Answers to reviewer 2

October 31, 2025

This paper addresses a critical issue for passive remote sensing of clouds from infrared spectral measurements. Previous measurements (e.g., Bantges et al 2020) indicated inconsistency in the ice droplet properties in the current database, which leads to difficulty in achieving radiance closure across the visible-MIR-FIR spectra in the measurements. This paper revisits this inconsistency issue using the measurements from a new campaign with a different deployment strategy, i.e., measuring cloud spectra from ground as opposed to airborne. I found this study has a well-motivated objective and a great potential to help found methods utilizing future FIR satellites such as FORUM for cloud remote sensing. However, I also found the current manuscript has several major issues. The presentation and interpretation of some results especially raised concerns, which should be addressed before it is published.

We sincerely thank the reviewer for the careful, thorough, and constructive evaluation of our manuscript. The review highlighted important points of uncertainty that required clearer explanation, allowing us to improve the clarity and rigor of our work. At the same time, we greatly appreciate the reviewer's recognition of the potential of this study and the value it can offer to the scientific community. The insightful comments have been instrumental in strengthening and improving the manuscript.

A major comment is that this work, as it currently stands, shouldn't be mistaken as a retrieval test that proves or disapproves the feasibility of retrieving cloud microphysical properties from the FIR spectral measurements. In essence, this is a radiance closure test, showing sensitivity to ice habit as well as other potentially retrievable parameters. If the authors intend to establish this as a retrieval work, the paper needs to more systematically and comprehensively test whether and how the cloud microphysical properties (size, habit, etc) can be "unambiguously" determined from macrophysical ones (optical depth, temperature, etc) and from other atmospheric states (temperature, humidity, ozone, etc). This should be done using both synthetical data with perfectly known truth to quantify such quantities as averaging kernels and degrees of freedom for signals (DFS) and using independently measured cloud data to validate retrievals from actual spectral measurements. For example, the use of atmospheric profiles from ERA5 as both initial guess and validation is unfit to represent an actual retrieval. Moreover, although varying the multiple parameters is shown to lead to reasonable agreement between simulated and measured spectra, there is no proof that there is enough information content to determine them altogether in a real retrieval. In fact, some results, such as the noticeable differences in the sizes "retrieved" when different habits are assumed (Fig 15), suggest there is substantial degeneracy. If this (retrieval) isn't the intention, the paper should be clear about it and avoid misleading claims such as "first retrieval" in Abstract (Line 1) and throughout the paper. It would be more appropriate to state the tests as "adjusting", as opposed to "retrieving", the relevant cloud parameters.

The reviewer is correct in stating that this is a kind of radiative closure test, which is performed using the retrieval technique, but only to "adjust" the state vector of atmospheric parameters among the local minima of the χ^2, because of local variability that cannot be perfectly reproduced. The inversion algorithm allows us to overcome this issue while maintaining consistency between in situ/remote sensing measurements and the model. As stated in our response to Reviewer 1, the retrieval of atmospheric profiles is crucial to achieving consistency among all the available measurements. The reviewer is correct in noting that we lack sensitivity to cloud altitude; however, that is not the goal of our analysis. The reason for using the inversion technique is to "adjust", as correctly suggested by the reviewer, the parameters around the minimum of χ^2, since we cannot know, within the associated uncertainties, how much the measurements should vary in order to achieve full consistency. The retrieval is the only correct and rigorous procedure to do that. This is because local factors and variables come into play that are difficult to account for when setting up the simulation framework, even when attempting to incorporate all available information. We

have made revisions to the text, emphasizing that the retrieval is not the main objective of the work, but rather a means to achieve consistency between the measurements and the model.

We changed the reference to retrieval in the abstract but also in the rest of the manuscript. In particular in the Introduction we emphasized that the sensitivity of FIR to distinguish the habit composition has already shown in previous studies with synthetic observations and a previous consistency study between cloud properties was already performed from Antarctica by using ground-based instruments but, critically, not in situ observations. The sentence we added in the Introduction is the following: "We use these data to provide a well-characterised test of our ability to achieve consistency between measured and retrieved atmospheric temperature and water vapour profiles, ozone total columns and cloud optical and micro-physical properties given currently available parameterizations of ice crystals, with a particular emphasis on demonstrating observationally how FIR radiances can constrain crystal habit. This aspect is well known and has been studied in the literature (Di Natale et al., 2024). However, to the best of our knowledge, the capability to achieve a better consistency with one habit distribution compared to another has never been demonstrated. Furthermore, a previous study of the consistency between the optical and microphysical properties of clouds, exploiting spectral radiance measurements in the FIR together with ground-based data such as radar reflectivity and particle imaging, has already been carried out from Antarctica (Di Natale et al., 2022). However, in these studies remotely sensed cloud microphysics (particle size and habit) were only compared with ground-collected measurements of precipitating ice crystals: they have never before been compared with in situ data acquired inside cirrus clouds, as is done in the present work." Also in Conclusions we have changed the initial sentence as follows: "In this paper, we present the first demonstration of consistency between atmospheric measurements and Arctic cirrus cloud parameterizations by combining information from a ground-based spectrometer and sensors, ceilometer, and radiometer with in situ aircraft observations of cloud particle size and habit.".

