RESPONSE TO RC1

We thank the reviewer for the detailed assessment and constructive feedback. The answers to each comment are detailed below in blue.

General Comments:

In this paper, the authors compare coherent and incoherent L-band emission models by simulating radiometric measurements conducted in the Canadian Arctic, applying an optimal estimation method to reduce uncertainties.

While the idea of using a coherent model to explain in-situ measurement with a small footprint is novel and potentially feasible, its extension to satellite-scale footprints remains unclear. Overall, the method and results require further investigation and validation before the work reaches the standard expected for publication in a journal such as The Cryosphere. I therefore recommend major revision.

Specific Comments:

1) Introduction

It is stated that coherence is often neglected in practical modelling and satellite retrievals. In contrast to local measurements with ARIEL, which have a footprint as small as 1m, satellite footprints typically extend over several kilometers, implying that coherent effects are likely averaged out at larger scales. This raises an important question regarding to the applicability of the coherent approach beyond local measurement. A more detailed discussion on the scale dependency of coherence and its relevance for different observation platforms is necessary.

The present work focuses on interpreting the in situ measurements collected with ARIEL. The objective is to assess which modelling approach, coherent or incoherent, better reproduces the observed signal. In this context, the main contribution of the study is to demonstrate that coherent effects can occur at the local scale, something that has not previously been shown for a dataset such as the one analysed here.

We agree that the relevance of these effects at the satellite footprint scale is an important question. Satellite observations integrate signals over areas spanning several kilometres, and coherent effects may be partially or fully averaged out. However, investigating how local-scale coherence propagates to larger spatial scales is beyond the scope of the present study. We have therefore limited our analysis to the interpretation of the ARIEL measurements and added text to clarify this point. The potential impact of coherent effects on satellite retrievals remains an important topic for future research.

2) Field study and data preparation

A detailed description of ice conditions surrounding the measurement sites would be beneficial. For instance, what is the distance between the three sites, and what is the spatial extent of the SAR image used? Are the measurements done on first-year ice floes? What do the different backscatter responses indicate, do they correspond to different ice types? Referring to table 1, there is no clear gradient in ice and snow thickness across the three sites. What about the ice salinity and ice temperature? In which range do they vary?

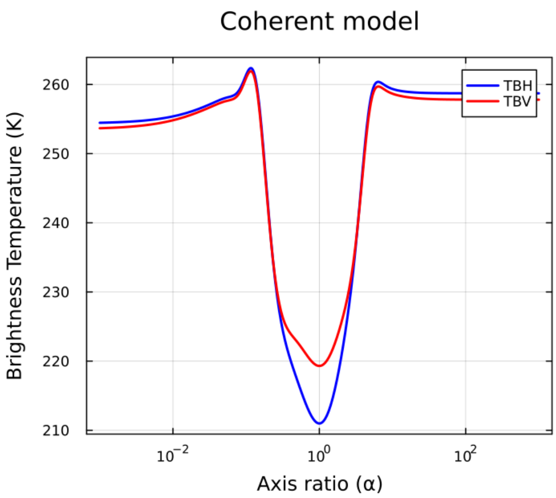
The three sites were located at approximately 5 km (CLO), 10 km (MID), and 12 km (FAR) from the CHARS base, with CLO and MID separated by ~11 km, CLO and FAR by ~13 km, and MID and FAR by ~2 km. The SAR image covers an area of approximately 15 × 15 km, encompassing all three sites. As detailed in the manuscript, the SAR image indicates that the different sampled sites were grown at different times. Therefore, all of them represent FYI, so being the same ice type but with slightly different thicknesses.

The sea ice temperature and salinities measured per site are shown in Figure 4, as their priors correspond to the ice core data. As shown, the temperature has a range of variation of around 10°C between sites, while the salinity is fairly constant, varying less than 2 between sites. We agree that the terminology of calling in situ measurements a “prior” for the optimal state estimation is maybe a bit confusing. Our intention was to allow the optimal model state to adjust the in situ values within their uncertainty ranges to find the state of highest probability, the maximum a posteriori (MAP) state. We will clarify this part in the manuscript.

