, this reference sphere no longer accurately represents the local geometry of the Earth's ellipsoidal surface."

L801: "can be corrected by adjusting the impact heights ...". Add "and altitudes".

Response" We apply the correction only to impact heights. There may be other options for implementing the correction.

L801-802: "... by a correction factor termed the sideways sliding correction." Use of the word "factor" implies that something should be multiplied by a factor, which is not the case. Text needs slight modification.

Response: We have deleted "factor" from the sentence.

L808: "Fig. 17: Difference in radius of curvature (dRc in km) along and across ray path ...". I suppose it is "across" minus "along" that is displayed in the figure, but the text is not clear on that. Please clarify what is subtracted from what.

Response: Yes, the difference is "across" minus "along." The caption has been made clear.

L812-815: "Tests of the impact of the sideways sliding correction by EUMETSAT and UCAR demonstrated that the vertical variation of the effect depends on how the nominal location or point of an occultation (termed occultation point by UCAR and georeferencing by EUMETSAT) is defined ...". Is there a reference that could be included here?

Response: Jan Weiss in his presentation at the 2nd ROMEX Workshop at EUMETSAT 25-27 February 2025 showed a figure depicting the magnitude of the impact height correction vs. impact height for different definitions of occultation point. We have added a reference to this presentation and rewritten the sentence as "The magnitude of the correction varies with impact height depending on how the nominal location or point of an occultation (termed occultation point by UCAR and georeferencing by EUMETSAT) is defined (Weiss et al. 2025)."

L827-831: "The sideways sliding correction results in a small reduction in the average positive C2-ERA5 BA and N biases in the UCAR-processed data by approximately 0.05% in the stratosphere. It also corrects negative biases associated with polar orbiting satellites, mostly in the tropics, by a similar amount. At higher latitudes, the effect on

observations from polar orbiters is negligible (less than 0.01%).". Please provide references.

Response: This is based on tests we did but did not show the results here. However, we deleted this paragraph because the magnitude of the effect of the correction on BA and N is illustrated in Fig. 18 (now Fig. 19 in revised paper) and described in the following paragraph.

L834-835: "... and the resulting C2-Spire bias is shown in Fig. 18. The reduction is smallest at 10 km ...". Lower than that, I suppose (but not shown). What is the typical altitude (or range of altitudes) of the tangent point for which the excess phase is 500 m?

Response: Yes, there is no change (0 reduction) at the occultation point, which is defined where the excess phase is 500 m, corresponding to a typical tangent point altitude of ~4 km.

L835: "... because of the definition of occultation point in the UCAR data". Insert "the" in front of "occultation point".

Response: Suggestion accepted.

L839: "Fig. 18: Bias of C2 relative to Spire for UCAR standard (solid profiles) ...". Perhaps skip the word "profiles" here.

Response: Suggestion accepted.

Figure 18: I suggest adding a plot showing the same for refractivity.

Response: We added refractivity as suggested to this figure (now Fig. 19).

L845: "For C2, the off-boresight angles exceeding 40° are mostly concentrated between 40-45°N/S". It would be interesting to see this in a figure.

Response: Because the concentration of large off-boresight angles in the 40-45° N and 40-45° S latitude bands do not seem to play a role in larger biases there we have deleted this sentence.

L852-857: "An average of 35,000 RO profiles per day from 13 different RO missions from the United States, Europe, and China are being used in NWP models at major international centers to study how different numbers of RO profiles affect the analyses and forecasts. This paper evaluates the characteristics of the ROMEX data used in these experiments, with emphasis on the three largest datasets, COSMIC-2, Spire, and Yunyao." My understanding is that the data analyzed in this paper are not the same as the data provided to the NWP centers for all missions (C2 may be an exception). There may be differences in the biases and uncertainties due to different processing, and I have pointed to some examples in my comments above (L138-141). It is fine that this paper

analyses the UCAR-processed data, but I don't think you can write that it is generally the ROMEX data that are being used in experiments at NWP centres. Please modify text.