Tests demonstrating the robustness of the SACR inversion algorithm across various atmospheric and cloud scenarios have already been conducted and published in several previous works, both using synthetic simulations (Di Natale et al., 2020) and real measurements from different field campaigns Di Natale et al. (2021); Palchetti et al. (2016). In particular, extensive analyses have been carried out in Antarctica, where 11 years of spectral radiance data from the REFIR-PAD spectrometer have been examined. In Di Natale et al. (2020) the first 4 years are published, the complete dataset of 11 years is coming up for publication. This instrument also operates in the FIR, extending down to 100 cm^{-1}. Moreover, a retrieval algorithm specifically designed to derive the habit distribution has already been implemented and validated using synthetic simulations in nadir-viewing configuration for the FORUM mission observations (Di Natale et al., 2024). The results demonstrated that the FIR radiance, when associated with noise of this magnitude, that is similar to FINESSE's above 450 cm^{-1}, exhibits sufficient sensitivity to the ice crystal habits.

As noted in our response to reviewer 1, we have introduced a sensitivity study based on the vertical distribution of the averaging kernels (AK) for temperature and water vapor, as shown in Fig. 1, where it can be seen that the sensitivity for temperature and water vapor is mainly limited to about 1 km and 4 km above the surface, respectively. So, as the reviewer pointed out, there is not much sensitivity to the internal temperature of the cloud. The average degrees of freedom for signal (i.e., the trace of the AK) were found to be 3 and 7, respectively. For this reason, the vertical levels were limited to about 1 km for temperature (3 levels) and to about 9 levels for water vapor below 4 km.

This choice allows us to adjust the profiles around a minimum that is assumed to be close to, but not exactly coincident with, the ERA5 profiles — as indeed turns out to be the case. In this context, there is strong motivation for this approach: ERA5 profiles are not radiosonde measurements but are derived from models and data assimilation. Nevertheless, even radiosondes may not be exactly co-located with the measurements and can be affected by small biases and local variability in the lower atmospheric layers.

For these reasons, we believe that presenting the retrieval of the atmospheric profiles is an integral part of the study and can help colleagues when considering how to approach similar studies in future, so should not be overlooked.

We have added a discussion on this aspect and included the corresponding figure in section 3.1.3 of the manuscript.

ERA5 profiles are not assumed as a priori/initiale guess, to generate these we have perturbed the ERA5 baseline by values reported in Table 2.

The reviewer's points regarding information content (IC) is correct; therefore, we show the distribution of the IC, the correlations between D_{ei}–OD, and the number of degrees of freedom for the different habits. We find that there are essentially no differences in IC and DOFs — up to 0.3/0.4 and 10^{-4}, respectively — and the differences in correlations are smaller than 0.25. The plots are shown in Fig. 2. This indicates that, a priori, there is no greater or lower sensitivity in distinguishing cloud parameters when using different habit distributions. Please see our responses to reviewer 1 for further comments around this general point.

Another major comment is that the paper doesn't provide a clear answer to the motivating questions. For example, is the pan-spectral inconsistency pointed out in earlier works (e.g., Bantges et al) now reconciled, e.g., by using the ground measurements or by considering a HBR habit? Given that

