Dear Referee,

We would like to thank you for the very useful suggestions to improve the quality of the manuscript. Please see below our response to the comments.

All the changes are highlighted in the revised manuscript.

Sincerely,
The Authors

General Comments

The novelty of this paper is the combination of Ka-band (35 GHz) and G-band (239 GHz) radar observations for the purpose of retrieving liquid water content (LWC) in very thin clouds during the EPCAPE experiment. 15,000 total vertical profiles of thin cloud were examined in this study, and the retrievals of LWC using this dual-frequency approach demonstrate a convincing improvement compared to previous retrieval efforts using combinations of lower-frequency radar observations. I agree with all of the key results, and especially agree that this approach is a significant advancement even when issues such as Mie scattering or radar volume mismatching are present. Figures 6 and 7 also cleanly show how their Z-LWC relationship fares against previous studies without misleading the readers about the (obvious) spreads in values that are characteristic of such relationships. In addition to this set of important results, this manuscript adds a significant contribution to the realm of G-band radar observations – which will certainly motivate further studies and field campaigns, especially those focused on thin, low-level cloud (which remain a source of high uncertainty in both modeling and observation based studies). The manuscript also does an excellent job of quantifying uncertainty among all used measurements/datasets.

These manuscript qualities make this study an important and significant contribution worthy of publication.

However, I am recommending minor revisions prior to publication for the following reasons, as I believe my comments should not require significant time to address:

The introduction as it stands is well-written but lacking context and relevance to previous works and would benefit from at least another paragraph's worth of context discussing (for example, but not limited to) CloudCube's precursors, previous spaceborne remote sensing cloud retrievals, airborne remote sensing algorithms and related validation studies, and general instrument limitations of previous-generation cloud remote sensing. I was especially surprised – going from the introduction to the methods – the lack of connection (and motivation) to previous spaceborne remote sensing studies using (for example) CloudSat measurements and why CloudCube will be an improvement over a long period of time. I have listed several reading recommendations in my specific comments below – and I encourage the authors to review embedded references within these references to strengthen the introduction further. In addition, I've recommended at several points to either comment on or carry out some additional analysis to better connect your work with the existing literature (the paper itself already has enough publishable results, but I will leave it to the authors to decide the best course of action as I do believe some of these small-but-important details are necessary to strengthen the manuscript).

There are also numerous places in the text (see specific comments below, especially after about ~L120 or so) where the authors need to be more quantitative. In most places, saying "small differences" or "small percentage" (among other similar phrases) is technically correct – but values need to be provided so the reader is not misled in any way. This is especially true for relative humidity or any variable involving moisture.

We have addressed this issue in the new version of the manuscript.

Specific/Technical Comments

L37-39: Sub-cloud evaporation should probably be mentioned here too.

Kalmus, P., & Lebsock, M. (2017). Correcting biased evaporation in CloudSat warm rain. IEEE Transactions on Geoscience and Remote Sensing, 55(11), 6207-6217.

Evaporation of drizzle beneath cloud base is indeed an important thermodynamic influence on the boundary layer structure and therefore cloud amount and extent. We chose not to bring up this detail in the introduction however since there are many processes that similarly influence the clouds including at least cloud top entrainment, radiative cooling, precipitation initiation, aerosol scavenging, etc.

L39: Given this manuscript's connection to CloudCube, it is very important (in my view) to mention limitations of previous satellite-based remote sensing efforts – especially with measuring thin clouds in the lowest 1-km above ground.

Stephens, G. L., et al. (2008), CloudSat mission: Performance and early science after the first year of operation, J. Geophys. Res., 113, D00A18, doi:10.1029/2008JD009982.

This is a great point. In fact, in a follow-up paper, we plan to explore the possibility of using similar spaceborne measurements given realistic spaceborne radar performance characteristics. The focus of this paper is on ground-based methods to retrieve the LWC profile. For the foreseeable future, we will not have dual-frequency satellite observations with the sensitivity to detect cloud water backscattering signals, so we want to focus on ground-based in this paper where we feel there is a good opportunity to advance observational capability over the coming years.

L45-47: Can you provide some sort of numeric example explaining what value(s) of differential attenuation correspond to value(s) of LWC? This won't be obvious to your casual reader.

The differential attenuation that corresponds to a value of LWC depends on the frequency of operation of the radar, the frequency separation between the two radar frequencies, the cloud properties, etc. We believe that it is complicated to provide such example without misleading the reader.

L51: You explain this more in the next sentence, but this statement should be concluded with relevant citations (i.e., what studies "suggest the use of high frequencies and large frequency pair separations?).

