Response to Referee #1

General response

We sincerely thank the referee for the careful reading of our manuscript and for the constructive comments. The comments helped us improve both the methodological rigor and the clarity of the presentation. In the revised manuscript, we (i) distinguished grid-cell occupancy from area-weighted surface coverage, (ii) recalculated the principal coverage statistics, (iii) redesigned the relevant figures, (iv) clarified the temporal representativeness of the analysis, (v) removed the ERA5-based retrieval evaluation, and (vi) expanded the discussion of regional data gaps. Our point-by-point responses below identify the exact sections, figures, tables, equations, additions, and deletions involved.

Major comment 1

Comment: Are lat/lon bin boxes the best choice for this analysis when the area size of the boxes has extreme variation on a global scale? Consider whether it might be better to use boxes of equivalent area coverage for some of the calculations. If this is not possible, please consider if there are any options for presentation/display or calculation that can help compensate for the different spatial coverage of the binning boxes with latitude.

Response: We agree that assigning equal weight to all latitude–longitude grid cells can overrepresent high-latitude regions because their physical areas decrease with latitude. We therefore retained the regular latitude–longitude grid for reproducibility and direct comparison among missions, but replaced the principal unweighted coverage results with area-weighted surface coverage. The revised manuscript now explicitly distinguishes grid-cell occupancy (the fraction of grid cells containing at least one event) from area-weighted surface coverage (the fraction of the Earth's gridded surface area represented by occupied cells).

The recalculation changes the reported magnitudes but not the principal mission ranking or the conclusion concerning multi-mission complementarity. For example, the 12-mission seven-day area-weighted coverage is 92.08%, 99.71%, and 99.995% at 0.5°, 1°, and 2°, respectively, and the mean joint 6 h coverage at 2° is 76.79%. The complete mission-by-mission and time-window values are provided in Table 2 and the corresponding figures.

Changes made in the revised manuscript:

- Section 3.1 (Coverage metrics and statistical methods): added four equations defining grid-cell occupancy, area-weighted surface coverage, the physical area of each spherical

latitude–longitude grid cell, and the area-weighted blank fraction (revised Eqs. 1–4). The later equations were renumbered accordingly.

- Abstract; Sections 3.5, 4.2, 4.4, and 6; Table 2; and Figures 5 and 9: replaced the principal unweighted coverage values with the recalculated area-weighted results and revised the associated interpretation.
- Sections 3.3 and 4.2, and the captions of Figures 3 and 7: replaced the potentially misleading term ‘event density’ with ‘event counts per grid cell’ and explicitly stated that these panels show raw counts rather than counts normalized by physical grid-cell area.
- Figures 2, 3, 6, 7, and 11: replotted the global distributions using the Mollweide equal-area projection so that the displayed map area is proportional to surface area.
- Section 4.4: retained the conclusion that the joint 12-mission configuration substantially increases short-window coverage, while revising all absolute and relative gains using the area-weighted calculation.

Minor comment 1

Comment: Can you make any statement about whether the one-week period is indicative of longer periods?

Response: Thank you for this important comment. The one-week period used in this study should be regarded as a short-term observational sample rather than as being fully representative of longer-term or seasonal conditions. As stated at the end of Sect. 3.5, the four 6 h windows describe the selected day and do not establish that the results are independent of the UTC window. In addition, the final paragraph of Sect. 6 explicitly notes that the seven-day and one-day analyses provide only short-term snapshots of mission sampling characteristics and that longer-term and seasonally stratified analyses are required to assess temporal representativeness. Therefore, the orbital sampling patterns identified in this study may provide a useful indication of the relative characteristics of the missions during the selected period, but the numerical coverage values should not be interpreted as annual or seasonal averages.

Minor comment 2

Comment: ERA reanalysis was used to evaluate observation errors, but some of these observations may have been assimilated.

