Responses to Comments

We sincerely thank Editor Eriksson, and two anonymous reviewers for the constructive and thoughtful comments.

Comment are in *blue italic lettering*, responses in black.

Reviewer 1 Comments

General Comments:

The manuscript describes and evaluates a synergistic methodology to retrieve ice-cloud microphysics from synergistic radar and radiometer observations and provides. The evaluation is based on synthetic observations derived from a numerical weather prediction model. Overall, I find the manuscript well written and informative. However, the fact that radar and the radiometer are characterized by significantly different Field of Views (FOVs) should be addressed (or at least thoroughly discussed) in the manuscript. Specifically,

The radar considered in the manuscript is a nadir-looking instrument similar to the Cloud Profiling Radar (CPR) of the CloudSat mission, while the radiometer is a conically scanning instrument with a view angle of 450 from the nadir. While the radiometer's horizontal resolution is not specified, it is presumably coarser than that of the radar. It is not clear from the manuscript whether this aspect was considered in deriving the synergistic retrievals. In principle, one can account for the fact the that two instrument's FOVs are not the same, but the performance of the retrievals or the computational effort may be significantly different from those obtained when using simplifying assumptions. This should be discussed in the manuscript.

Thanks for your general comments very much, and sorry for not mentioning the difference in horizontal coverage and viewing geometry between the active and passive sensors in the previous manuscript. This study focuses on investigating the synergistic retrieval performance when the fields of view are perfectly coincident. We have added specific statements in section 2.4 for the assumptions, as shown in Lines 113-120 in the revised manuscript. We also mention the simplifications in the summary section, as shown in Lines 507-510. The questions regarding the influence of footprints and viewing angles are great, and we will try to address them in future work once those characteristics are known.

Minor Comments:

Page 5, Line 110. How exactly are the radiative transfer calculations done? Is the plane- parallel assumption made? Are any attempts to account for 3D effects made, such as slant-path calculations (Bauer et al., 1998)?

The radiative transfer model in this study runs at the 1D atmosphere mode. As mentioned above, we assume that both sensors always have the same fields of viewing at nadir angle, and the 1D atmosphere could work well under such simplifications. The discussion could also be seen in Lines

113-120. 3D simulations are much more advanced in actual retrievals, but they are beyond the scope of the present study.

Page 7, Line 155. I assume this means a finite difference scheme. If so, it is probably better to just call it a finite-difference scheme, as perturbation may be confused with the ensemble approach.

This sentence has been rephrased to state the finite difference approach. The meaning of perturbations in the revised context should be clear now. Please check it in lines 160-162.

Page 14, Line 323. These results are rather idealized than analytical.

The present idealized retrieval experiments are done under a lot of assumptions such as the same fields of viewing, very simplified cloud species, single ice cloud habits, etc. We indicate these simplifications in different sections such as lines 109-111, lines 113-120, and the lines 507-510. We will keep improving the forward model and retrieval algorithms in the following work.

Page 15, Line 335. Water vapor may be a significant source of uncertainties in the radar retrievals. It would be useful to investigate how the radiometer-retrieved water vapor impacts the synergistic retrievals.

Thanks for your suggestion very much. Water vapors influence radiative transfer in (sub)millimeter significantly, and it is definitely worth investigating this problem more deeply. We currently only have IWC and NC as the state variables in the synergistic retrievals, as indicated in section 3.3 in lines 296-300. We mention that we neglect the impacts from water vapor variability in the summary section, as shown in line 525. A general way to see the impact of the water vapor in radiative transfer is through the figure 8, which shows the Degrees of freedom as a function of the integrated water vapor. More complicated simulation experiments will be done in the following studies to make the ACCP assessments more realistic.

Reviewer 2 Comments

General comments:

The authors made a conceptual study about a synergistic microwave (MW) radar and MW/SubMM(submillimeter)-radiometer retrieval. The topic of the study is similar to the study of Pfreundschuh et al. (2020, AMT). Main differences are the different retrieval methods and that the authors' study is more restricted to a simpler atmospheric setup. The authors compare the synergistic retrieval to radar only and radiometer only retrieval. The synergistic retrieval is a combination of an optimal estimation (OEM) retrieval for the radar and Bayesian Monte Carlo integration for the radiometer. The basic story of the study is clear. The authors first define the hypothetical sensors, then explain the retrievals and retrieval databases, and show and discuss the results.

Despite the basically clear general story, the study is partially confusingly written and needs some restructuring. Some examples:

The retrievals are described in Sect. 3 but the actual values for the different thresholds, minimum numbers etc. are given in Sect. 5. This would make sense, if several retrieval configurations for each of the three retrievals were used, but this is not the case. The same holds for the actual retrieval quantities. They are given in the text of Sect. 5 but even there it is difficult to grasp what are the actual retrieval quantities, for example is log(IWC) or IWC a retrieval quantity.

