This manuscript presents methods to remove clutter and range sidelobe artifacts in vertically pointing radar Doppler velocity power spectra. The manuscript also describes a method to combine spectra from four different modes to produce a merged moment dataset.

It appears that the authors have done some good research exploring Doppler velocity power spectra, yet, the manuscript does not provide enough quantitative analysis for an AMT reader to adapt the proposed methodologies to different radar systems.

Also, the manuscript does not provide enough examples of "clutter" in different weather conditions to convince this reviewer that the radar is observing non-meteorological clutter. From the imagery presented in the manuscript, it appears to this reviewer that the "clutter" is actually clouds being detected in the same radar resolution volume as precipitation. One possibility is instead of identifying and removing "clutter" from the power spectra, the manuscript should explore using multiple-peak processing methods to identify multiple hydrometeor populations occurring within the same range resolution volume. For example, in Fig. 1a, it appears to this reviewer that the radar is detecting both raindrops (with Doppler velocities exceeding 8 m/s) and cloud particles (with Doppler velocities near zero).

I encourage the authors to continue their work analyzing Doppler velocity spectra and make improvements to this manuscript.

The authors would like to thank the reviewer for constructive comments on the manuscript. The comments will help to sharpen and clarify the paper, all of them will be addressed in some manner. Please see the point-to-point response below in blue color.

Major concerns

- 1. Line 117.

  The text states, "…the implementation of pulse compression techniques in modes 2 and 4 usually results in significant range sidelobe around the melting layer, which does not significantly affect Ze and V estimates, but can severely degrade the estimation of spectrum width." This sentence is not logical. If there is "significant" range sidelobes, then power that should be assigned to the central range gate is being "significantly" distributed into different range gates, and Ze and V will be incorrect in the central range gate and in the range sidelobe gates. Will the error in Z and V be "significant"? This manuscript needs to describe how much power is leaking into the range sidelobes and how that is affecting the Ze and V estimates. Including that quantitative analysis through simulations or detailed analysis would be valuable to AMT readers.

  We agree with the reviewer. In the revised manuscript, we have added a new section "5.3 Quantitative evaluation". In section "5.3.2 Sidelobe mitigation", we have quantitatively analyzed the impact of sidelobe removal on spectral moment estimation (Tab. B1 and B2).

Regarding the magnitude of power leakage, we have added a new paragraph in Section "5.1 Case study".

"In addition, we have calculated statistics of the power leakage to range sidelobe, and the results for Ku-/Ka-band radars are given in Fig. D1 (Appendix). The results show that the sidelobe signals are usually below -20 dB. Since the reflectivity enhancement in the melting layer usually does 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^{-1} and the sidelobe signal becomes evident."

- 2. Figure 1 and Line 135.
  "The cause of such clutter signals is unclear yet we hesitate to classify them to insects (Williams et al. 2018), since the spectral powers at different modes deviate from each other significantly." This reviewer agrees, the spectral peaks near zero velocities are probably not due to scattering from insects. From examining Fig. 12, it appears that the spectral power near zero velocity is scattering from clouds. Thus, Fig. 1a probably shows return power from precipitation and cloud particles. In Fig. 12, between time 20:00 through 21:00 LST and near 2 km, there is a cloud feature in the reflectivity and velocity time-height cross-sections that suggest this 'clutter' peak near zero velocity in Fig. 1a is scattering from cloud particles being detected in the more sensitive modes 4 and 2. The manuscript should provide more imagery of this "clutter" signal to convince the AMT reader that the radar is observing non-meteorological clutter. For example, a time-spectra plot showing spectra at one range gate over multiple profiles could indicate whether this signal is coherent over many profiles, indicative of a cloud.

We thank the reviewer for this good suggestion. In the revised manuscript, we have added a time-spectra plot and the following descriptions:

"Figure 2 shows the time series of Doppler velocity spectra on 6 June 2020 from 22:40 to 23:01 LST at 2.34 km range (the same range bin as Fig. 1). The clutter signals are in the vicinity of 0 m s^{-1} and are not continuous with time. Compared with meteorological signals, it appears that clutter echoes randomly occur with some dependence on the observing mode."