Response:
We thank the reviewer for raising this important concern. We agree that ERA5 is not a fully independent reference because GNSS-RO observations from some missions may have been assimilated into the reanalysis. Moreover, differences in the geographical and latitudinal sampling of the missions complicate a direct global comparison of their departures from ERA5.

In response to this comment and to related concerns raised by another anonymous referee regarding the interpretability of the inter-mission comparison, we have reconsidered the scope of the manuscript. We have removed former Sect. 5 in its entirety, including the ERA5-based bending-angle and refractivity comparisons, Fig. 12, and Eqs. (6)–(13). We also removed the description of the ERA5 dataset from Sect. 2.2 and revised the abstract, introduction, and conclusions to eliminate statements concerning inter-mission retrieval accuracy. The revised manuscript now focuses more clearly on the spatiotemporal sampling characteristics, coverage, and complementarity of the GNSS-RO missions. We believe that these revisions address the reviewer's concern and avoid presenting the ERA5 comparison as an independent assessment of retrieval accuracy.

Minor comment 3

Comment: Figure 9 uses wedges whose perceived magnitude is influenced by area.

Response:
We agree that the original radial/wedge representation visually encoded the values by area and could exaggerate differences. Figure 9 has therefore been replaced by a three-panel linear comparison plot. The panels correspond to the 0.5°, 1°, and 2° grids; the four rows in each panel represent the four UTC windows; gray points show the individual missions; the blue point marks the best individual mission (Yunyao-1); and the orange diamond marks the 12-mission joint coverage. A horizontal segment reports the joint-coverage gain in percentage points. Because all values are read from a linear horizontal axis, the visual magnitude is now directly proportional to the reported percentage.

Changes made in the revised manuscript:

- Figure 9: deleted the original wedge diagram and inserted the new three-panel linear comparison plot.
- Figure 9 caption: added an explicit explanation of the gray mission points, the best-mission marker, the 12-mission joint marker, and the percentage-point gain.
- Section 4.4 and Table 2: updated the surrounding text and numerical summary to match the redesigned figure and the area-weighted calculations.

Minor comment 4

Comment: Consider using an equal-area projection for the maps.

Response:

Thank you for this helpful suggestion. We agree. We selected the Mollweide projection, which, like Gall–Peters, is an equal-area projection but provides a compact global view that is well suited to the present distributions. We emphasize that the projection addresses visual area distortion, whereas the area-weighted formulas in Section 3.1 address the quantitative weighting of grid cells; both changes were made.

Changes made in the revised manuscript:

- Figures 2, 3, 6, 7, and 11: replaced the previous global map projection with the Mollweide equal-area projection.
- Relevant figure captions: revised the map descriptions to match the new projection and retained the stated latitude–longitude grid resolution.
- Section 3.1: added physical grid-cell-area weighting so that the numerical coverage statistics do not depend on the visual projection alone.

Minor comment 5

Comment: The paper by D. L. Wu (2024) is relevant to the observational gap over Russia and Ukraine.

Response:

Thank you for this relevant reference. We added it to the discussion while keeping the causal interpretation appropriately cautious. The revised text explains that Wu (2024) identified interference signatures using normalized RO signal-to-noise ratio at deeply occulted tangent heights (HSL < -140 km) and reported affected regions extending across the Mediterranean, Eastern Europe, and the Middle East toward Russia. We also clarify that this evidence does not directly demonstrate a reduction in the number of retrieved atmospheric profiles in our dataset; quality control, data transmission, and data-access restrictions remain plausible contributing factors.

Changes made in the revised manuscript:

- Section 3.2, in the paragraph discussing the localized Russia–Ukraine gap: added the Wu (2024) evidence, its diagnostic basis, and its geographical context.

- Section 3.2: added a caution that the cited interference study does not by itself prove profile-count loss in the present dataset, and retained alternative explanations.
- Reference list: added Wu, D. L.: 'GNSS Signal Jamming as Observed From Radio Occultation', IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 17, https://doi.org/10.1109/JSTARS.2024.3385738, 2024

Technical corrections

Technical correction 1: Mathematical formatting

Comment: Line 180: n_i(r) should be in math style.

