The authors present a framework for processing the Doppler spectra collected by a vertically-pointing, dual frequency radar operating at the bands Ka and Ku. The framework includes a method for the removal of clutter and range sidelobe artifacts. The resulting clean spectra from three of the operational modes of the radar are merged and used to compute four moments of the spectrum.

In my opinion, the proposed framework is a good contribution to the radar community. It is presented in a clear way and most of the methods are described with a sufficient level of detail. However, there are few additional details (discussed in the next two sections of the review) that I believe need to be included in the explanation of the framework. I also found no major issues in the writing, but there are some instances (listed among the "Technical corrections") in which I suggest some modifications to make the text easier to understand.

I recommend the article for publication after addressing the issues listed below.

We sincerely appreciate the reviewer for the positive comments on our paper. We have amended the manuscript as suggested. Please see below our response to your comments.

Specific comments

- Section 3.1

  The clutter mitigation algorithm is described clearly. The examples shown in the figures 1 and 3 illustrate its correct functioning when the tail of the power distribution of the precipitation signal is far enough from the 0 m/s fall velocity. In my opinion, it would be useful to briefly discuss in the text how the algorithm reacts in cases in which the meteorological signal is closer to 0 m/s (e.g. light precipitation, drizzle) and there is a more significant overlap between the signal and the clutter. Are there specific cases in which the algorithm fails or mislabels part of the precipitation as clutter?

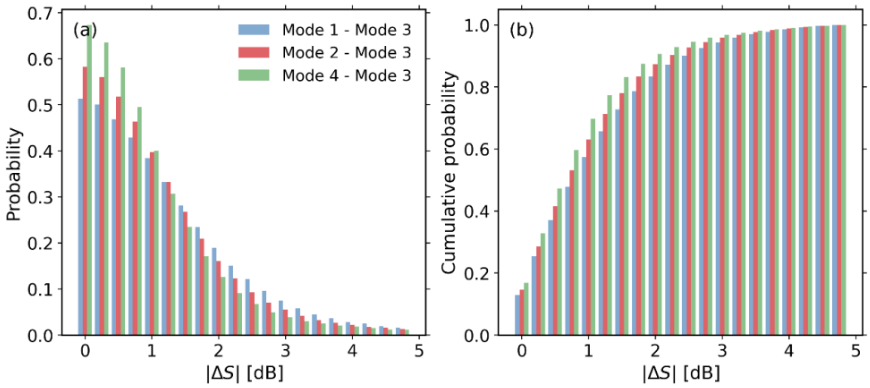
  We thank the reviewer for this question which led to a more thorough discussion on our method.

  The declutter method in this paper deals with clutter signals that are not consistent at different observing modes (See Fig.2 in the revised manuscript). In contrast, the meteorological signals are usually coherent and are consistent at different observing modes. If meteorological signals coexist with clutter signals, there are two scenarios:

  1) If the spectral powers of meteorological signals exceed those of clutter signals, the meteorological signals will be preserved since they are consistent and $|\Delta S|$ is not expected to be large.
  2) If the spectral powers of meteorological signals are below those of clutter signals, clutter signals will dominate the spectral power. If they are consistent at different modes ($|\Delta S|$ is not very large), they can be mislabeled as

precipitation/clouds.

The critical point here is to get a threshold for |Δ*S* |. As we know, the selection of the threshold is a comprise between false-alarm and miss hit. We want to preserve the meteorological signals at our best, therefore we checked that for the meteorological signals how large the |Δ*S*| can be. We attach the statistical plots of meteorological signals (Doppler velocity of 2 ~ 5 m/s) below (Appendix A in the revised manuscript). We have used 3 dB since the probability of |Δ*S*| tends to be flat after this value. If a value higher than 3 dB is used, more clutter signals can be mislabeled as precipitation.



(a) Probability density and (b) cumulative distribution of spectral power ratio of meteorological signals between different modes at Ku-band

In the revised manuscript, we have clarified this point in Section 3.1.