3) Emission modelling

The axis ratio appears to have a strong influence on the penetration depth. It would be therefore be helpful to quantify the sensitivity of the brightness temperature to this parameter. For example, how much does TB change when the axis ratio changes from 4 to 6 keeping the other parameters constant?

The figures below (R1 and R2) show the TB as a function of the axis ratio for both modeling approaches, fixing T_{ice} = −10°C and S_{ice}= 5. As shown, TB is clearly influenced by variations in the axis ratio overall, although the effect is more limited in the 4 to 6 range. Nevertheless, the 5 to 10 K variation within this interval provides sufficient flexibility for the optimization to adjust meaningfully. In general, in the presented approach, varying the axis ratio, salinity and temperature independently within their realistic borders allows us to shape the probability distribution of the permittivity. To further clarify this in the manuscript, a reference to [Hernández-Macià et al., 2026] has been added, as Figure 1 in page 7 shows the permittivity (and so TB) dependence on the axis ratio.



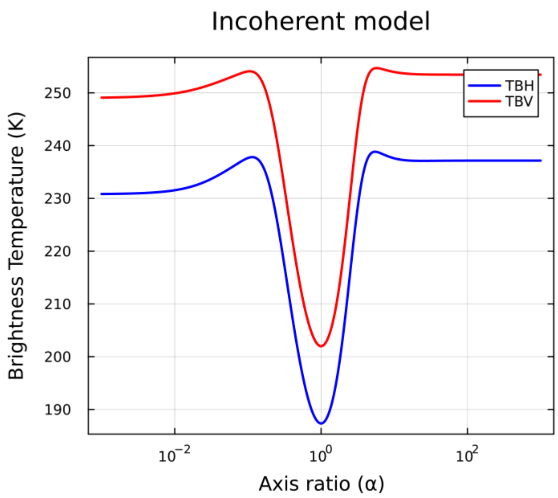


Figure R1. Brightness temperature modeled with the coherent (left) and incoherent (right) approaches, as a function of the axis ratio of the brine inclusions modeled as ellipsoids. The sea ice conditions are fixed as T_{ice} = -10ºC and S_{ice} = 5.

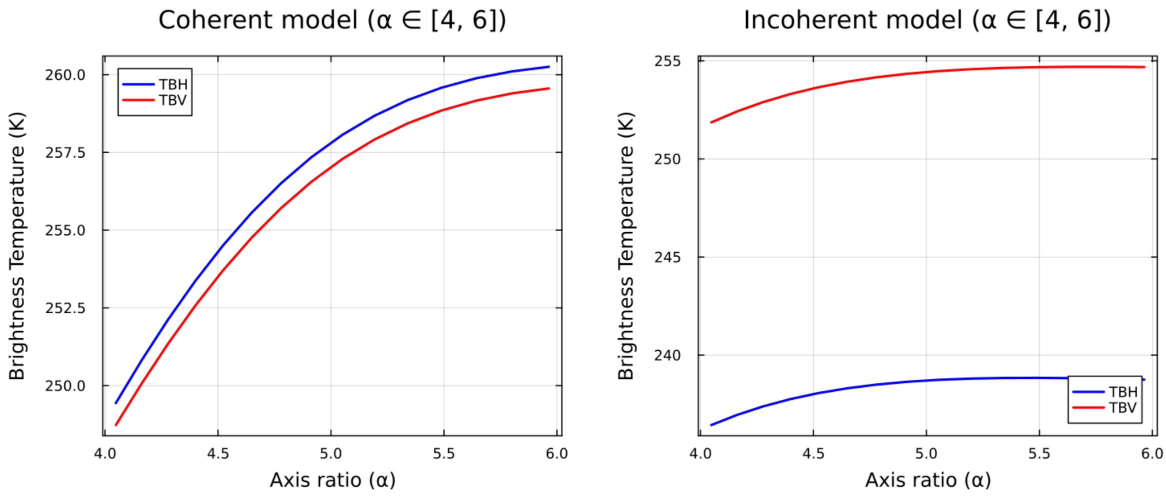


Figure R2. Brightness temperature modeled with the coherent (left) and incoherent (right) approaches, as a function of the axis ratio, limited between 4 and 6, of the brine inclusions modeled as ellipsoids. The sea ice conditions are fixed as T_{ice} = -10ºC and S_{ice} = 5.