Response:
Corrected. The symbol n_i(r) and the other variables introduced with the coverage metrics are now consistently formatted as mathematical notation.

Changes made in the revised manuscript:

- Section 3.1: standardized the mathematical formatting of n_i(r), N_r, A_i, and related variables in the text and equations.

Technical correction 2: Lower limit in the former Equation 10

Comment: Equation 10: is this r_a or r_t?

Response:
Thank you for identifying this ambiguity. The intended lower limit was r_t. However, the former Equation 10 belonged to the ERA5-based retrieval-evaluation section, which has now been removed in response to Minor comment 2. Therefore, the ambiguous equation no longer appears in the revised manuscript.

Changes made in the revised manuscript:

- Deleted the former Equation 10 together with the entire former Section 5 and renumbered the remaining equations.

Response to Referee #2

General response

We sincerely thank the referee for the careful and constructive assessment of our manuscript. The comments helped us sharpen the scope of the study and strengthen the interpretation of the sampling results. In the revised manuscript, we (i) added the missing GeoOptics context and clarified the data-access scope, (ii) expanded the discussion of the relevance of spatial and local-time sampling to NWP, climate, and space-weather applications, (iii) added the ROMEX context, (iv) reframed the COSMIC-2 analysis as a diagnostic sampling-exclusion scenario, (v) redesigned Figures 9 and 10, (vi) replaced the general COSMIC-2 reference with a more appropriate peer-reviewed source, and (vii) removed the ERA5-based retrieval-comparison section in its entirety. Our point-by-point responses and the corresponding manuscript changes are provided below.

General comment and scope of the mission overview

Comment: This paper is a useful summary of the orbits and spatiotemporal coverage of almost all of the radio occultation (RO) missions, starting with GPS-MET in 1995 through the commercial missions in 2026. The exception is the absence of GeoOptics (launch in 2017, Chang et al., Earth, Planets and Space, 2022, https://doi.org/10.1186/s40623-022-01667-6). Although the paper has the potential to be a good contribution to the scientific literature, it can be improved in several ways.

Response: Thank you for noting the omission of GeoOptics. We agree that GeoOptics is an important commercial GNSS-RO provider and should be acknowledged in an overview of the development of RO missions. GeoOptics observations were not available to us through the two data channels used for the 1-7 January 2026 analysis, namely the WMO Global Telecommunication System and the operational products authorized by the China Meteorological Administration. GeoOptics could therefore not be included in the quantitative comparison.

We have added GeoOptics and the CICERO constellation to the mission-development overview and cited Chang et al. (2022). We have also clarified throughout the manuscript that the quantitative analysis covers 12 mission systems available through the specified data channels and is not intended to be an exhaustive analysis of every operating RO mission.

Changes made in the revised manuscript:

- Figure 1 and Section 2.1: added GeoOptics/CICERO to the mission-development context and summarized its role as a commercial GNSS-RO constellation.
- Section 2.2: stated explicitly that GeoOptics data were not available through the two data channels used during the analysis period and therefore were not included in the quantitative comparison.
- Abstract and Introduction: replaced potentially exhaustive wording with a precise description of the 12 mission systems accessible through the stated data channels.
- Reference list: added Chang, H., Lee, J., Yoon, H., Morton, Y. J., and Saltman, A.: 'Performance assessment of radio occultation data from GeoOptics by comparing with COSMIC data', Earth, Planets and Space, 74, 108, https://doi.org/10.1186/s40623-022-01667-6, 2022.