"The selection of the threshold is a comprise between false-alarm and miss hit. We want to preserve the meteorological signals at our best, therefore we checked the magnitudes of |Δ*S*| for meteorological signals. Figure A1 (Appendix) presents the statistical plot of |Δ*S*| for meteorological signals (height of 2 ~ 3 km and Doppler velocity of 2 ~ 5 m s^{-1}). It appears that the probability of |Δ*S*| tends to be flat after 3 dB, and the use of 3 dB can ensure that 95.6 % of precipitation cases are well preserved (Fig. A1). Therefore, 3 dB is used in this study. If a larger threshold is employed, we expect more clutter signals will be mislabeled as precipitation."

The clutter removal method was modified in the revised manuscript (see Fig. 3), we have added more discussions as below:

"It should be noted that this method relies on observations recorded at different observing modes. However, the sensitivities of different modes are not identical. Therefore, if the clutter is presented in the most sensitive mode (e.g., mode 2) only, it cannot be filtered out with the |Δ*S*| method. In this case, the width of valid meteorological spectral mode is assumed to be longer than 2 m s^{-1}, otherwise it is attributed to clutter. We are aware that Shupe et al (2004) have used a width of

0.448 m s^{-1} to identify supercooled liquid water. We have tried this value, but the width of clutter present in this dual-wavelength radar system easily exceeds 1 m s^{-1} (Fig. 2). Actually, the selection of the spectrum width is similar with the use of a signal-to-noise ratio (SNR) value in noise-removal. Higher SNR means a stricter noise-removal but higher chance of losing valid signals. We have tested the width of 1, 1.5, 2, and 3 m s^{-1} (visual inspection, not shown), and found that 2 m s^{-1} can effectively remove clutter signals for both radars though very light precipitation (detected by the most sensitive mode only) can be removed as well. Admitting this potential issue, it suffices the application in rainfall. In addition, for clouds with highly variable reflectivity, the presented algorithm may mislabel them as clutter according to our assumption that meteorological signals are coherent in a round of observation (28s)."

- Section 3.1 – 4.2

  The techniques illustrated in this section are always applied to the Ku-band in the various examples and their associated figures. This choice is motivated by the more common appearance of clutter for this band (Section 3.1) and the better functioning of the standard artifacts removal technique for the Ka-band (Section 3.2). Similarly, during the description of the mode merging in Section 4.1, only the statistics for ΔZ and ΔV for the Ku-band are shown. However, section 4.2 describes the result of the shift-then-average method for both the Ka and Ku bands. I have a couple of questions regarding this last section:
  - Are all the techniques described before section 4.2 also applied to the Ka-band?
  - If the same techniques developed for the Ku-band are used also for the Ka-band, are they applied in exactly the same way? (for example: is the mode 1 excluded from the shift-then-average method also for the Ka-band? Are the statistics of ΔZ and ΔV similar to the Ku-band case?

  Sorry for the unclear description in the original manuscript. The techniques were applied to Ka-band. The different point is that Ka-band observations at modes 3 and 4 were used, while Ku-band uses data from modes 2, 3, and 4. In the revised manuscript, the procedures for generating the estimates of spectral moments are presented in Fig. 14.

  In addition, ΔZ and ΔV plot of Ka-band is given in Fig. 10. We can see that the coherent integration has a decent impact on Ka-band, therefore we did not use mode 2 data at Ka-band.

Technical comments

- Line 16

  "Then, the abnormal distribution of the probability density of the Doppler spectrum in presence of range sidelobe due to the implementation of the pulse compression technique was identified and used to separate sidelobe artifacts."

This sentence stands out to me as particularly long and slightly convoluted. If possible, I would suggest to re-phrase it, maybe splitting it into two shorter sentences to make it easier to understand for the reader.

This sentence has been rewritten as "Then, for the Doppler spectrum affected by the range sidelobe due to the implementation of the pulse compression technique, the characteristics of the probability density distribution of the spectral power were used to identify the sidelobe artifacts."