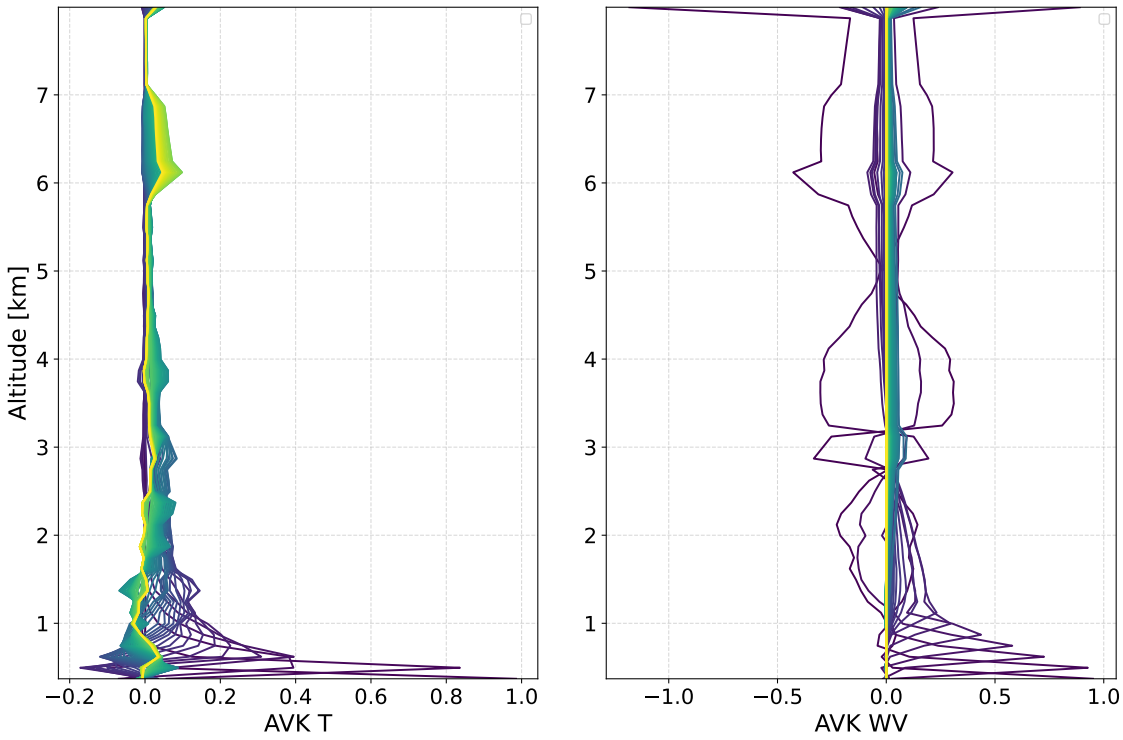

Figure 1: Left panel: vertical distribution of averaging kernels of temperature. Right panel: same for water vapour.

some coauthors here were those who championed the earlier works, I would very much like to see such answers, which would help put this work in context and better identify its value. To these questions, combining Fig 16 with Fig 18/19 and showing how the residuals can (or cannot) be minimized by using different residuals would be helpful. Regarding the ground-based measurement strategy, I would appreciate more discussions on its advantage and disadvantages compared to the airborne approach. For example, the cirrus as visualized in Fig 2 indicates clearly spatial inhomogeneity and, as noted in the paper, varies in measurement time; how does this affect sampling consistency and representativeness of retrieval (e.g., the optical depth) from spectra collected over a finite (200-m) FOV? Reflections on these questions and/or suggestions for future campaigns would be especially useful. A naïve question is: did the airplane affect the cloud fields and exacerbate the inhomogeneity issue, as indicated by the contrails? Fig 16: There seems to be equally discernible signals in MIR (around 800 cm-1), which raises the question on the FIR benefits claimed.

As we also pointed out to Reviewer 1, a dataset of 11 measurements cannot, of course, be representative of the wide variety of scenarios that can occur in nature. However, the range of optical depths between 0.05 and 0.2 represents a typical thin-cirrus case and constitutes a first attempt to demonstrate that it is possible to achieve consistency in the parameterization of cloud microphysics with in situ measurements, although we see that some inconsistencies in the modeling of FIR radiances are still present.

It should also be emphasized that simultaneous measurements of this kind are still rare to date, as they are clearly expensive and logistically challenging. Therefore, we believe that every small step in this direction provides valuable progress in the understanding and modeling of clouds, even with the awareness that much remains to be done. We have attempted to stress this in the revised manuscript.

Regarding the issue of inhomogeneity raised by the reviewer, we can respond that this is a very complex aspect to address and has been extensively studied, starting from satellite observations, where it is necessary to estimate the level of pixel contamination in the signal measured by the instrument (Sgheri et al., 2022). However, unlike those cases — where the area observed by the instrument at cloud level can span several kilometers — in ground-based observations this effect is significantly reduced. In fact, for FINESSE, as mentioned earlier, the field of view (FOV) at cloud altitude is less than 200 m (approximately 180 m), which corresponds to about 1/40 of the circular area defined by the aircraft track shown in Fig. 2. Therefore, the effect of inhomogeneity is strongly mitigated, and we can reasonably assume that the FOV coverage is homogeneous to a good approximation in this case.

To better clarify the imperfect consistency between the simulations and the spectral measurements in the FIR, we calculated, in agreement with previous studies, the mean residuals of all simulations with respect to their corresponding measurements. These were then compared with the mean squared error - defined in Eq. 20 in the text - derived from NESR and calibration, in 13 microwindows used in previous studies (Turner, 2005) as shown in Fig. 4: the root mean square (RMS) of the average residuals in radiance are compared with the average noise in each micro-window. The comparison is shown in Fig. 3, while Fig. 4 presents a histogram of the mean (root mean square, RMS) residual values relative to the measurement error, clearly showing that, while the values fall fully within the error in the MIR, they do not in the FIR. Fig. 4, along with the corresponding explanation, has been added to the text, replacing Fig. 19.

Fig 17 doesn't show convincingly different performance between the two results (with vs without FIR). Even if it did, this wouldn't make strong evidence given the aforementioned degeneracy and strong sensitivity to habit. To elucidate this point, a formal retrieval assessment based on DFS as suggested above would be more quantitative and convincing.

As also replied to reviewer 1, in contrast to the case with different habit distributions, when we consider whether or not to include the FIR component in the retrieval procedure, Fig. 5 shows that IC changes significantly, decreasing from 9 to 6; the correlation between D_{ei} and OD parameters increases notably to about 0.8/0.9, and the difference in DOFs in this case is on the order of 10^{-2} — that is, one hundred times larger than in the case of different habits.

We performed several retrieval tests simulating FINESSE observations, both for the values obtained from the analysis in this work and for other cases with larger optical depths and particle effective diameters. Specifically, we tested the capability of the retrieval algorithm to recover the "true" values with and without including the FIR spectral region. To this end, we generated synthetic observations using the FINESSE noise and two different atmospheric profiles, together with varying cloud parameters — optical depths ranging from 0.07 and 0.18 (representative of the values obtained from the FINESSE measurements) up to 0.8 and 1.5 — while fixing the D_{ei} value at 30 μm .