In Sect. 4.2, it seems that the retrieval database is described but then the authors suddenly write about ensemble generation.

Update Sect. 3 explicitly stating for each retrieval the retrieval quantities, the measurement quantities, the assumed non-retrieval quantities, and all the retrieval specific a priori assumption, thresholds, minimum numbers etc.. Additionally, please do not mix ensemble generation and retrieval database.

Thanks for the general comments regarding the manuscript structure. Following your advice, we add a new subsection 3.3 to explicitly state the measurement space and state space in this work, as shown in lines 287-300 in the revised manuscript. Also, the algorithm configurations such as the threshold and number of cases in the ensemble approach are stated when we discuss the corresponding retrieval algorithms in section 3, such as the Lines 195-200, Lines 249-253 show. Further, the prior PDF calculation step has now been transferred to the EnPE algorithm description in section 3.2.2, as can be seen in lines 272-285.

As I understand your paper, the idea is to combine a conical scanning radiometer with nadir pointing radar. This has two implications that you did not address in your study:

It is very unlikely that both sensors will have the same footprint.

Due to the different viewing geometry, both sensors have a different view on the atmosphere.

I think, it is not needed to expand your study to include these effects, because focusing on a 'best case' retrieval is still a formidable task. Nonetheless, you should explicitly mention that you neglect any footprint or viewing geometry effects and discuss at least briefly the implications.

Thanks for your advice. We have added comments that we do not consider the footprint and viewing angles in this study in the simulated observation and the summary sections, as can be seen in lines 113-120 and lines 507-510. The influence of different fields of view and horizontal resolutions between active and passive remote sensors will be addressed in future work once we better understand the specifics of the sensors that will be flown.

Section 1 Introduction

p. 3, l. 51: "The retrieval results are obtained through interpolation over the precalculated databases." Neural network retrievals are not an interpolation over a database.

This sentence has been deleted.

Section 2 Simulated observations

2.1 Remote sensors
Please include information about assumed footprint sizes and write explicitly the assumed viewing geometry of both sensors.

The footprint and scanning modes of the radar have been added, as shown in lines 69-70. The assumption on the viewing geometry when simulating the observations and conducting retrievals are specified in section 2.4, as shown in lines 116-120.

p. 4, l. 77-78: Put the channel description including noise, channel number, main spectral feature (H2O-line, O2-line, window...), etc. into a table and refer to it.

p. 4, l. 80: Please insert a sketch with the viewing geometry of the sensors.

The noise characteristic of the candidate radiometer is listed in Table 1. However, we are not allowed to disclose too many details beyond the critical parameters in the simulation experiments because it will harm the competitive postures of the instrument teams. Also, the final instruments parameters may differ from what was assumed in the study. More information about the instrument designs will be published by the ACCP instrument teams when those instruments are established and known, as we indicate in lines 77-79.

p. 4, l. 79: "Most frequency channels are centered on water vapor absorption lines." Change to something like this: 'The 183 GHz and 380 GHz channels are centered around H2O lines and the other channels are centered around the O2-line or a place within the window region.'

This sentence has been revised following your advice, as shown in Lines 73-75.

2.2 Reference cloud scenes

p. 5, l. 94-95: "The reason for these simplifications is still to be consistent with the a priori database that will be discussed in section 4." Did you consider the possible errors due to this simplification?

We do not investigate the consequences of this simplification in this work, but we do continue to improve the simulation experiments including the differentiation of hydrometers to better assess the ACCP remote sensor. More result discussions in this aspect will be done in future work.

p. 5, l. 97-100: What is the horizontal spacing between each model profile and what is the actual horizontal grid size of the ECCC model?

The horizontal resolutions of the ECCC model and the dataset we used are both 250 meter, as shown in line 96.

2.3 Radiative transfer model

Does the radar simulator includes attenuation?

Yes, the radar forward model includes the attenuations.

p. 5, l. 106-108: Please add what kind of particle size distribution (PSD) including used parameter and constants you used.

The particle size distribution used in the ARTS model has been added, as shown in lines 113-114.

p. 5, l. 109-110: Please include briefly the other forward configurations here and not by just referring to the other paper.

More information about the ARTS model, including the scattering solvers, gas absorption database, and the surface module has been added, as shown in lines 101-103.

2.4 Simulated observations

p. 5-6, l. 116-119. In the text you wrote cloud ice and in your figure 3, you distinguish between snow and ice but in Sect. 2.2 (p.4, l. 93), you write: "...we do not differentiate the cloud ice and snow...". Please be consistent or explicitly state in the corresponding lines you distinguish between ice and snow. Otherwise it can be confusing.