We have added the following citations in line 53:

Hogan, R. J., Gaussiat, N. and Illingworth, A. J.: Stratocumulus liquid water content from dual-wavelength radar, J. Atmos. O. Tech., 22(8), 1207-1218. https://doi.org/10.1175/JTECH1768.1, 2005.

Williams, J. K., and Vivekanandan, J.: Sources of error in dual-wavelength radar remote sensing of cloud liquid water content. J. Atmos. O. Tech., 24(8), 1317-1336. https://doi.org/10.1175/jtech2042.1, 2007.

L54-61: This is an important statement, but to this point of the introduction, there is limited context for other multi-platform techniques that attempt to quantify cloud liquid (or rain) water. The introduction is especially limited in context from other spaceborne cloud remote sensing studies given this manuscript's connection to CloudCube.

CloudSat + MODIS warm rain retrieval algorithm:

Lebsock, M. D., & L'Ecuyer, T. S. (2011). The retrieval of warm rain from CloudSat. Journal of Geophysical Research: Atmospheres, 116(D20).

L'Ecuyer, T. S., and G. L. Stephens (2002), An estimation-based precipitation retrieval algorithm for attenuating radars, J. Appl. Meteorol., 41, 272–285, doi:10.1175/1520-0450(2002)041<0272:AEBPRA>2.0.CO;2.

Airborne radar & radiometric retrievals of cloud and rain water designed for thin stratocumulus in the SE Atlantic Ocean:

Dzambo, A. M., L'Ecuyer, T., Sinclair, K., van Diedenhoven, B., Gupta, S., McFarquhar, G., O'Brien, J. R., Cairns, B., Wasilewski, A. P., and Alexandrov, M.: Joint cloud water path and rainwater path retrievals from airborne ORACLES observations, Atmos. Chem. Phys., 21, 5513–5532, https://doi.org/10.5194/acp-21-5513-2021

Once again, we chose to just focus on the ground-based retrievals in this manuscript.

L57: Given the scope of this manuscript, I highly recommend expanding your introduction here to discuss triple-frequency radar observations, and discuss how/why a G-band/Ka-band retrieval is optimal for thin cloud (this will be obvious at this point to most readers, but not everyone will be aware of triple-frequency radar algorithm technology).

Battaglia, A., Tanelli, S., Tridon, F., Kneifel, S., Leinonen, J., & Kollias, P. (2020). Triple-frequency radar retrievals. Satellite Precipitation Measurement: Volume 1, 211-229.

Triple-frequency techniques have primarily been used to probe the microphysics of frozen hydrometeors. We feel that adding these references would prove distracting to uninformed readers as we are working here with liquid-phase hydrometeors where the density is constrained.

L71-72: To be clear, your study is *not* a statistical analysis of the whole EPCAPE dataset, but rather a single case study based on 100 continuous minutes of data? Please clarify. This information would be more appropriate at the beginning of Section 2.

We have clarified this in line 95-99:

"We have selected two case studies in two different days for the analysis developed in this work. The first case, recorded on 17 April 2023, at 21:19:00 UTC starting time, lasts 100 minutes while the second data set, taken on 25 April 2023, at 13:12:00 UTC starting time, continues for 20 minutes. The radar data that have been used for the LWC retrieval consist of close to 18000 and 1800 profiles of observed echo power at G-band and Ka-band, respectively, which have been averaged over 60 s to retrieve 120 LWC profiles."

L90: Consider one of two things in your next version of this paper, either (1) comparing your results (at an appropriate point later in the paper) against those produced by the classic Hitschfeld and Borden (1954) attenuation correction scheme, which is widely used and known, or (2) commenting on how your approach might compare against the classic Hitschfeld and Borden attenuation correction. Most studies that I'm aware of on the topic of radar attenuation use Hitschfeld and Borden – it would be prudent (for visibility sake) that you not neglect this detail.

Hitschfeld, W., & Bordan, J. (1954). Errors inherent in the radar measurement of rainfall at attenuating wavelengths. Journal of the Atmospheric Sciences, 11(1), 58-67.

We have added the following paragraph in lines 302-307 and added the Hitschfeld and Borden reference:

"An alternative method to account for the radar attenuation is based on the Hitschfeld and Borden (1954) scheme, where the reflectivity would be corrected at each range gate prior to computing the LWC from a reflectivity-based relationship. For a range resolution of 30 m and LWC smaller than 1 gm^{-3}, the attenuation by cloud liquid water at Ka-band is expected to be on the order of 0.01 dB per range gate as computed using ITU (2013). Even over the depth of a 300 m cloud, the cumulative attenuation at Ka-band would be on the order of 0.1 dB. Therefore, the reflectivity-based retrieval is not significantly affected by attenuation in this particular scene."