Our tests demonstrated that the retrieval algorithm is capable of reproducing the true state from synthetic observations whether or not we include the FIR if we fit the observations with habit distribution equal to those used to generate the "truth", as shown in Fig. 6 and 7. However, when we invert the real measurement, we find that we can only match the values measured by INCAS when the FIR is included. This is likely due to the fact that the actual microphysics of the cloud is more complex than what our models can reproduce, and by adding spectral information in the FIR we can approach more closely the absolute minimum of the χ^2 distribution.

The fact that retrievals performed while neglecting the FIR portion yield underestimated effective diameter values compared to those obtained when including the FIR is likely due to the actual microphysical structure of the cloud being more complex than what can be represented by our parameterization. However, a much more detailed investigation would be required to fully explore this, which is beyond the scope of the present work, although it remains an interesting topic for future research. We added the following sentence in the text in section 5: "We would like to emphasize that, based on the FINESSE measurements presented and analyzed, performing the inversion with limited information that excludes the FIR leads to an underestimation of the effective diameter values, but this result cannot, at this time, be generalized to every possible scenario. This clearly calls for a more in-depth investigation, which will be addressed in future work".

In addition, we have modified the abstract as follows: "Furthermore, we show that the radiance information contained within the far-infrared (wavenumbers ¡ 650 cm^{-1}) spectrum is critical to achieving this level of agreement with the in-situ aircraft observations. The results emphasize why it is vital to expand the current limited database of measurements encompassing the far-infrared spectrum, particularly in the presence of cirrus, to explore whether this finding holds over a wider range of conditions."

References

Di Natale, G., Bianchini, G., Del Guasta, M., Ridolfi, M., Maestri, T., Cossich, W., Magurno, D., and Palchetti, L.: Characterization of the Far Infrared Properties and Radiative Forcing of Antarctic Ice and Water Clouds Exploiting the Spectrometer-LiDAR Synergy, Remote Sensing, 12, https://doi.org/10.3390/rs12213574, 2020.

Di Natale, G., Palchetti, L., Bianchini, G., and Ridolfi, M.: The two-stream δ-Eddington approximation to simulate the far infrared Earth spectrum for the simultaneous atmospheric and cloud retrieval, Journal of Quantitative Spectroscopy and Radiative Transfer, 246, 106 927, https://doi.org/https://doi.org/10.1016/j.jqsrt.2020.106927, 2020.

Di Natale, G., Barucci, M., Belotti, C., Bianchini, G., D'Amato, F., Del Bianco, S., Gai, M., Montori, A., Sussmann, R., Viciani, S., Vogelmann, H., and Palchetti, L.: Comparison of mid-latitude single- and mixed-phase cloud

optical depth from co-located infrared spectrometer and backscatter lidar measurements, Atmospheric Measurement Techniques, 14, 6749–6758, https://doi.org/10.5194/amt-14-6749-2021, 2021.

Di Natale, G., Turner, D. D., Bianchini, G., Del Guasta, M., Palchetti, L., Bracci, A., Baldini, L., Maestri, T., Cossich, W., Martinazzo, M., and Facheris, L.: Consistency test of precipitating ice cloud retrieval properties obtained from the observations of different instruments operating at Dome C (Antarctica), Atmospheric Measurement Techniques, 15, 7235–7258, https://doi.org/10.5194/amt-15-7235-2022, 2022.

Di Natale, G., Ridolfi, M., and Palchetti, L.: A new approach to crystal habit retrieval from far-infrared spectral radiance measurements, Atmospheric Measurement Techniques, 17, 3171–3186, https://doi.org/10.5194/amt-17-3171-2024, 2024.

Palchetti, L., Natale, G. D., and Bianchini, G.: Remote sensing of cirrus microphysical properties using spectral measurements over the full range of their thermal emission, J. Geophys. Res., 121, 1–16, https://doi.org/10.1002/2016JD025162, 2016.

Sgheri, L., Belotti, C., Ben-Yami, M., Bianchini, G., Carnicero Dominguez, B., Cortesi, U., Cossich, W., Del Bianco, S., Di Natale, G., Guardabrazo, T., Lajas, D., Maestri, T., Magurno, D., Oetjen, H., Raspollini, P., and Sgattoni, C.: The FORUM end-to-end simulator project: architecture and results, Atmospheric Measurement Techniques, 15, 573–604, https://doi.org/10.5194/amt-15-573-2022, 2022.

Turner, D. D.: Arctic mixed-Phase cloud properties from AERI lidar observation: algorithm and results from SHEBA, Journal of Applied Meteorology, 44, 427–444, 2005.