- Line 28

  "As a remote sensing instrument, cloud radars [...]"

  Since "cloud radars" is plural, I would suggest using the plural for the first part of the sentence too (i.e. "As remote sensing instruments")

  Corrected.

- Line 49

  "Alternatively, cloud/precipitation signals can be well reserved if the clutter removal is made in the radar Doppler spectrum"
  I did not fully understand the sentence. Is the term "reserved" correct here?

  This sentence has been revised to "Alternatively, cloud/precipitation signals can be discriminated from clutter properly if the clutter removal is made in the radar Doppler spectrum".

- Line 60

  "[...] a wider pulse is used which on the other hand decreases [...]"

  In my opinion, this part of the sentence would benefit from being re-phrased more clearly.

  The sentence has been rewritten to "To enhance the detection sensitivity, modulated wide pulses are transmitted and then compressed into short pulses after received."

- Line 76

  "[...] the emitting of long pulses leads to an increase in radar blind range, [...]"

  In my opinion it should be "emission" instead of "emitting".

  Corrected.

- Line 86

  Could you provide the altitude of the site at which the radar has been deployed?
  The altitude of the site where the radar has been deployed is 80.3 m. We have added the altitude to the revised manuscript.

- Lines 97-98

  "[...] to improve the sensitivity to detect clouds with weaker radar echoes at higher latitudes"
  Do you mean "higher altitudes"?

  Yes, we have corrected it in the revised manuscript.

- Line 100

  "There are four different modes routinely cycled in operations [...]

  Since the four modes have already been introduced in the previous sentences, the beginning of this sentence feels like repetition. In my opinion, it could be rephrased as "These four different modes are routinely cycled in operations [...]".

  We have rephrased this sentence to "These four different modes are routinely cycled in operations and each mode takes 7 s to finish the observation.".

- Line 105

  Since the height of the blind zone for two of the modes is mentioned, I would also explicitly write in the text the height for the remaining ones.
  Thanks for the suggestion. We have added the blind zone of the other two modes in the revised manuscript. "The blind zones of modes 1 and 3 are 30 m."

- Line 116

  "[...] the implementation of pulse compression techniques in modes 2 and 4 usually results in significant range sidelobe around the melting layer"
  Why specifically around the melting layer? Is it just because the melting layer is often characterized by a strong echo?

  The range sidelobe caused by pulse compression technology is present in both the upper and lower range gates of the target bin, which is weak compared with the echo of the target. The theoretical peak sidelobe ratio (the ratio of the main lobe peak power to the highest sidelobe peak power) is 36 dB and 30 dB for mode 2 and mode 4, respectively. Our statistics (Fig. D1) show that the sidelobe signals are usually below -20 dB. Since the reflectivity enhancement in the melting layer usually do not exceed 10 dB (Li et al., 2020), the sidelobe contamination in rain is not significant. However, the fall velocity of snow is much slower than rain drops. Namely, no meteorological signals present in the range of 3 ~ 10 m/s and the sidelobe signal becomes evident.

- Line 135

  "The cause of such clutter signals is unclear yet and we hesitate to classify them to insects (Williams et al., (2018), since the spectral powers at different modes deviate from each other significantly."
  In my opinion, the verb "attribute" would fit better the sentence than "classify". Additionally, the parenthesis opened before the name "Williams" is not closed later in the phrase.
  Thank the reviewer very much for the suggestion. The verb "classify" has been changed to "attribute" and the parenthesis has been closed.

- Figure 1
  In my opinion, there is a mismatch between the label and the unit on the y-axis. The unit "dBZ" is used for reflectivity, but the label of the axis says "power".

  The unit of Doppler power spectral density data is $mm^6\ m^{-3}\ (m\ s^{-1})^{-1}$. There is no accepted nomenclature for denoting the spectral power in the dB scale according to Li and Moisseev (2020), so we are going to with the unit "dBZ", but we added some explanation in the caption of the figure.