The plots in figure 3 have been updated.

3 Hybrid Bayesian algorithms

p. 6, l. 135: "...and it[BMCI] is highly efficient since the retrievals are done by interpolating the database cases" BMCI is strictly speaking not an interpolation.

This sentence has been corrected, as can be seen in line 142.

3.1 Radar-only retrievals

p. 7, l. 158: "...where K is the Jacobian matrix to linearize the forward model." Is K the Jacobian matrix of the retrieved state or of the a priori state? Please clarify within the text.

The K is the Jacobian matrix of the retrieved state, as shown in line 165.

3.2.1 Synergistic radar and radiometer retrievals

p. 8, l. 182-183: What are "standard normalized vectors". Please explain it within the text. Furthermore, do you generate only profiles of IWC and NC or do you generate also temperature and humidity profiles?

The "standard normalized vectors" has been changed to "a vector of standard Gaussian deviates", as shown in line 189. The state variables in different algorithms have been summarized in section 3.3 in lines 296-300. Since the ensemble is generated from the covariance matrix obtained by the radar OEM algorithm, the state vectors in synergistic and in radar-only retrievals are consistent, and they only contain IWC and NC.

3.2.2 Radiometer-only retrievals

p. 9, l. 197-202: I understand that you want to give a brief explanation of your retrieval. Nonetheless, your algorithm is complex. Therefore, I suggest to add a flowchart/algorithm chart especially in the view that you want to give a brief explanation of your retrieval algorithm.

It is a good idea to add a flowchart to summarize the improvements of the EnPE algorithm and to make the algorithm more understandable. This flowchart has been added in Figure 5.

p. 9-10, l. 209-211: "Following this step, the sampling module starts by reselecting the cases according to their posterior value to multiply cases with high weights and kill cases with low weights, and the weights of the selected cases become equivalent again." Please rephrase it. The sentence is hardly understandable.

This sentence has been corrected, as shown in lines 227-228.

p. 10, l. 211-214: "The sampling module then adds correlated random noise to the selected cases using the two-point correlation statistics in the covariance matrix. The covariance matrix is computed using the posterior PDF based on Bayesian MCI..." I do not fully understand what do you mean with "cases". Is this an atmospheric state or is this the whole database entry including brightness temperature and full atmospheric state? Is the mentioned covariance matrix calculated from the full atmospheric state or just from the retrieval quantities? Please clarify within the text.

The "cases" represent the selected state vectors from the resampling module, and we mention it in lines 242-244. The covariance matrix is only computed for the retrieval quantities, as shown in line 230.

p. 10, l. 218-221: Please consider to use mathematical formulas and equations.

Formula of this step has been added, as shown in Eq. (8)

p. 10, l. 222-223: "...the algorithm evaluates these cases based on the prior PDF and likelihood PDF,..." Please explain, what "likelihood PDF" and "prior PDF" in that context mean? Is "prior PDF" the PDF of the previous iteration? Please clarify within the text.

The "likelihood PDF" is calculated in the measurement space, and we have changed it to "conditional PDF" to be consistent, as seen in line 246. The prior PDF is discussed in the last part of subsection 3.2.2, as shown in lines 272-285. Also, clear mathematical relationships could be found in the flowchart shown in Figure 5.

Section 4 Prior information

I would suggest to rename this section to 'retrieval databases', because this is the actual topic of this section.

The section has been renamed as retrieval database.

4.1 Radar retrieval database

Please add a sentence for what you need this database, because at first view it seems strange to have a retrieval database for an OEM retrieval.

The discussions have been added in lines 321-326.

p. 11, l. 254: How and where do you get the temperature information?

The temperature is measured by the Meteorological Measurement System on the DC8 aircraft platform, as shown in lines 309-310.

4.2 Radiometer retrieval database

p. 13, l. 305-306: According to Eriksson et al. (2020, AMT) and the citation therein "E" is a matrix with each column an eigenvector. Please correct.

The meaning of E has been corrected, as shown in line 356.

p. 14, l. 313-316: Please add the noise quantities to a table with the other channel specific properties, see also my comment about 2.1 Remote sensors.

The noise quantities have been added in Table 1, and we specify the measurement uncertainties used in the retrieval experiments in lines 293-295.

Section 5 Retrieval simulation experiment and results

p. 14, l. 331: "Similarly, the Gaussian noise of 1K is added to the simulated BT observations in each channel to characterize the measurement accuracy of the submillimeter-wave radiometer,..." Why do you add only 1 K of noise to the simulated observations? The noise values in given in Sect. 4.2 are much higher. This seems to make no sense.