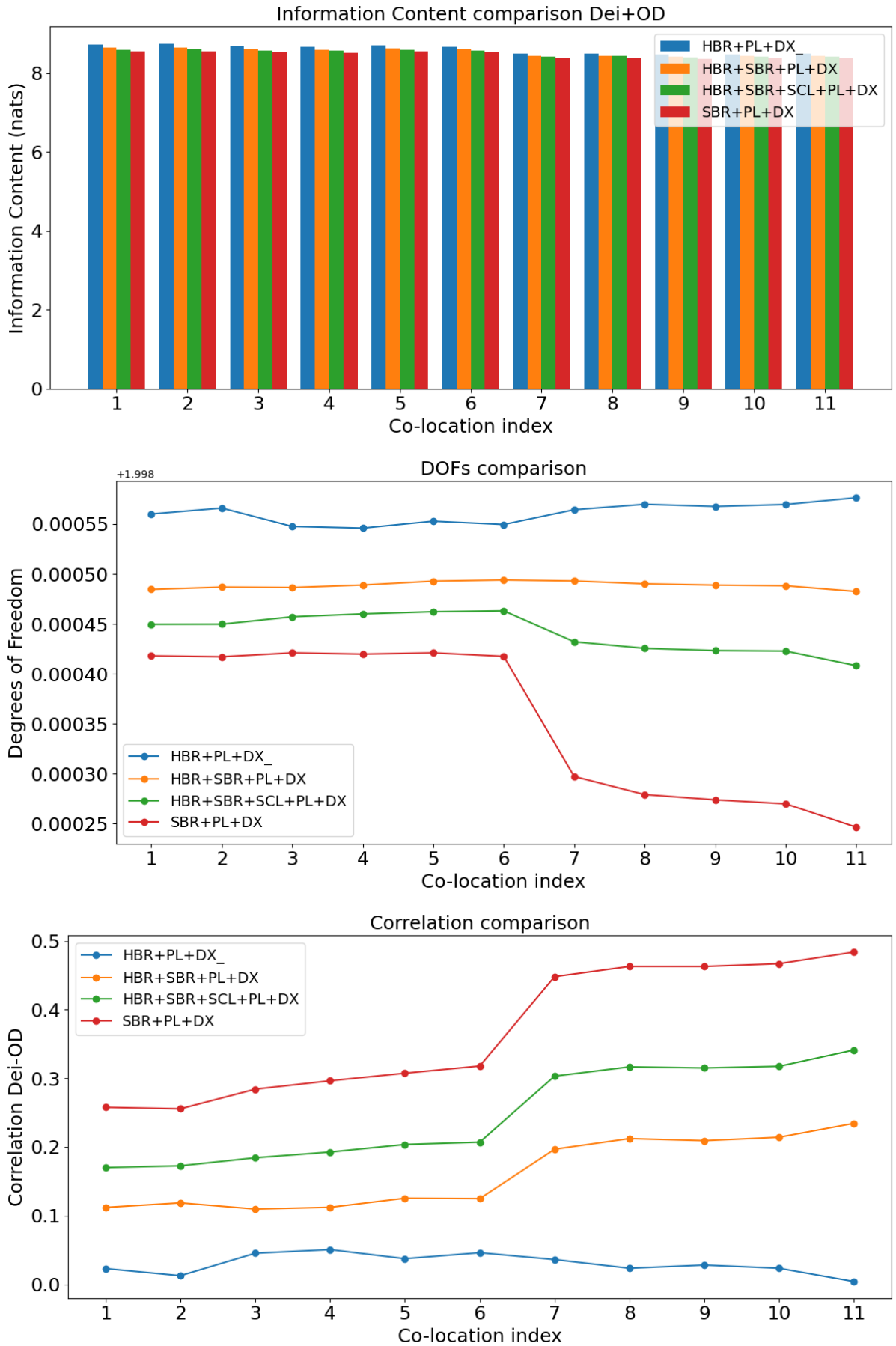

Figure 2: Upper panel:Information content of retrieval for the 4 habit distributions, corresponding to the different colors, considered in the analysis. Middle panel: degrees of freedom. Bottom pane: correlations OD-D_{ei}.