- Line 172

  "(see for example (Li and Moisseev, 2020))"

  I think that the parenthesis around "Li and Moisseev, 2020" could be removed.
  The parenthesis around "Li and Moisseev, 2020" has been removed.

- Line 179

  "[...] received spectral power from 2 km and 7 km".

  From my understanding of the figure, in this sentence the "and" should be substituted by "to" (i.e. "from 2 km to 7 km").

  Corrected.

- Line 180

  "For Doppler spectra without the sidelobe contamination, PDFs are relatively uniform."
  From what I understood from panel (a) of figure 4, the term "uniform" may be

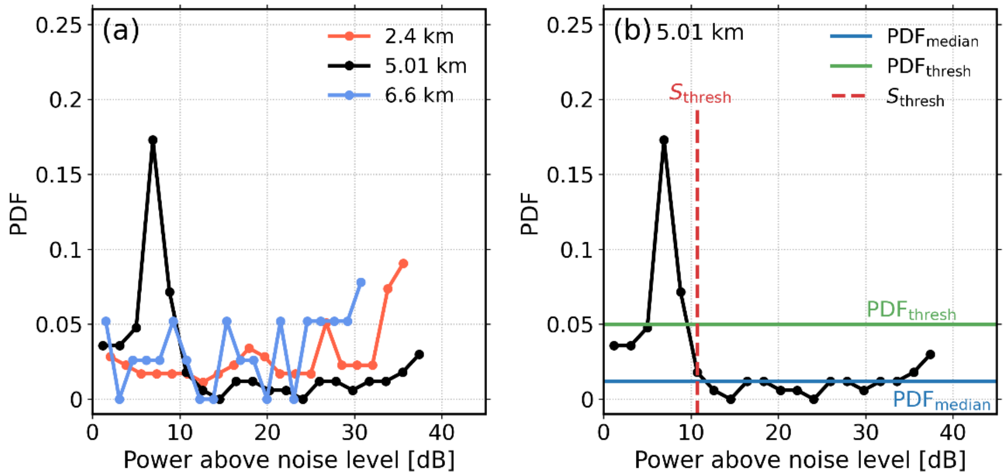
confusing here. If I understood correctly, what is meant by this sentence is that the PDF observed at different range gates are similar to each other, in absence of the sidelobe issue. If this is the case, I suggest rewriting the sentence, avoiding the term "uniform", since it can create ambiguity with the idea of "uniform distribution" (which the various PDF of panel 4.a are not).

We have rewritten the description of figure 4, please check it in the response below.

- Figure 4
  In my opinion, there are two small issues with this figure:
  ◦ In panel (a) the orange and red curves cover completely the ones below. I would suggest adding some transparency to the lines so that also the curves below are visible. I also suggest inverting the order in which the lines are plotted, so that the light blue ones sit on top of the darker red ones.
  ◦ Panel (b) is never mentioned in the main text of the article. Since the quantity S_{thresh} is introduced in line 184 of the text, maybe you could expand the explanation including a mention of the panel (b).

  To present the results to the reader more clearly, we modified Fig. 4 in the original manuscript to show only the probability distributions of spectral power of range bins at 2.4 km, 5.01 km, and 6.6 km, which respectively represent the liquid precipitation, Doppler spectra contaminated by range sidelobe, and solid precipitation (Fig. 5 in the revised manuscript). The following descriptions have been added to the revised manuscript:

  "An interesting feature of the range sidelobe caused by pulse compression is that its spectral power is much flatter than cloud and precipitation signals. Figure 5a shows the probability density functions (PDFs) of received spectral power at 2.4 km, 5.01 km, and 6.6 km, which respectively represent the liquid precipitation, Doppler spectrum contaminated by range sidelobe, and solid precipitation. For the sidelobe-contaminated Doppler spectrum, It can be seen that the range bins contaminated by range sidelobe have different spectral power distributions, the peak of the PDFs appears close to the noise level and is mostly below 15 dB above the noise level. A closer look into the radar Doppler spectra at 5.01 km (Fig. 6a) shows that the strong PDF peak in Fig. 5b is explained by the relatively flat range sidelobe signals. Here, we introduce a parameter spectral power threshold (S_{thresh}) to distinguish the range sidelobe from meteorological signals."