The noise added into the simulated observations and that used in the retrievals are now consistent, as stated in section 3.3 in lines 293-295.

p. 15, l. 336: "For the radiometer-only retrievals, except for the IWC and NC profiles, we retrieve the water vapor profiles as well." The sentence is confusing. Please rephrase.

This sentence has been deleted, and the state variables for all retrievals are now specified in section 3.3 in lines 296-300.

p. 15, l. 352-353: "The EnPE optimization and the final MCI computations are done directly in the state space, not in the logarithmic space." Some lines above (l. 348) you wrote "The Bayesian MCI computation is also done in logarithmic space". Please explain why do make a difference?

We find that the EnPE passive-only algorithm works better in the non-log state space, as we indicate in lines 299-300.

p. 15, l. 356-357: Why is the radiometer retrieval (Figure 8) so noisy?

p. 16, l. 363-365: Do you have any idea, why the synergistic retrieval is noisier than the radar-only retrieval?

The ensemble approach generally makes the results noisier, but I am not sure if the noise is in a reasonable range. It seems like the retrievals are especially noise for the thin cloud with IWP smaller than 100 g m-2. We will try other methods to see we can make it more smooth in the following work.

p. 16, l. 380-381: What do you mean with "non-Rayleigh effects and attenuation"? Please explain within the text.

This description has been deleted.

p. 16-17, l. 371-396: Please add some discussion about the consequences that you use a combined PSD for snow and ice within your retrieval. For me, it seems, that some of the bias in IWC of the radar retrievals is due to fact that you do not separate between ice and snow.

We add a sentence saying a possible reason for radar-only bias is that we do not differentiate the cloud ice and snow in the forward model, as shown in line 403. We will do more work in this aspect.

p. 17, l. 400: What is meant with "retrieval uncertainty" and how do you estimate it?

The retrieval uncertainty is created by different retrieval algorithms associated with the retrieved quantities, and we indicate in lines 420-421.

p. 18, l. 414-415: Please add a sentence explaining what an error of 1 dB corresponds to.

This sentence has been added, as shown in line 435.

p. 18-19, l. 414-438: Your error unit seems to be wrong. For example, according to Figure 10 (top left) for true IWC of 10^-5 g/m^3 the maximum error ratio is about 10^-4, which corresponds to -4 B or -40 dB. Your error values in dB are off by a factor of 10.

I agree that the unit of logarithmic error definition in Eq(14) should be B instead of dB, and we have corrected all the units in both manuscript and figures.

p. 18-19, l. 430-438: Please discuss the CDFs of Figure 13 or remove them.

The CDF plots has been deleted.

p. 19-20, l. 439-463: Except for the IQR the plots of Figure 14 seem to show no added value. Remove them or show the added value.

The PDF plots are good, but we always need quantitative parameters to assess the retrieval accuracies and make the comparison more straightforward. The top two panels are used to directly compare with the results in Figure 11 in Pfreundschuh et al., (2020), and the bottom panels show the statistics of the absolute retrieval errors, and they serve as the ultimate quantitative parameters for the assessments. We will keep these plots here.

p. 20, l. 459: Please define explicitly and explain the median fractional bias. An equation could be helpful.

A sentence saying that “50% of the retrievals have an error less than the median error, and 50% have a larger error” is added, as shown in lines 478-479.

Section 6 Summary and conclusions

Please add some (short) comments comparing your results to Pfreundschuh et al. (2020, AMT) and about your main retrieval assumptions (viewing geometry, footprint sizes, no liquid ...).

The comments are added in lines 510-512.

Figures and Tables

Figure 1:
Please mark in the spectrum plot the relevant spectral lines and features. For example, add an ‘O2’ to the 118 GHz line and so on.

The spectral features have been added.

Figure 2:
Within the study, you do not distinguish between ice and snow. Therefore, replace “Frozen (Ice + Snow) Water Content” with ‘ice water content’. Furthermore, replace “water content (WC)” with ‘ice water content’ (IWC).

The text has been revises.

Figure 3:
Combine ice water path and snow water path.

Done

Figure 8:
Replace “Ice + Snow Water Content” and “Ice + Snow Number Concentration” with ‘Ice water content’ and ‘Number concentration’, respectively.

Done

Figure 9:
Unit of the y-axis is wrong.

Figure 10:
IWC and IWP units are wrong.

Figure 11:
IWC and IWP units are wrong.

Figure 12:
IWC and IWP units are wrong. Furthermore, the error unit is wrong. The given numerical values correspond to ‘B’ not ‘dB’.

Figure 13:
The unit for the PDF seems to be missing.

Figure 14:
The unit of the y-axis is missing.

The units are all corrected.