Response: Correct, most NWP experiments have used the EUMETSAT-processed ROMEX data. We replaced “used in these experiments” by “processed by UCAR.”

L884-885: "This apparent bias is investigated and found to be a result of their different orbits." I think the statement is correct that it is due to different orbits (or orbit configurations). However, I don't see any real evidence in the paper. I see a reduction in C2 bending angle biases when doing DD (sampling error correction) in Fig. 16, but that was already shown by Schreiner et al. (2019). Could more evidence that the reason is to be found in the different orbit configurations/azimuths be provided (cf. my comments to L724-725 and L747-749)?

Response: We have added a figure showing the different azimuth angles (new Fig. 15) and the opening statement of Section 5.2 is “The small positive biases of C2 relative to Spire and other ROMEX missions in BA between 10 and 35 km result from their different orbits around the non-spherical Earth.”

L889: "... is different azimuth or viewing angles on the average ...". This is the first time "viewing angles" are mentioned, and they are not discussed further. Please clarify.

Response: We deleted the reference to viewing angles.

L895: "... sideways sliding of the occultation planes during occultations." I suggest to say "... sideways sliding of tangent points" (cf. comment to L784-785).

Response: We have referred to this effect as the “sideways sliding of the occultation plane and tangent point” in the revised document. Josep Aparicio used both terms in his November 15, 2024 presentation.

L896: "This sliding results in different radii of curvature of Earth ...". The sliding does not result in different radii of curvature, they are already there. Please rephrase.

Response: This text has been revised to: "The second source is the horizontal sliding of the RO tangent point, which leads to a height difference between its position relative to the Earth's ellipsoid surface and the reference sphere. This difference results in a positive bias of ..."

L895-896: "... and different impact parameters ...". The impact parameters are not changed, only the height of tangent points (which are more accurately referenced to the surface of the ellipsoid instead of to the surface of a reference sphere). Please rephrase.

Response: Rephrased as stated in the previous response.

L897-899: "... and creates a positive bias of about 0.05% in the UCAR-processed C2 bending angle (BA) and refractivity (N) observations in the stratosphere compared to those of the polar orbiters". The positive bias seems less than 0.05% in Fig. 18. (perhaps half of that at 30 km where the difference between C2 and Spire is largest).

Response: We changed this to "and creates a positive bias of up to 0.05%" in the revised paper.

L899: "The sideways sliding effect was identified and discussed by Josep Aparicio in November 2024. It can be easily corrected in the processing of the RO data by applying a correction to the impact height." I don't agree with this statement. My understanding is this: The impact height is not involved in the processing of RO data (the impact parameter is involved, but it is not changed). The impact height is used when we compare bending angles on a vertical scale (where we then subtract the radius of curvature from the impact parameter), and it is here we need to make a correction. Would you agree with this?

Response: We may not fully understand the exact point of disagreement, but we would like to clarify our perspective. In the context of RO data processing, the impact height serves as the argument of the BA function. It is not an arbitrary choice but a direct result of the processing itself. Therefore, whether or not the impact height is considered as being "involved" in the processing may be more of a semantic distinction. We choose to use impact height as the argument for the BA because it facilitates direct comparisons of BA produced by different data processing centers and allows for meaningful statistical averaging. Such comparisons would not be straightforward if BA were instead expressed as a function of impact parameter.

In his presentation on 15 November 2024 (personal communication), Josep Aparicio applies his sideways sliding correction dR to the impact height h , where $h = a - R_c$ is the uncorrected impact height, a is the impact parameter, R_c is the local radius of curvature, and h' is the corrected impact height

$$h' = h - dR = a - R_c - dR. \quad (1)$$

Eq. (1) may be written in terms of a corrected impact parameter

$$h' = a' - R_c \quad (2)$$

We apply the correction in the UCAR CDAAC revised processing by correcting the impact height according to (1). However, we also supply the correction dR with the processed data in case users wish to apply the correction in a different way.