L118-121: This section can probably be merged with the previous paragraph. Also, "... deduced from the ceilometer cloud base measurement" is somewhat confusing – do you mean to say if the ceilometer detects a cloud base near the surface? I would explain this further.

We have merge both paragraphs and modified the sentence (line 122):

"… we have excluded regions below the cloud base measured by the ceilometer."

L126: I presume these "small" differences also accounted for diurnal variability? I would quantify what a "small" difference is in temperature, humidity, etc.

We have added the following correction in line 128:

"…less than 0.5 K, 7 hPa, and 3%, respectively"

L127: Again, quantify what this "small percentage" is.

We have added the following correction in line 130-131:

"Even if there had been a variation of 1 K, … would be smaller than 0.03 gm^{-3}…"

L130-134: This information needs to be at the beginning of Section 2, so the reader is clear about what data from what times are used in this analysis. This will also improve the flow of your Section 2 here, as this is awkwardly placed here.

We have moved and provided more clarity in this paragraph (line 96-102).

L146: Specify in the caption what positive/negative Doppler velocity corresponds to (i.e., toward or away from the radar).

We have added the following sentence in line 147-148:

"Negative Doppler velocities correspond to particles moving towards the radar."

L159: What is the value of the "uncertainty in the radar reflectivity measurement"? Quantify please.

As shown in Eq. (2), the value of the uncertainty in the radar reflectivity measurement depends on multiple radar parameters. We believe that providing values for particular radar configurations can be confusing for the reader.

L164: "huge leap" is a bit informal, and could mean different things to different readers. It may be worth mentioning here (please check in the literature to be sure) that a Ka-band/G-band technique *may* be the widest frequency differential for a technique of this kind (and this will make the novelty of your work more obvious to your reader!).

The recommendation has been accepted (line 159-160).

L221: what exactly is a "short profile"?

We have changed the sentence in line 218:

"We fit a portion of the DFR(r) profile…"

L300: You can abbreviate liquid water content to LWC.

The recommendation has been accepted (line 301).

L416-423: These are great results – some of these number should be weaved into your abstract to make it more quantitative.

The recommendation has been accepted.

Summary and Conclusions: I have no issues with your algorithm and results and maintain that this work is novel and should be published as soon as possible... however, readers who are familiar with radiometric + radar-based retrievals of cloud LWC may not totally be convinced your work/algorithm is a significant advancement over existing radiometric + radar-based algorithm technology. It would be overkill to add this to your paper, but you should definitely mention in this section as a "future work" that you intend to compare your results against an optimized radiometric + radar joint algorithm to see which one performs better. In particular, a radiometric observation of total optical depth was valuable in constraining the *total* liquid water path of the cloud, and in combination with radar data, can also be used to constrain rainwater contents (see the aforementioned Lebsock and L'Ecuyer, 2011 and Dzambo et al. 2021 references). Again, this would be overkill for this study, but your summary paragraph here should include at least a couple sentences (perhaps a full paragraph) discussing these caveats and avenue of future work.

This section should also include a statement (1-2 sentences) that this work was based on a single set of continuous (100-minute) measurements, and that the robustness of your work will be tested when more data (or similar datasets from other campaigns) are made available.

As an aside – I would really like to see you and your group carry out this suggested follow-on study using radiometric + radar-based retrievals of LWC from EPCAPE!

We have added the following paragraph (line 492-498):

"Future work will be devoted to testing, improving, and validating the results retrieved in this work. KAZR and CloudCubeG will be participating in the Cloud and Precipitation Experiment at Kennaook (CAPE-k), where close to one-year worth of data will be available by the end of 2025. At CAPE-k, KAZR and CloudCubeG will be accompanied by the W-band ARM Cloud Radar (WACR), and we will exploit the availability of a triple-frequency radar system to benefit the LWC retrieval as described in Sect. 7. Finally, we intend to compare the results against a radiometer and single-frequency radar joint retrieval, as combining the radiometric observation of total optical depth with the radar capability of profiling can also be used to constrain the cloud LWC."

L449: "indicative of their radiative properties" – LWC is not the *only* property of clouds that matter! Please expand/rephrase to make this more accurate.

We have modified the sentence in line 458:

"…is key to better understand"

L481: I'd say "atmosphere" rather than "medium".

The recommendation has been accepted (line 491).