Answers to referee#2 on "**Establishment and preliminary application of forward modeling method for Doppler spectral density of ice particles**"

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The authors would like to thank the anonymous referee for the comments on the manuscript. The comments are constructive and will help to sharpen and clarify the paper, all of them will be addressed in some manner. In the following, the comments are given in blue. The answers are given in normal black. The modified text in the manuscript is given in quotation marks.

General response:

After carefully considering all the comments of the reviewers, we have made the following modifications to the manuscript:

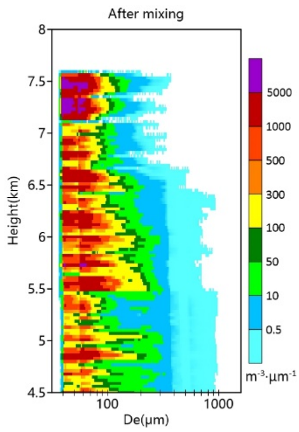
- We added some references to the studies of ice cloud properties using Doppler spectrum density data and discussed the differences between our work and theirs in the introduction and discussion part.
- With respect to the PSD retrieval method, we rewrote the relevant description in a clearer way.
- We realized that our simulation work wasn't good enough. We redid this part and the influence of turbulence and radar sensitivity on Doppler spectrum are evaluated.
- We are sorry for the inadequate description of the data post-processing, we have added the processing method to the data section.

The paper presents a methodology for the simulation of Doppler ice spectra for different ice habits. based on an hydrodynamic and scattering model (the self-similar Rayleigh Gans approximation). The topic is certainly timely and relevant. However I do not see how this paper is providing any novelty and any original contribution to the state of the art. First, radar spectra have been simulated for years both in rain and ice but the authors miss to cite any relevant reference in the field. Second, the simulations as provided clearly lack a lot of realism (no turbulence, no noise floor,). The only simulated spectra that I can see are those produced in Fig.4, right panel. Such spectra have nothing to do with real spectra, do they? Why the authors are not plotting some of their spectra of Fig.6 for comparison? Therefore it does not make any sense to me to attempt a retrieval (the pre-condition to that is that the forward model can reproduce the measured spectra). The results plotted in Fig.6 and 7 therefore make no sense to me. In addition to that it is totally unclear how the authors have accounted for the vertical velocity (the retrieval of the vertical velocity is not a trivial task!), for turbulence and spectral broadening, for attenuation (how can you retrieve IWC if you have not corrected for attenuation?) and for radar calibration. The comparison with the aircraft data is also extremely nebolous. Plot 11 with ice water contents all over the place clearly shows that there is something not right. At a certain point the authors are even extending their methodology to rain (again all previous work on the field is never mentioned), distracting the reader from the main topic. I do recommend the authors to properly refine/revisit their methodology and resubmit later.

Response to specific concerns:

Novelty and original contribution:

We have established a method that can retrieve the complete PSD of ice crystals for the first time, and evaluated the feasibility using the data observed by China's first radar with a solid-state transmitter. According to the results, as long as the proportions of different kinds of ice crystals are known, it is possible to use our method to retrieve the PSD accurately. Because our field measurement only obtained one dataset of aircraft and radar joint observations, to compare with the results of the aircraft, our work is under the assumption that there is only one particle type exist in cloud, further verification requires the support of more data in the future (long-term observation and statistical analysis are needed to provide the priori information). When there are more than one kind of particle exists, it is possible to convert their concentration ratio to the ratio of the Doppler spectrum generated by different kinds of particles based on the σ-D and v_t-D relationship we established, and calculate the PSDs of various kind of particles. We tried to perform PSD inversion by using the ice crystal distribution model given by Baum et al.(Baum et al., 2005), the results are shown in the figure below:



Introduction:

We have added references to the related research in this field. Additionally, an explanation of the strengths of our work and the differences between our work and that of others are added in the introduction and discussion section.

Line 54: "Many studies have focused on raindrop size distribution retrieval using Doppler spectral density data (Liu et al., 2014;Kollias et al., 2011;Gossard et al., 1997)"

Line70: "…Z_e-IWC relationships. In order to obtain more detailed information, many studies have developed using dual-frequency and triple-frequency radar due to the self-richness of these radar data. However, only the inversion of rain DSD or part of the ice PSD and the identification of some microphysical processes in the cloud can be achieved (Liu et al., 2019;Barrett et al., 2019;Kneifel et al., 2016;Kollias et al., 2011). So far, research on ice particle retrieval using MMCR Doppler spectral density in China has not been found. Therefore, we establish the relationship between ice particle microphysical parameters and Doppler spectral density data apply it to analyze microphysical and dynamic properties to verify the feasibility. At the same time, the results were compared with aircraft data in order to evaluate the performance of China's first cloud radar with a solid-state transmitter."