Regarding the clutter in Fig. 12 (Fig. 15 in the revised manuscript), we have checked the spectral observations and found that the unsuccessful declutter was because no signals from another mode can be used to compare with the most sensitive mode (mode 2). This can also be evidenced in Fig. 2 in the revised manuscript. Clutter signals at 22:48 presented at mode 2 (the most sensitive mode), and our algorithm cannot identify them. We have added the following discussions in the last paragraph of section 3.1

“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 $|\Delta S|$ 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 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). ”

- 3. Line 144.
  “The selection of |Delta S| = 3 dB is a compromise …”. The manuscript has omitted important processing steps needed to compare different operating modes collected from the same radar system. Specifically, the manuscript needs to describe how the spectra from the different modes are cross-calibrated. Each mode has their own noise level, sensitivity, and velocity resolution such that the Doppler velocity power spectral density magnitudes will not be the same for the different modes. The modes must be cross-calibrated and scaled in order to produce the spectra shown in Fig. 1 in units of dBZ (this includes a calibration offset plus range squared correction). Regarding the 3 dB threshold, the manuscript needs more analysis showing the range of power differences between the modes in order to justify a particular threshold so that AMT readers to apply the proposed technique to other radars.

  We agree with the reviewer. 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 $|\Delta S|$ for meteorological signals. Figure A1 (Appendix) presents the statistical plot of $|\Delta S|$ for meteorological signals (height of 2 ~ 3 km and Doppler velocity of 2 ~ 5 m s^{-1}). It appears that the probability of $|\Delta S|$ tends to be flat after 3 dB, and the use of 3 dB can ensure that 95.6 % of precipitation cases are well preserved (Figure 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.”

4. Section 3.2.

This section is very confusing for the reader and needs to be re-written.

- a. The manuscript needs text describing the physical process that is causing the range sidelobes. That is, the de-coding of the phase modulated signal has errors and is causing power to appear in the wrong range gates.

  Our Ka/Ku-band cloud radar use the linear frequency modulation (LFM) technique for signal modulation, the range sidelobe is generated by the response of the signal outside the matched filter. We have added the description of the cause of the range sidelobe.

  "To improve both the radar detection performance and range resolution, Linear Frequency Modulation was used to widen the signal bandwidth when transmitting pulses in modes 2 and 4 at both Ka- and Ku-band. But, the matched pulse compression filter output exhibits sidelobe behavior, making the power of range sidelobe appear in the wrong range gates." has been added to Section 3.2 in the revised manuscript.

- b. Line 173.

  The description "sidelobe caused by the pulse compression drags a long tail in the relatively large velocity bins…" is not correct or is poorly worded. The range sidelobe does not move power (or drag power) into different velocity bins to cause a long tail. The power appears in different range gates at the same Doppler velocity. Please clarify text.

  We have rewritten the sentence to clarify the description.

  "Compared with radar Doppler spectrum observations without the sidelobe contamination (see for example Li and Moisseev, 2020), Doppler spectra above the melting layer at large velocity bins were contaminated by the range sidelobe of the echo below."

- c. Lines 177- 187.

  The description of the PDF powers is not described well. I do not understand what analysis techniques are being performed in this paragraph.

  Sorry for the unclear description in the original manuscript. We have added the determination of PDF_{thresh} in Appendix B.

- d. Figure 4 is confusing.

  To present the results to the reader more clearly, we modified Fig. 4 in the original manuscript (Fig. 5 in the revised manuscript) to show 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. 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 2a (figure 5a in the manuscript) 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. It can be seen that the range bins contaminated by range sidelobe have different spectral power distributions. For Doppler spectra without the sidelobe contamination, the spectral powers corresponding to maximum probability are relatively large. In contrast, for the sidelobe-contaminated Doppler spectrum, its maximum probability corresponds to small power 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 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."

- e. While the manuscript describes the excess power above the melting layer, the manuscript does not address the excess power in the range gates below the melting layer. The manuscript should include a range sidelobe correction for range gates below the melting layer.

  The reviewer is correct that the range sidelobe caused by pulse compression technology appears in both the upper and lower range gates of the target bin. 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 does 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.

- 5. The text on Line 223 states, "This effect leads to the underestimation of V, which is critical in the merging process, and Ze." And line 235 states, "In Fig. 8a1, significant biases of Delta Z and Delta V can be identified, and Delta V increases with Delta Z." There are several issues:
- a. Fig. 8a1 does not show Delta V increasing with Delta Z.
- b. Fig. 8a1 does not show that coherent integration in mode 1 is causing a bias in Z and V relative to mode 3. In fact, the reflectivity difference shown in Fig. 8a1 is of the wrong sense with mode 3 having a smaller reflectivity than mode 1 (Delta Z = mode3 - mode1) Also, there is not a velocity difference between mode1 and mode3 in Fig. 8a1.