4) Model-based optimization of measurements

The quality of Optimal Estimation depends strongly on the quality of the forward model and parameter sensitivities. If the forward model itself has many assumptions and simplifications, the estimated values can be biased. Furthermore, the error covariance and prior covariance can strongly affect the results. It would be interesting to see how the coherent and incoherent models perform without OE? Could they reproduce the measured TBH and TBV? Does the coherent model still outperform the incoherent model without OE method? If so, it would be useful to quantify the difference in performance and clarify the physical reasons.

We thank the reviewer for this valuable comment, which makes us realize that our framing of the methodology with “similar to optimal estimation”, meant as a familiar entry point for earth observationalists, instead obscured what we were actually doing.

Firstly, our procedure is not geophysical retrieval but more of a forward constrained consistency check. Traditional OE retrieval uses a state vector with unknown geophysical variables which are estimated from the instrument measured brightness temperatures. This makes the concern of the reviewer regarding the forward model assumption and corresponding biases very valid. In our case, the state vector is a set of measurements with their own uncertainties, and most of the variables are very much constrained by these uncertainties instead of being more or less freely retrieved as in typical OE. As stated in the text around Eq. 2, there is no fundamental asymmetry in the lefthand side (y, the TB space) and righthand side (x, the state space). Both are mainly measured quantities connected through the forward model F. The minimization of the cost function is therefore not a retrieval of the state, but asks the question if the given state with its associated uncertainty is explainable by each forward model given the measurement of the instrument and the given instrumental uncertainties.

Beside the difference of accounting for the phase of the electromagnetic field, both forward models are identical in practice and follow the same assumptions. Any bias coming from the forward model-assumptions or from the choice of the S_ϵ or S_a, is therefore affecting cost in both models. The differences in the cost between the models is thus directly related to the difference in the model (coherent vs non-coherent) and not to the OE configuration. We agree however, that an unreasonable assumption in the forward model could penalize one model more than the other. The state of all variables are and corresponding assumptions align with the stated source.

The "without the OE" comparison is hard to evaluate. The metric for evaluating a mismatch of TBs to a given state with uncertainty, related over a model, is essentially the OE cost function in Eq. 2. However, we will perform the forward simulation for the given physical state and the corresponding evaluation of the brightness temperature mismatch below.

For assessing and showing how the models perform without OE, now Figure 4 has been split in two figures. The geophysical variables that are optimized will be shown in the same figure, but the original third row will be included as a new figure (shown below, Figure R3). This will show not only the ARIEL-measured and the optimized TBs, but also the TBs computed with the prior values of the geophysical variables. The optimized value generally lies between the observation and the prior simulation. This figure decoupling is also very convenient because now there is one plot for the geophysical priors (the x_a) and the measurements (y), thus having both parts of the cost function discussed separately

To further assess this, both the coherent and incoherent forward models can be run using fixed prior parameters (the same prior mean values used in the optimization) together with the in situ measured snow depth and sea ice thickness, without any parameter optimization (see Table 2 in the manuscript). The results are presented in the new Figure R4 below, clearly showing that the coherent model better matches the measured TBs, particularly for TBH. In contrast, the incoherent model exhibits an almost flat response, failing to follow the 1:1 line.