Determine the vertical velocity and the retrieval method:

Actually, the Doppler spectrum observed by radar is defined as the function of the backscattering cross-section of the particles in the detection volume with respect to their fall velocity. The rationale of ice PSD retrieval is similar to the liquid drop size distribution. In fact, we consider the velocity corresponding to the leftmost point of the Doppler spectrum as the air speed at that layer, then the Doppler spectrum is shifted to correspond to zero vertical air motion, the actual droplet size distribution (DSD) in stratiform precipitation can be retrieved form the Doppler spectrum under the assumption that turbulence effects on Doppler spectral density data are negligible. Similarly, for a certain type of ice crystal, the scattering cross-section and falling velocity is one-to-one with the particle scale, which means that we can match the radial velocity detected by radar to the particle size with the air motion removed (so Sz becomes a function of particle fall velocity, i.e. particle size). Since we can calculate the backscattering cross-section of particles of any size, then the PSD can be derived according to Eq. (1).

Doppler spectrum simulation:

The main purpose of our simulation work using the same certain PSD to simulate the Doppler spectrum is to show that even if the same PSD, if the ice crystal habit is different, the Doppler spectrum they produce will also very different. After careful consideration, we adjusted the simulation work of and rewrite this part. We use the maximum diameter to describe the given PSDs and the effects of turbulence and radar sensitivity were evaluated after calculating the S_Z. The rewritten section 2.3.2 is in the following:
"which has been widely used then:

$$N(D) = N_0 exp(-\lambda D), \quad (6)$$

$$Z_e = \int_0^v S_z(v_f) dv \quad (7)$$

Here, $N(D)$ (m^{-3} mm^{-1}) is the number of particles per unit volume per unit, N_0 (m^{-3} mm^{-1}) is the intercept parameter, and λ (mm^{-1}) is the shape parameter. We use the Marshall-Palmer constants given by Platt (1997) at −10°C~−5°C, with N_0 and λ values of 9560 m^{-3} mm^{-1} and 1.32 mm^{-1}, respectively. For single ice crystals, we assume that D ranges from 100 to 5000 μm, and the average PSD was used to calculate the Doppler spectral density produced by four kinds of single ice crystals (based on Eq. (1)). The PSD used for Doppler spectrum simulation are shown in Fig. 4a. By using Eq. (7), the equivalent reflectivity values generated by the four crystal types are 25.8, 24, 24.7 and 12.9 dBZ (hexagonal plates, hexagonal columns, sector-like plates, stellar crystals). Additionally, we calculated the

Doppler spectrum affected by air turbulence at different intensities. According to Gossard et al. (1997), the convolution of Doppler spectrum in clear-air and the air turbulence can be written as:

$$S_{zT}(v_r) = \frac{1}{\sqrt{\pi} w_\sigma} \int_0^\infty S_z[v_f(D)] exp\left[\frac{-(v_r - v_f)^2}{{w_\sigma}^2}\right] dv_f \,, \tag{8}$$

Here, S_{zT} and S_z represent the Doppler spectral density affected by turbulence and in clear-air, respectively. w_σ is the intensity of turbulence. As can be seen in Fig. 4b, air turbulence will broaden the Doppler spectrum while weakening its peak. The stronger the turbulence, the more severe the spectral distortion. For the turbulence of the same intensity, a narrower Doppler spectrum has more severe distortion. Because of the higher sensitivity of mode 3 of the radar, the sensitivity has a limited effect on the detection of Doppler spectrum.