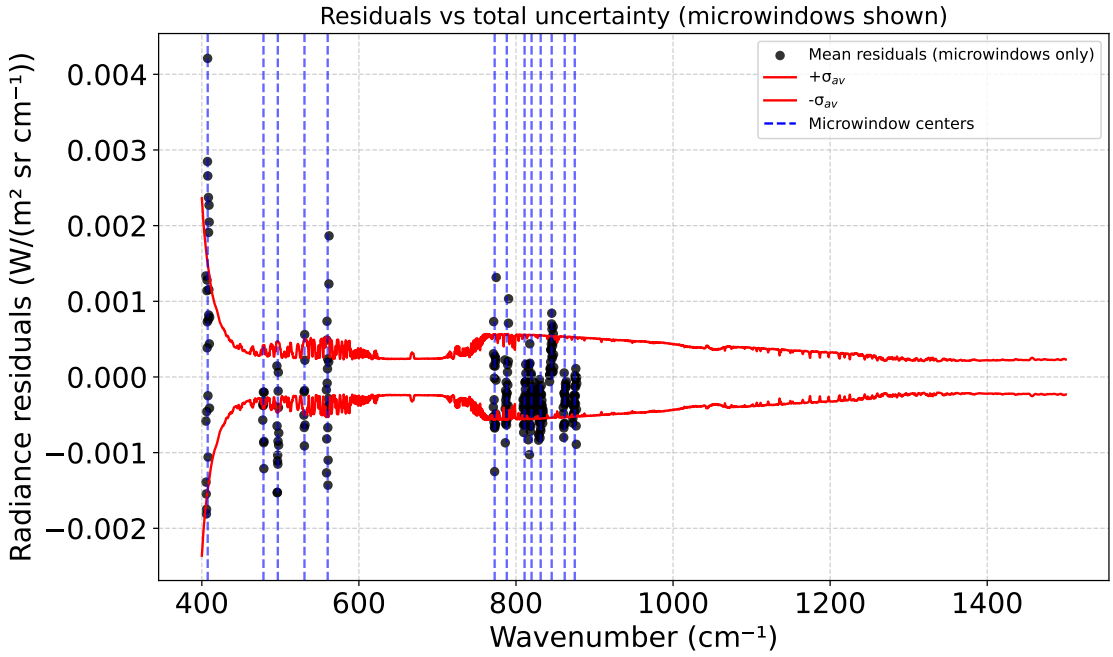

Figure 3: Average residuals (black circles) are reported in comparison with the average noise σ_{av} (red curve) in 13 main microwindows discussed by Turner (2005) indicated by the center band (blue dashed line).

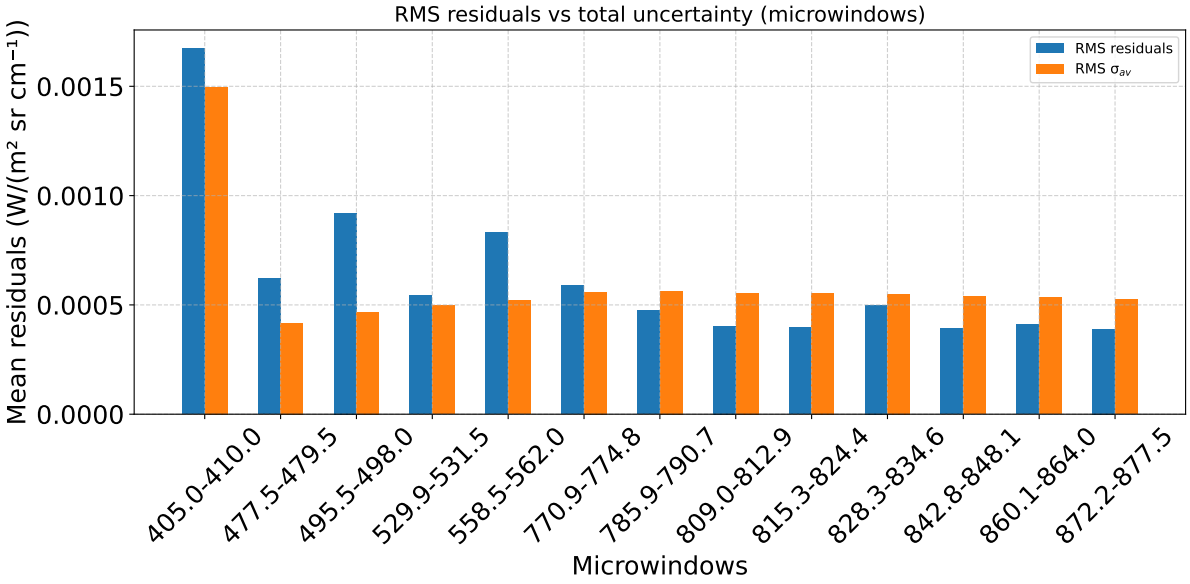

Figure 4: Histogram of the comparison between the root mean square (RMS) of the residuals (blue boxes) and the average noise over all scenarios (orange boxes) in the 13 selected microwindows.