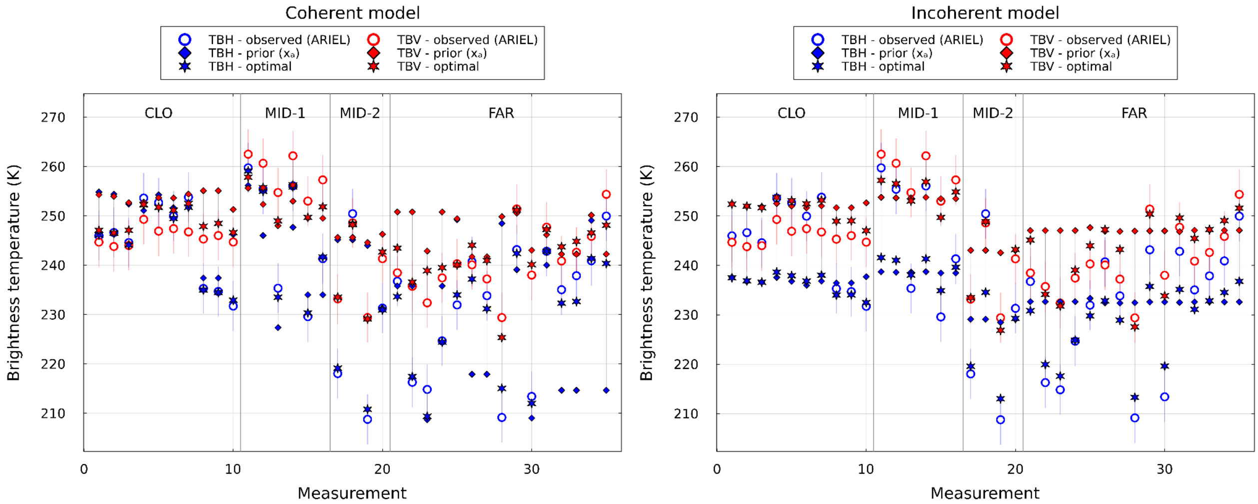


Figure R3. Brightness temperatures TBH and TBV for each measurement in each sampled site, for the coherent (left) and incoherent (right) forward models. The optimal values are shown as stars, the ARIEL measurements are shown as open circles with their uncertainties as error bars, and the brightness temperatures obtained by evaluating the forward model on the prior geophysical state x_a (i.e. without optimization) are shown as diamonds.