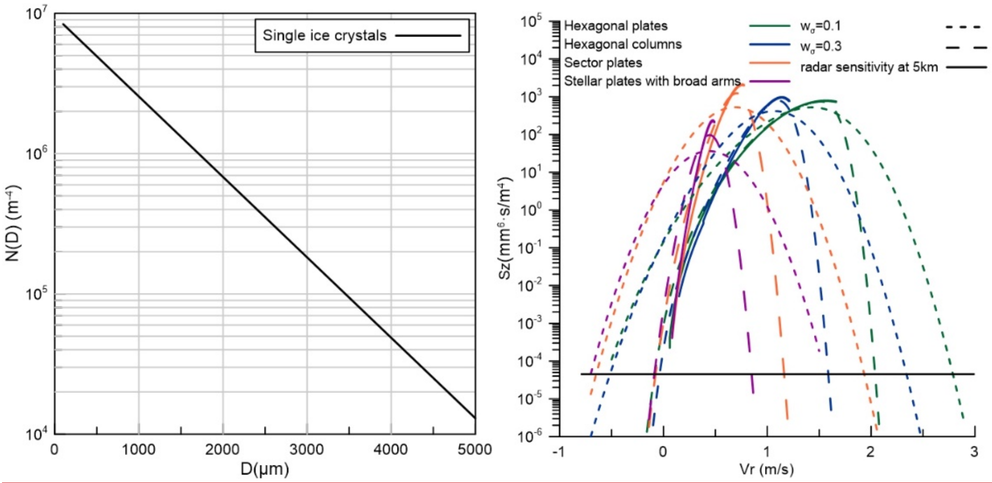


Figure 4. (a) Exponential distribution used in this paper. (b) The Doppler spectral density calculated from the exponential distribution without turbulence (the solid line) and at different turbulence intensities (the dashed line). Radar sensitivity at 5 km of M3 are marked by a solid black line.

Compare the Doppler spectra generated by different types of ice crystals with the same PSD in Fig. 4b, the width of the spectra is mainly inversely proportional to the rate at which the falling velocity increases with the particle scale. The faster the velocity increase with size, the wider the generated Doppler spectrum and vice versa. The value of S_Z is jointly determined by particle backscattering cross-section and $\partial D / \partial V_f$ as shown in Eq. (1), which is proportional to the σ and inversely proportional to the rate of velocity change with particle size.”

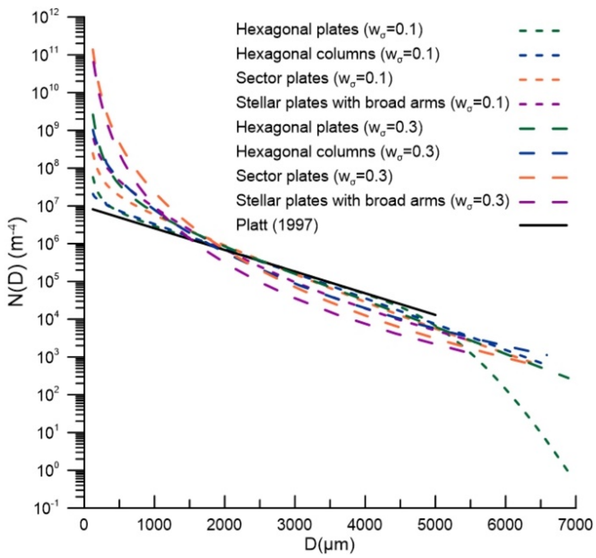


Figure 5. PSDs retrieved from Doppler spectra affected by turbulence shown in fig. 4b. The solid black line is the PSD given by Platt (1977) at −10°C~−5°C (same as fig. 4a).

"To further study the effect of turbulence on inversion of the PSD, the affected Doppler spectra were used to invert the new PSD and compared with the original given PSD. According to fig.5, the new PSDs are significantly wider than the original, an overestimate of the number of particles was occurred when D is small, and an underestimate of the particle number was occurred at the large D. It can be easily seen that stronger turbulence has a greater impact on the inverted PSD, which will cause the particle number deviate from the true value seriously. Moreover, different types of ice crystals have varying degrees of sensitivity to turbulence. Compared with sector crystals and stellar crystals, hexagonal plates and hexagonal columns are less affected by turbulence."

Data processing:

Actually, all the spectrum data is quality controlled before use. We have calculated the noise level and removed the non-meteorological echo, and calculated the attenuation coefficient using the inverted rain droplet size distribution and corrected it. Since the stable stratiform precipitation occurred during the observation and the width of Doppler spectrum was wide, the influence of turbulence was ignored during the inversion.

We will add the details about data post-processing in the manuscript:

"The raw Doppler spectral density data from the four work modes are post-processed and used to recalculated reflectivity, retrieve the vertical air motion. The data post-processing includes quality control (QC), merging for Doppler spectra and recalculating Doppler moments (Liu, et al, 2019). QC for Doppler spectra includes dealiasing singly wrapped aliased Doppler spectral density data and detecting and removing artifacts produced by pulse compression. After QC and merging, we directly estimated the vertical air velocity using the velocity bin of small particles such as liquid droplets and small ice crystals assuming that these particles can be considered tracers of clear-air motion in the measured spectra, we conducted attenuation correction of Doppler spectral density bin by bin from the first range to the end. We calculated the attenuation coefficient from liquid drop size distribution (DSD)."

References:

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