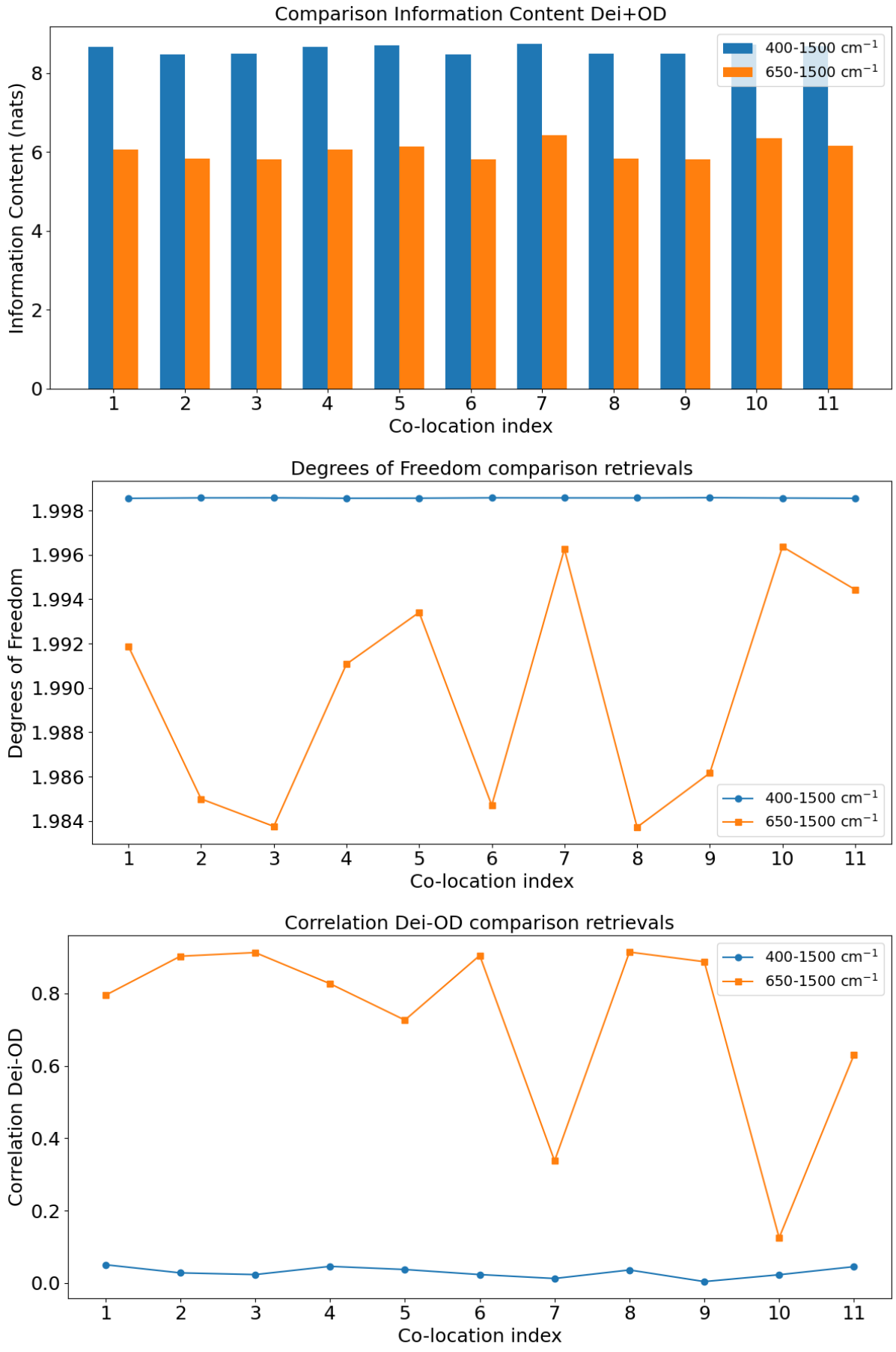

Figure 5: Upper panel:Information content of retrieval for the case FIR was considered (blue) and neglected (orange). Middle panel: degrees of freedom. Bottom pane: correlations OD-D_{ei}.