Major comment 1

Comment: The Abstract states that the paper "assesses the benefits of multi-mission integration and the potential effects of COSMIC-2 retirement on the integrated observing capability." However, it does not discuss the impact (benefit) of RO observations in the three application areas of RO-space weather, climate, and weather prediction and why complete coverage of Earth every day and all local times is important in these applications. Therefore, it is unclear why differences in space and local time are important, what the benefits are of multi-missions, or what the impacts of the loss of COSMIC-2 will be. For example, do the gaps over the Russia-Ukraine region make any difference in the accuracy of NWP forecasts or climate data records? Are the extremely small differences between the combined 11 missions excluding

COSMIC-2 (black lines) and combined 12 missions including COSMIC-2 (red lines) in Fig. 10 important? Why is coverage of all local times important?

Response: We thank the referee for this important comment. We agree that the original manuscript did not sufficiently explain the application relevance of spatial and local-time sampling and that its wording could be interpreted as claiming application impacts that were not directly evaluated.

We have revised the Abstract, Introduction, Results, and Conclusions to distinguish sampling capability from demonstrated application performance. For NWP, observations distributed within short assimilation windows can provide broader constraints on spatially varying analysis errors, but their forecast impact depends on observation quality, error treatment, redundancy, and the data-assimilation system. We therefore cite ROMEX as an example of the application-specific experiments needed to quantify the forecast impact of increased RO observations. For climate applications, stable sampling across latitude and local time helps limit sampling errors associated with incomplete representation of the diurnal and semidiurnal cycles and with changes in the observing-system composition. For ionospheric and space-weather applications, latitude and local time are important because electron density structures and ionospheric irregularities exhibit pronounced equatorial, regional, and diurnal variability.

We have also clarified that complete coverage should not be interpreted as requiring every location to be observed at every hour of a single day. Rather, broader spatial and local-time coverage reduces dependence on individual orbital configurations and provides more representative sampling of spatially and temporally varying atmospheric and ionospheric conditions.

The discussion of the Russia-Ukraine gap has been made explicitly cautious. We retain it as an observed spatial feature and cite Wu (2024) as evidence that GNSS interference can affect RO signal tracking, but we do not claim that the gap has a demonstrated effect on NWP accuracy or climate records. Such an assessment would require a dedicated observing-system or data-denial experiment.

We agree that the nearly overlapping 11-mission and 12-mission curves in the original Fig. 10 did not clearly communicate the contribution of COSMIC-2. Figure 10 has therefore been redesigned to show the absolute COSMIC-2 contribution and the percentage reduction caused by its exclusion in each latitude band. Within 5°S–5°N, excluding COSMIC-2 reduces the number of RO events from 5,539 to 4,334, corresponding to a loss of 1,205 events or 21.75%. The revised discussion therefore describes the global change as modest but the equatorial sampling loss as locally substantial. We emphasize that this is a diagnostic sampling-exclusion result and not direct evidence of degradation in weather forecasts, climate records, or space-weather products.

Changes made in the revised manuscript:

- Introduction: added two paragraphs explaining the relevance and limitations of spatial and local-time sampling for NWP, climate, and space-weather applications.
- Introduction and Discussion: added the ROMEX context and clarified that observation quantity and coverage do not translate linearly into forecast improvement.
- Abstract: replaced the broad phrase ‘assesses the benefits’ with wording that specifies the sampling changes quantified by the analysis.
- Section 3.2: revised the Russia-Ukraine-gap discussion to separate the observed sampling feature from untested forecast or climate impacts.
- Figure 10： replaced reliance on two nearly overlapping total curves with explicit absolute and relative COSMIC-2 contributions by latitude.
- Section 4.5: renamed the section ‘Sampling contribution of COSMIC-2 to the multi-mission observing system’.
- Conclusions: distinguished improved observational sampling from demonstrated changes in forecast skill, climate-record uncertainty, or space-weather prediction performance.

Major comment 2

Comment: The brief section on the comparative performance of all the RO missions is weak and misleading. The details of the ROPP method for calculating bending angles from ERA5, including equations 8-10, are unnecessary, because ROPP is well documented. A much shorter summary of the ROPP method with references would be sufficient.