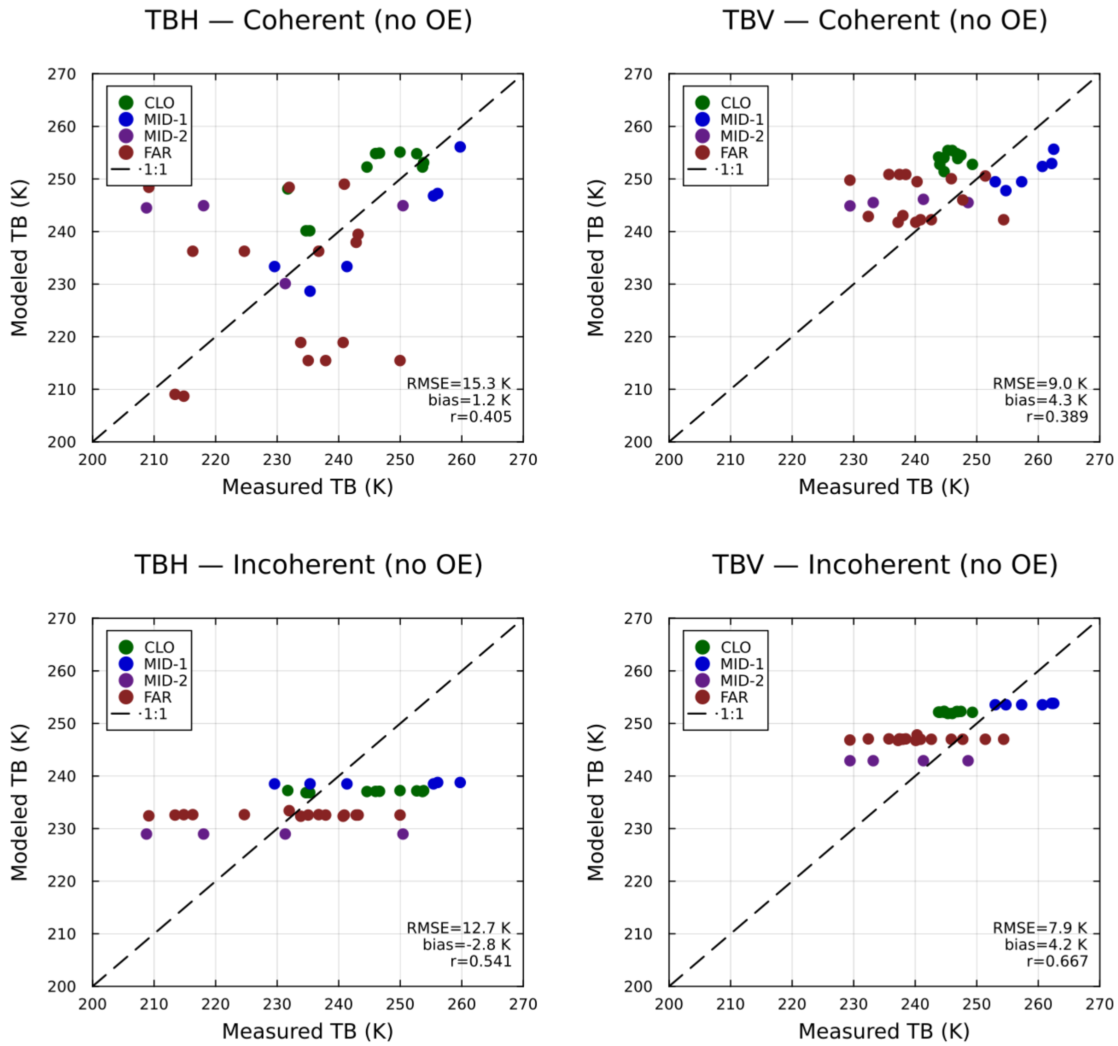


Figure R4. Scatter plots of measured versus modeled brightness temperatures for the coherent (top) and incoherent (bottom) forward models applied without Optimal Estimation, using fixed prior parameters and in situ measured snow depth and sea ice thickness. Left and right columns show H- and V-polarization, respectively. Colors denote the four measurement scenarios: CLO (green), MID-1 (blue), MID-2 (purple), and FAR (dark red). The dashed line is the 1:1 reference. Overall RMSE, bias, and Pearson correlation coefficient (r) computed across all scenarios are annotated in the bottom-right corner of each panel.

5) Results and discussion

In Figure 4, optimized snow density varies strongly in site FAR. What is the reason for such strong variability in snow density compared to other sites? Is there any physical explanation why the optimized axis ratio varies strongly from measurement to measurement?

The variability in the optimized snow density, in particular in the coherent model, originates from the fact that the snow density measurements in that region were highly variable, resulting in a wide prior. During the optimization this value is particularly tweaked by the optimizer to better match the brightness temperatures observed. The snow density has a similar effect as the snow depth on the brightness temperatures and thus slightly modifies the effective path length of EM field propagation in the snowpack through its influence on the snow permittivity. Because of interference, this strongly influences the brightness temperatures. On the opposite side, the snow depth has no effect on the brightness temperatures as per model configuration in the incoherent model and the snow density is weakly related to the permittivity and thus has a little influence on the TBs, in the incoherent model.

Particularly, the strong variability observed at the FAR site is likely related to the limited number of measurements available there compared to the other sites. As FAR was the least sampled site, the optimization is subject to larger uncertainties, which can result in a greater spread of the retrieved parameters.

Page 11 " even though the incoherent model shows more variation as it relies on these variables, alongside the axis ratio, to change the permittivity trying to match the low PD of some measurements. For the same reason, the optimized axis ratio presents more variation for the incoherent model." I can't agree with this statement. The low PDs appear when snow depth is about 5 cm (e.g. in Site CLO), for these measurements Coherent model shows more variation in axis ratio. This might be the reason that Coherent model produces low PD and high TBH.

We agree that the original wording was unclear and could lead to a misleading interpretation. The text has been revised accordingly in the manuscript.

Our intention was not to suggest that the incoherent model necessarily exhibits a larger spread in axis ratio for all measurements. Rather, we meant that the coherent model is able to reproduce the low PD values observed in some cases through the inclusion of coherent effects, while requiring only small adjustments to the retrieved physical parameters. In contrast, the incoherent model cannot reproduce these low PD observations. As a result, the optimization attempts to compensate by adjusting the physical variables, including the axis ratio and therefore the effective permittivity, but still converges towards solutions that do not fully reproduce the observations, in particular around 5 cm of snow depth.

It might be interesting to plot axis ratio and PD in both models. The parameter axis ratio is not measured and cannot be validated. What happens if axis ratio is not included in the parameter list for OE? Do the results change?