(a): Probability distributions of Doppler spectra at 2.4 km (liquid precipitation), 5.01 km (melting layer), and 6.6 km (solid precipitation) at mode 2; (b): Probability distribution of Doppler spectrum recorded at 5.01 km.

- Line 186

  "The procedures are briefly summarized as follows,"

  I would replace the comma (",") with a colon (":") since the procedure is provided in a numbered list just after this sentence.
  Corrected.

- Lines 199-201

  "Below half of the peak power above the noise level of the Doppler spectrum,

  find the power bins' probability density just exceeds the PDF_{thresh}, and the corresponding spectral power is set as S_{thresh}"
  I did not fully understand this step in the procedure. Could the sentence be rewritten differently?
  This sentence has been revised to:

  "1) Sort the spectral power values above noise level in an ascending order to get a PDF curve of each Doppler spectrum;
  2) Calculate the median and standard deviation (SD) of the PDFs, set $PDF_{thresh} = PDF_{median} + PDF_{SD}$; Note that the determination of this relation is given in Appendix B.
  3) Below half of the peak power above the noise level of the Doppler spectrum, find the power bins' probability density just exceeds the PDF_{thresh}, and the corresponding spectral power is set as S_{thresh}; (The range of PDF_{thresh} is limited to half of the peak power above the noise level to avoid finding the PDF_{peak} corresponding to large spectral power, which makes the determined S_{thresh} corresponds well to the power of sidelobe in this way.)

4) If the spectrum power with the Doppler velocity larger than the mean Doppler velocity is below the S_{thresh}, then it is flagged as sidelobe."

- Line 245

"[...] Doppler spectra observations from the modes 2, 3, and 4 were merged as

follows [...],"
I suggest the same correction as for Line 186.
Corrected.

- Lines 270-273

"Although the agreement among different modes is better than that at Ku-band

thanks to higher spectral velocity resolution and less uncertainties for the Ka-band radar, while the bias of kurtosis in snow at mode 3 (Fig. 11c) is more contrasting."
I think that "Although" should be removed from the beginning of the sentence.
Corrected.

- Figures 12 and 13
In the period of approximately 10 minutes before 21:00 LST, in both bands it is possible to see some very faint returns around 2 km of altitude. Do you know what is causing their appearance? In case it is unfiltered clutter, I would recommend discussing its appearance in the text, describing briefly why the proposed method does not filter it.
We checked why the clutter was still there. This is due to the different sensitivities of different observing modes. If the clutter signal is detected only by the most sensitive mode, then our method will fail to filter it out because there are no signals from other modes to compare it with. As shown in Fig.12 (Fig. 15 in the revised manuscript), the clutters that are not filtered out exist above 2 km which is because the blind zones of the most sensitive mode (mode 2) of our radar are below 2 km. To clarify this, these sentences have been added to the revised manuscript.

"It should be noted that this method relies on observations at different observing modes. However, the sensitivities of different modes are not identical. Therefore, if the clutter is presented in only one mode, it cannot be filtered out. " has been added in Section 3.1.

"It can be seen in Fig. 15 that there are still clutter signals above 2 km at Ku-band between 20:45 and 21:00 LST, which are all only detected by the most sensitive mode (mode 2). The clutter was not filtered out because no signals were detected by other modes." has been added in Section 5.1.

- Lines 314-315

  "[...] and the results show good performance of clutter/sidelobe suppression and spectral merging."
  Since the performances were not measured quantitatively, I would modify this sentence by using a less strong statement (e.g. "a visual inspection of the processed data suggests that clutter/sidelobe suppression and spectral merging demonstrated good performances").

  In the revised manuscript, we have added the quantitative evaluation. This statement has been changed to "and the quantitative evaluations of the processed data suggests that clutter/sidelobe suppression and spectral merging results demonstrated good performance."