Response: We agree. More importantly, after considering this comment together with the concern about the very different geographical and latitudinal sampling of the missions, we concluded that shortening the ROPP description alone would not resolve the underlying comparability problem. We have therefore removed the former Section 5 in its entirety, including the detailed ROPP description, the ERA5-based bending-angle and refractivity comparisons, former Eqs. (6)-(13), and former Fig. 12. The revised manuscript now focuses consistently on spatiotemporal sampling, coverage, and multi-mission complementarity.

Changes made in the revised manuscript:

- Deleted the entire former Section 5, including the ROPP methodological description, former Eqs. (6)-(13), and former Figure 12.
- Deleted the ERA5 dataset description from Section 2.2.
- Removed statements concerning inter-mission retrieval performance from the Abstract, Introduction, and Conclusions, and renumbered the remaining sections and equations.

Major comment 3

Comment: The RMS differences between RO and ERA5 include the bias differences, which is also shown separately. Therefore, it would be preferable to show the standard deviation of differences instead of RMS differences.

Response: Thank you for this observation. We agree that the standard deviation of the differences would distinguish random variability from the mean bias more clearly than RMSE. However, because the entire ERA5-based comparison has been removed

in response to the broader sampling-comparability concern (Major comment 4), neither the RMSE nor the bias profiles are retained in the revised manuscript.

Changes made in the revised manuscript:

- Deleted the former RMSE and mean-bias analysis together with the former Section 5 and Figure 12.

Major comment 4

Comment: I assume the ERA5 data are interpolated to the positions and times of the RO data, but this is not stated. The most important issue, however, is the large sampling differences among the different RO missions. It is well known that the biases and standard deviation of errors in RO vary strongly with latitude, as well as with longitude. Both biases and uncertainties are much larger in low latitudes compared to high latitudes; therefore, comparing COSMIC-2 with the other missions globally as is done here is meaningless. I suggest eliminating Section 5 entirely.

Response: We agree with the reviewer's central concern. The large differences in geographical, latitudinal, and local-time sampling among the missions confound the original global comparison. In particular, the predominantly tropical sampling of COSMIC-2 cannot be compared directly with that of near-polar missions without controlling for latitude, longitude, season, atmospheric state, and the possible statistical dependence of ERA5 on assimilated RO observations.

We have therefore followed the reviewer's recommendation and removed the former Section 5 rather than attempting to interpret the differences as mission-dependent retrieval performance. The ERA5 description has also been removed from Section 2.2, and all claims about retrieval accuracy have been deleted from the Abstract, Introduction, and Conclusions.

Changes made in the revised manuscript:

- Removed the former ERA5-based inter-mission comparison in full.

- Revised the stated scope of the paper so that all remaining conclusions concern sampling characteristics and coverage complementarity rather than retrieval accuracy.

Minor comments

Minor comment 1

Comment: Adding spacing between paragraphs and references would make the paper easier to read.

Response: Thank you for this suggestion. We have revised the paragraph structure. We also checked the spacing and formatting of the reference list while retaining the AMT manuscript style.

Changes made in the revised manuscript:

- Adjusted the spacing between entries in the reference list as suggested.

Minor comment 2

Comment: A reference to the Radio Occultation Modeling Experiment (ROMEX; https://irowg.org/ro-modeling-experiment-romex/) would be useful. A special issue of AMT that describes the benefits of increasing numbers of RO observations is available at https://amt.copernicus.org/articles/special_issue1367.html.

Response: We agree and have added the ROMEX framework to the Introduction. The revised manuscript cites Anthes et al. (2024) and relevant work from the AMT ROMEX special issue. This context explains why observation number, spatial distribution, and multi-mission sampling complementarity are relevant to NWP while also showing that forecast impact depends on observation quality, bias treatment, error correlations, and the configuration of the assimilation system.

Changes made in the revised manuscript:

- Introduction: added a description of ROMEX as a coordinated multi-centre experiment designed to quantify the NWP impact of increased RO observation volumes.