The axis ratio is among the temperature and salinity the parameter which can influence the permittivity of the medium. Not including it in the OE parameter list means either, fixing it to a value of unknown representativeness, or changing to another permittivity parameterization for sea ice. By including the value as part of the optimization we allow a slight deviation from a permittivity determined by a fixed temperature and salinity combination. We illustrate the consequences of fixing the axis ratio by explicitly providing the figures requested.

The PD comparison (Figure R5) reveals an important difference between the two models. The coherent model reproduces the measured PD across the observed range (approximately −10 to +30 K), with points distributed along the 1:1 line across all sites. In contrast, the incoherent model predicts a nearly constant PD of approximately 10–15 K, regardless of the measured value.

To assess the sensitivity of the results to the inclusion of α in the state vector, we repeated the OE with α fixed at its prior value ($\alpha = 5$) for both models. The results are shown in Figure R6, where the coherent model better reproduces the observations for both polarisations even when the axis ratio is fixed and excluded from the OE.

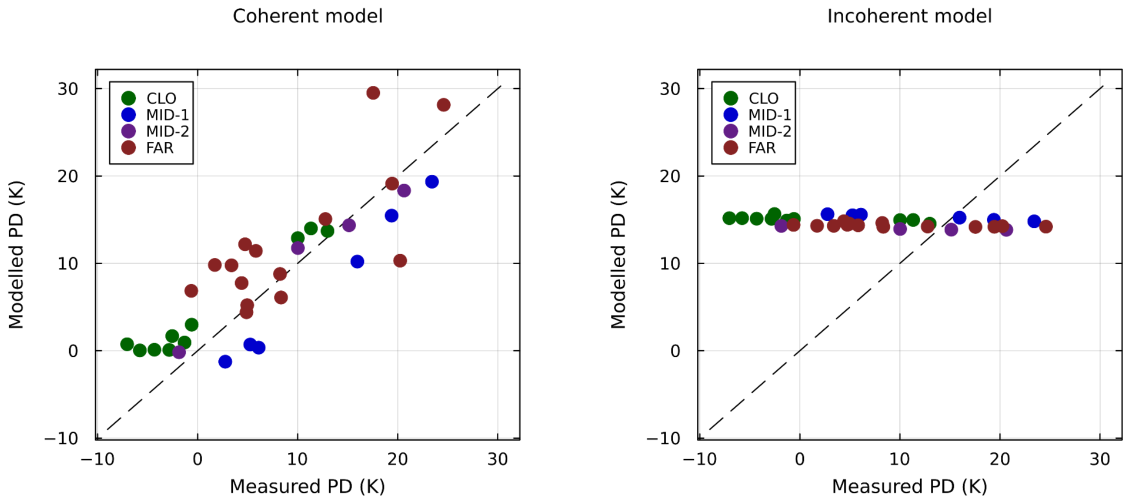


Figure R5. Measured vs. modelled polarisation difference (PD) for the coherent (left) and incoherent (right) models; the dashed line indicates the 1:1 relationship. Points are coloured by measurement site (CLO, MID-1, MID-2, FAR).