  We are sorry for the wrong figure labels in the original manuscript. The figure labels have been corrected in the revised manuscript.

- c. The manuscript needs to describe the expected differences in Z and V due to coherent integrations and then verify these expectations with the observations.

In this work, we aim to develop a new framework to generate merged spectral moments. In this section, we want to show that due to the coherent integration Ku-band mode 2 data is still applicable in spectral merging, while Ka-band mode 2 data should be used with caution.

The statistics of differences in Z and V were to assess whether the coherent integration has a significant impact on Z and V, given V is used in the following spectral merging process. The relation of deltaZ and deltaV depends not only on coherent integration but also on the size distribution of hydrometeors which may be simulated with various parameters. We agree that it would be interesting to look into this in a separate study.

- 6. Figure 12. There is still “clutter” in the moments shown in the left-hand panels. The clutter is present when there is no surface precipitation between 2 and 3 km height and between 20:45 and 21:00 LST. The clutter needs to be removed from this figure or text must be included describing why the clutter is still in this figure. See comment #2, the manuscript needs to verify that the “clutter” in Fig. 12 is due to either non-meteorological scattering or due to cloud particle scattering.

We thank the reviewer for raising this question. After checking the spectra data, we have found that this is due to the different sensitivities of different observing modes. If the clutter signal is detected only by the most sensitive mode, then the previous method will fail to filter it out because there are no signals from another mode to compare it with.

In the revised manuscript, we have improved the clutter removal method by adding a step which compares the width of a spectral mode (see Fig. 3 in revised manuscript) if the signal is present in the most sensitive mode only. A new paragraph has been added in Section 3.1 clutter mitigation:

“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 $|\Delta S|$ 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)."

Suggestions

- 7. Line 43. Define 'non-meteorological clutter'. Is the manuscript referring to reflection from stationary targets (e.g., buildings or poles) or moving targets (e.g., insects, birds, or power lines moving in the wind)?

  We replace the term "non-meteorological clutter" with "non-meteorological signal", which includes signals from stationary targets and moving targets.

  Line 45 has been rewritten as "1) The contamination of non-meteorological signals. The non-meteorological echoes produced by stationary targets (e.g., buildings, trees or terrain) and moving targets (e.g., insects, birds, or power lines moving in the wind) are unwanted but often detected by radar. Narrow-beam-width antenna…"

- 8. Table 1. Include the radar operating mode names to table (i.e., boundary layer mode, cirrus mode, etc)

  The names of operating modes have been added to Table 1.

- 9. Table 1. Include the transmitted pulse length (time and distance) and number of code bits in each mode.

  The pulse lengths of different modes have been added to Table 1.

  In this paper, our Ka/Ku-band cloud radar use the linear frequency modulation (LFM) technique for signal modulation, which is different from phase coding, so we cannot add the number of code bits to the Table. We have added the description of radar signal modulation in the introduction to the radar in Section 2.

  "To improve both the radar detection performance and range resolution, Linear Frequency Modulation was used to widen the signal bandwidth when transmitting pulses in modes 2 and 4 at both Ka- and Ku-band. But, the matched pulse compression filter output exhibits sidelobe behavior, making the power of range sidelobe appear in the wrong range gates." has been added to Section 3.2 in the revised manuscript.

- 10. Figures 12 and 13. Both figures show a gap in cloud structure near 2 km between 20:00 and 20:30 LST. It looks like the mode3 (right panel) shows low level precipitation that does not extend above 1 km and another mode is detecting precipitation above its blind zone near 2 km. The text should mention the vertical gaps in precipitation features and they are due to blind zone issues and different sensitivities of the modes.

To clarify this, these sentences have been added to the revised manuscript:

“Additionally, due to the differences in sensitivity and the blind zones between different modes, mode 2 with the highest sensitivity only participate in the data merging above 2 km at Ku-band, so it can be seen that there is a gap in cloud structure at 2 km which occurs at Ku-band” (Fig. 15 in the revised manuscript).