In contrast, assimilation systems typically operate using the impact parameter, a . However, this curvature radius (or reference sphere) is a simplified representation of the Earth's surface that applies uniformly for the entire occultation profile. As discussed in the paper, this introduces inaccuracies in the estimated ray heights over the true Earth's surface. Therefore, correcting for impact height effectively translates to a correction of the impact parameter for the purpose of assimilation.

If, as suggested by the referee, the impact parameter is left unchanged, this would indeed preserve its formal geometric meaning as the ray's miss-distance to the center of sphericity. However, the error (bias) related to the miss-representation of the reference ellipsoid by using the single center of sphericity will propagate into the data assimilation.

We acknowledge that formally correcting the impact parameter is not the only way to account for Earth's oblateness in assimilation systems; alternative methods are indeed under discussion. However, such assimilation-specific adjustments are beyond the scope of this paper.

L906-907: "Code and data availability. The ROMEX data are available free of charge through ROM SAF under the ROMEX terms and conditions.". Please give precise information which ROMEX data were used. Are you sure the data processed by UCAR and STAR are on the ROM SAF server? I was not able to find it. There are different datasets in different versions. Which ones were used for this study?

Response: As stated in L137-139 in the original paper, we have analyzed the UCAR-processed ROMEX data, which are similar to the EUMETSAT data in most respects. The UCAR-processed ROMEX data are not yet on the ROM SAF server; but they should be there very soon. They are available from UCAR upon request from interested users. We have added this information to the "Code and data availability" section.

L918: "JS assisted RA and JS by ...". There are two JS's.

Response: Full last names are now spelled out to avoid any confusion.

L980: I think "Chen" should be "Cheng".

Response: Yes, corrected.

L985: "Presentation at the 1st ROMEX Workshop April 17, 2024 at EUMETSAT, ..." I think you mean: "Presentation at the 2nd ROMEX Workshop February 27, 2025 at EUMETSAT, ..."

Response: Yes, corrected.

L1077-1081: The reference can be updated since the final revised paper has been published.

Response: Yes, updated.

Supplement:

There are detailed discussions in the figure captions of Figs. S1.2-S1.8, which corresponds to Fig. 12 in the paper. Wouldn't it be better to have these discussions in the text in the paper?

Response: We added a reference to the detailed discussions in the Fig.12 caption: "Larger versions of the panels with some comments on each level are presented in the Supplement (S1)." There are quite a few comments and to add them all in the caption of Fig. 12 would make a very long caption.

More information on what is shown in the three panels of Fig. S2.1 should be added to the figure caption.

Response: We have added comments to the caption of Fig. S2.1.

I think some of the N bias maps (Figs. S2.7 and S2.8) depend significantly on the use of a climatology in the statistical optimization at high altitudes (cf. my comment to L138-141.).

Response: We agree, but we are evaluating the UCAR-processed data and hence use the statistical optimization used in the UCAR processing. The effect of the statistical optimization on the refractivities is mainly above 40 km, and we do not discuss refractivities above this level in this paper.

Fig. S3.1: Why show this figure again?

Response: We want to have the vertical profiles of the CSY uncertainties in the same place as the global maps of the CSY uncertainties so the reader has all of them in one place.

Fig. S6.1: It seems that N is affected by climatology above 30 km, and there is no positive bias relative to ERA5 at 40 km, as there is in bending angle (Fig. S5.1). Could you comment on it in the Supplement (or in the paper)?

Response: The relationship between BA and N is non-local so there is not a one-to-one correspondence between the BA biases and the N biases at all levels. We added a comment to the caption of Fig. S6.1.

Fig. S6.6: "All three missions have similar distributions." I think that is an overstatement. I see significantly larger positive biases for C2, which is also seen in Fig. S6.1. Do you have an explanation for that? (cf. also my comment to Figure 18 in the paper).

Response: We have deleted the statement about similar distributions. We discuss the complicated C2 biases vs. ERA5 biases in the paper.

End of responses to Reviewer 2