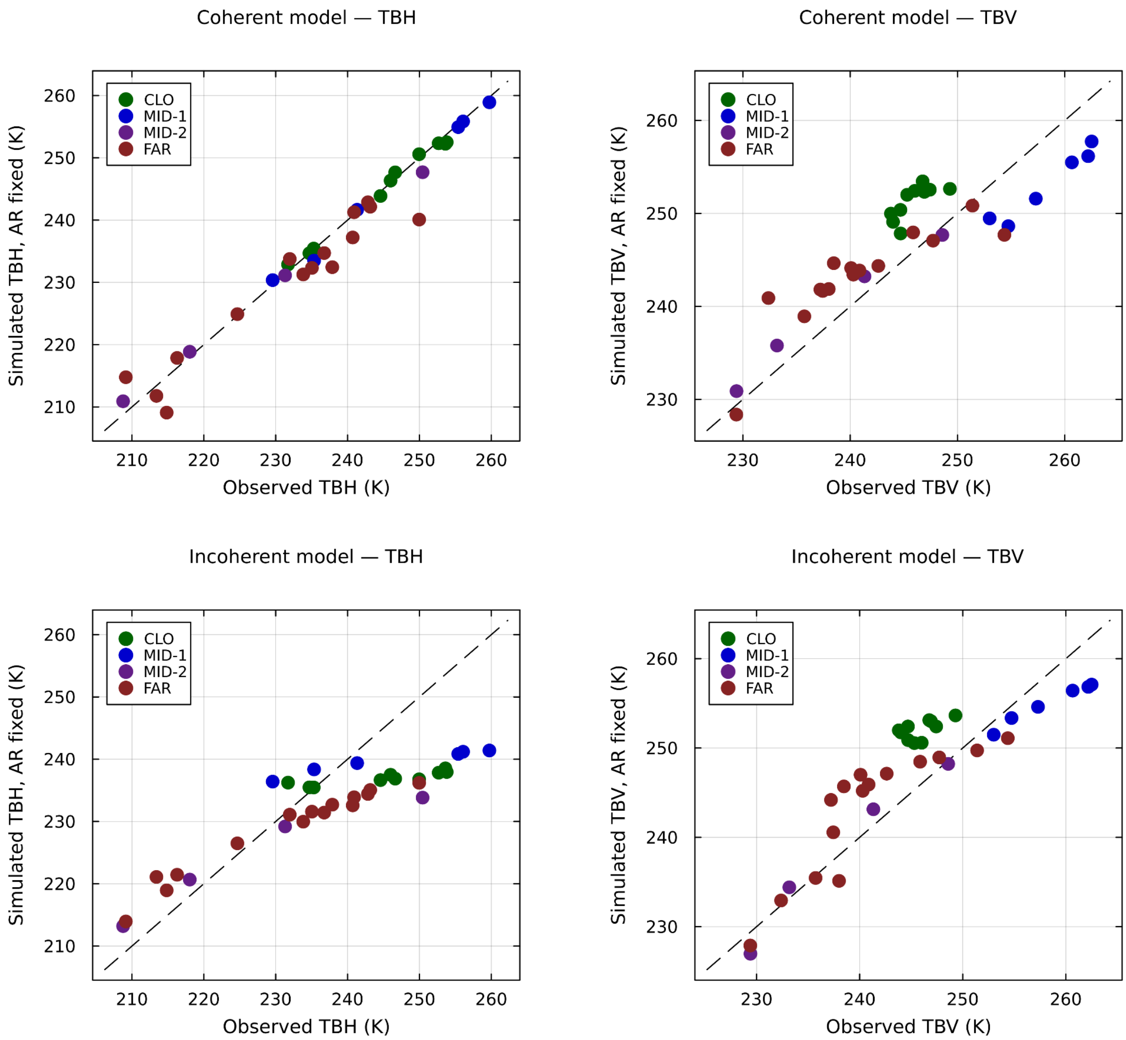


Figure R6. Observed versus simulated brightness temperatures from the optimal estimation (OE) retrieval performed with the axis ratio fixed at its prior value, for the coherent and incoherent models. Top row: coherent model; bottom row: incoherent model. Left column: horizontal polarisation (TBH); right column: vertical polarisation (TBV). Each point corresponds to one measurement, coloured by site (CLO, MID-1, MID-2, FAR); the dashed line indicates the 1:1 relationship.

Technical Corrections:

Aside from those pointed out by the reviewer, many other typos have been corrected in the manuscript.

Page 2 Line 49: a opening -> an opening

Corrected in the manuscript.

Page 9 Line 200: 0.005-0.01 cm -> m

Corrected in the manuscript.

Page 11 Line 220: even thought -> even though

Corrected in the manuscript.

Page 11 Table 2: Snow Uncertainty unit should be m here

Corrected in the manuscript.

References

[Hernández-Macià et al., 2026] Hernández-Macià, F., Escorihuela, M. J., Gabarró, C., Sanjuan Gomez, G., and Garcia-Mondéjar, A.: A Novel Synergistic Approach Using Altimeter Backscatter for an Improved Radiometer Thin Sea Ice Thickness Retrieval, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-422, 2026.