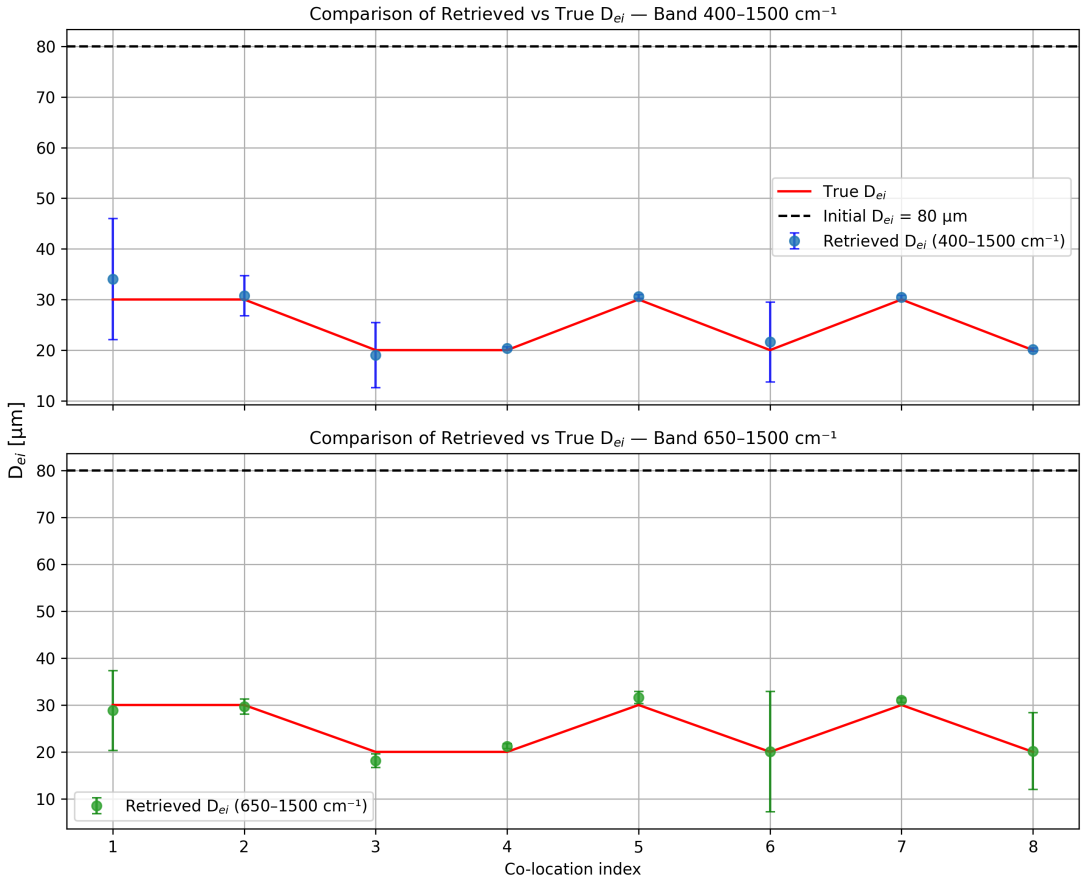

Figure 6: Top panel: comparison of the retrieved D_{ei} by including the FIR (blue dots) wit respect to the "truth" (red curve). Bottom panel: same but neglecting the FIR (green dots). In both cases the initial guess and a apriori is 80 μm as done with the analysis.

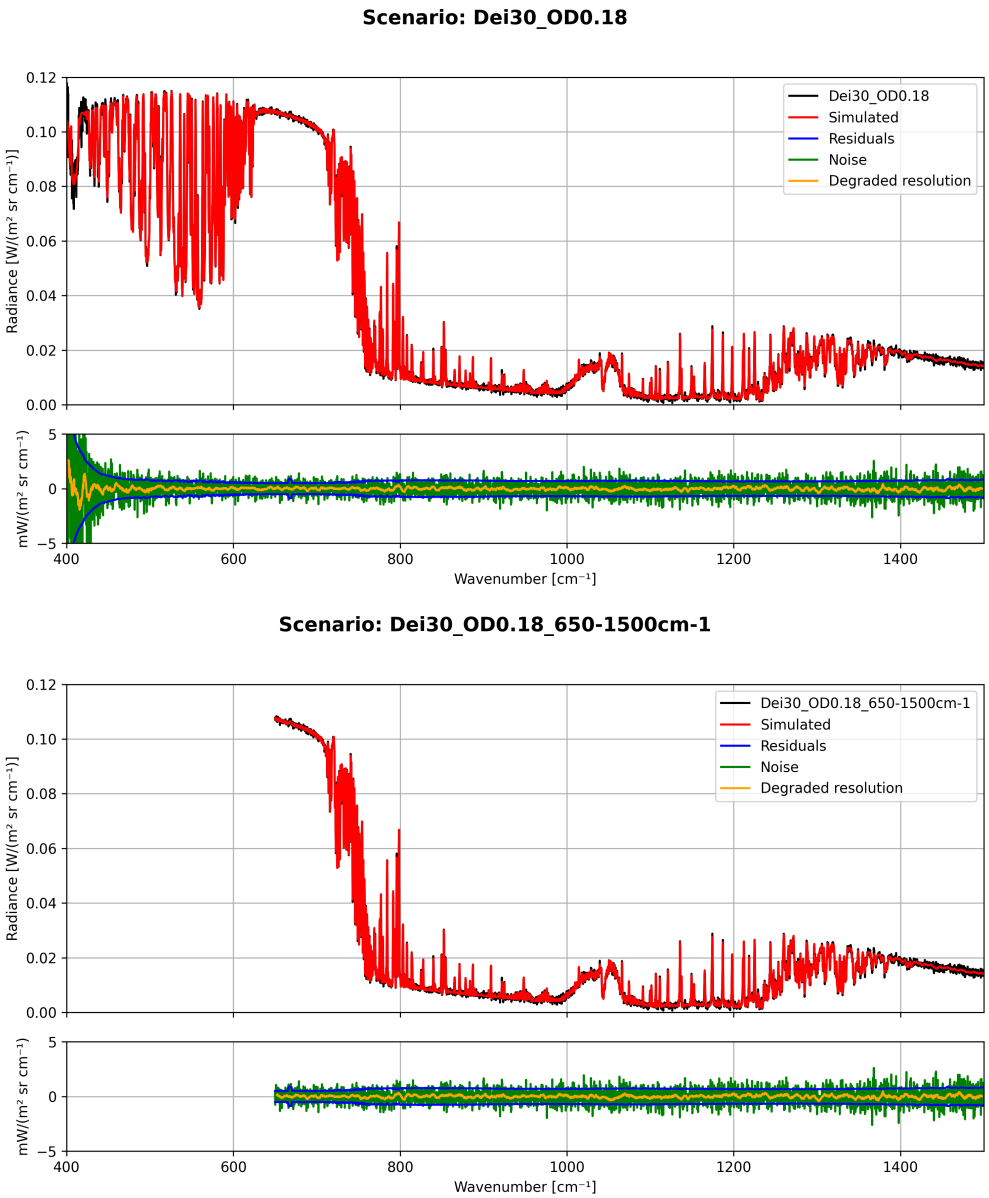

Figure 7: Top panel: fit and residuals by using the FIR for the case OD = 0.18 and D_{ei} = 30 μm . Bottom panel: same by neglecting the FIR.