- Discussion: added a description of ROMEX and cited Anthes et al. (2024) to clarify the role of application-specific NWP experiments.
- Reference list: added Anthes, R. A., Marquardt, C., Ruston, B., and Shao, H.: 'Radio Occultation Modeling Experiment (ROMEX): Determining the impact of radio occultation observations on numerical weather prediction', Bull. Amer. Meteor. Soc., 105, E1552-E1568, https://doi.org/10.1175/BAMS-D-23-0326.1, 2024.

Minor comment 3

Comment: Some of the references are not ideal or the best available, e.g. Jaeggi et al., 2021 for COSMIC-2 in line 84. More detailed peer-reviewed references are available, for example Schreiner et al. 2020, https://doi.org/10.1029/2019GL086841.

Response: We agree. We replaced the conference-abstract citation of Jaeggi et al. (2021) in the general COSMIC-2 mission description with the more comprehensive peer-reviewed study of Schreiner et al. (2020). We also corrected the observation-volume statement: the revised text refers to up to approximately 5000 RO profiles per day for the six-satellite constellation rather than more than 1000 profiles per satellite per day.

Changes made in the revised manuscript:

- Section 2.1, COSMIC-2 description: replaced Jaeggi et al. (2021) with Schreiner et al. (2020) for the general mission and measurement characteristics.
- Section 2.1: corrected the daily observation-volume statement to describe the constellation total.
- Reference list: ensured that the full Schreiner et al. (2020) peer-reviewed reference and DOI are provided.

Minor comment 4

Comment: Some of the figures need more interpretation. For example, what are the different colors in Fig. 9? Why are the very small differences between the four parts of Fig. 9 important?

Response: We agree that the original radial/wedge representation did not explain the visual encoding sufficiently and could exaggerate small differences because wedge area varies nonlinearly with radius. Figure 9 has been replaced by a three-panel linear comparison plot. The panels correspond to the 0.5°, 1°, and 2° grids; the four rows represent the four UTC windows; gray points show the individual missions; the blue point marks the best individual mission (Yunyao-1); and the orange diamond marks the 12-mission joint coverage. A horizontal segment reports the joint-coverage gain in percentage points.

The revised text now states that the differences among the four UTC windows are comparatively small for the combined dataset and should be interpreted as short-term descriptive variability for the selected day, rather than as evidence of a systematic dependence on UTC window.

Changes made in the revised manuscript:

- Figure 9: replaced the wedge diagram with a three-panel linear comparison plot using a common, directly interpretable scale.
- Section 4.4 and Table 2: revised the interpretation and numerical summary to match the redesigned figure and the area-weighted coverage calculations.

Minor comment 5

Comment: Section 4.3-impact of C2 retirement. What impact would this have on weather forecasts, climate, and space weather?

Response: Thank you for this important suggestion. We agree that the consequences of changes in COSMIC-2 sampling for weather forecasting, climate applications, and space-weather monitoring deserve further quantitative investigation. The sampling-exclusion analysis presented in this study provides a basis for such assessments by identifying the latitude bands and spatial scales most affected by the removal of COSMIC-2. Building on these results, we plan to conduct application-specific experiments in future work, including data-assimilation or data-denial experiments for numerical weather prediction, longer-term sampling-error analyses for climate

applications, and targeted assessments of ionospheric and space-weather products. These experiments will enable the practical impacts of reduced COSMIC-2 sampling to be quantified more directly. We have added this future research direction to the revised manuscript.

Changes made in the revised manuscript:

- Former Section 4.5: changed the title and scope from a general retirement impact to a diagnostic assessment of COSMIC-2 sampling contribution.
- Abstract: replaced broad application-impact language with a precise description of the sampling changes under the COSMIC-2 exclusion scenario.
- Conclusion: added an outlook on future application-level assessments of COSMIC-2 sampling changes for NWP, climate applications, and space-weather monitoring.