Response to Anonymous Referee #1

We thank the reviewer for his/her constructive comments and suggestions on this manuscript, which are very helpful for us to improve our paper. Our responses to these comments are given below.

- *The authors outline a radar cloud detection algorithm, apply it to simulated data, process 2 months of real data and show comparisons to ARM's operational cloud radar detection. The authors conclude that their algorithm is an improvement since it detects more clouds. Overall, there needs to be more done to show that the algorithm in indeed "new and improved" as they state repeatedly throughout the manuscript. As is, the study presents a slightly-modified detection algorithm, applies it to a small amount of real data without concretely showing if the increased detection represents a true improvement.*

Response: Our hydrometeor detection method first involves convolving the SNR image with a 2-D Gaussian filter to suppress the noise and selecting a proper SNR threshold to separate noise from signal. Since this method does not apply a spatial filter at the initial stage as in previous studies, it can reduce the tendency of removing cloud corners. Figure 1 shows that a threshold of 2.8 can keep a low false positive of 0.12% and a false negative of 2.52%. By aiming to recognize more hydrometeors (e.g. clouds with weak SNR) and maintain sharp cloud edges, the Gaussian filter with the bilateral filter enhances the contrast between weak signal and noise and preserve sharp cloud edges. In our method, the Gaussian filter with the bilateral filter, which has not been applied before, is followed by a spatial filter with a central weighting to further reduce both false positive and false negative. Following the reviewer's suggestion, we apply our radar cloud detection algorithm to longer periods of real data and compare with more MPL observations. We show that our method indeed improves cloud detection.

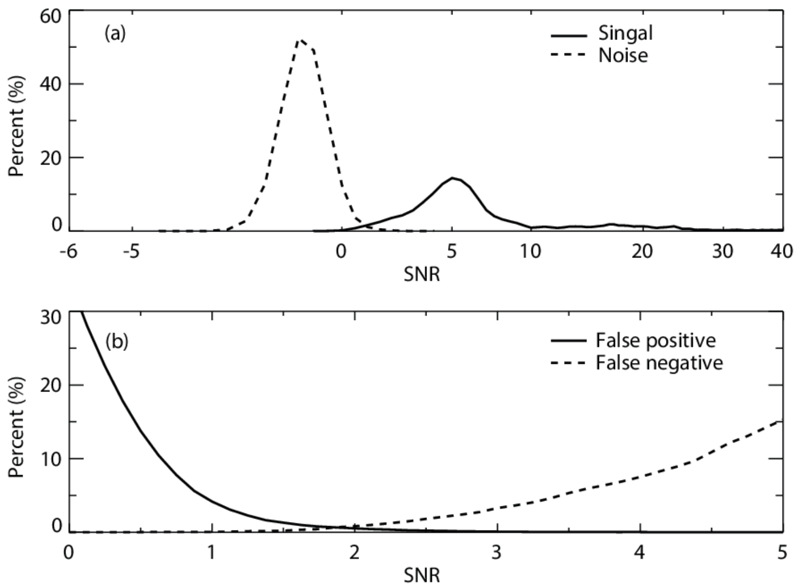


Figure 1. (a) SNR distribution of the noise and signal after convolving with a 3×3 Gaussian kernel, averaged from three simulated "square clouds" that have strong, medium and weak SNR values and random Gaussian noise. Both the noise and cloud signals are sampled from KAZR observation at the SACOL with SNR value from weak to strong; (b) false positive and false negative as a function of SNR threshold.

- The manuscript seems to claim that using the SNR for detection is better than previous work since SNR is Gaussian-distributed. First, the authors show the skewness of the noise distribution to be near-zero and conclude that the distribution is Gaussian. A skewness of zero is a necessary but not sufficient condition for a Gaussian distribution: this only implies the distribution is symmetric. Instead one should show that the noise PDF is best-fit by a Gaussian PDF. Regardless of the actual distribution of the SNR, the transformation from power-space to SNR-space (i.e. Eq. (1)) before applying averaging and a thresholding mask is pointless. As long as the noise is randomly distributed, averaging like the authors do will still reduce the noise and a threshold can still be applied. A Gaussian-distributed weighted average (i.e. Eq. 2) can still be used on non Gaussian noise. The only new part of the algorithm is to applying an existing bilateral filter to avoid smearing edges of cloud boundaries.

Response: We did examine whether the SNR of noise satisfies a Gaussian distribution. Thank the reviewer for pointing this out. We have corrected the improper statement in the revised manuscript. We agree with the reviewer that a Gaussian-distribution weighted average can be used on non-Gaussian noise and can narrow the noise distribution as long as the noise is randomly distributed. However, it is necessary for our method to use a Gaussian-like distribution. We did not mean that the use of the SNR is better than previous work, but just pointed out that SNR is close to a Gaussian Distribution. The application of the bilateral filter function is based on calculating the probability for a given range of SNR values, which relies on the Gaussian distribution. We have modified this part in the revised manuscript to clarify these issues.

- The authors also assume that a higher rate of detection by their algorithm is an improvement over the ARM method. However, they do not demonstrate whether or not this increase is caused by an increase rate of false detections. I suggest that the authors use the MPL as a truth for cloud detection and compare both their algorithm and ARM's to that. Otherwise, there is no way of knowing if the cloud mask is truly improved.

Response: Thanks for this suggestion. We compare the radar cloud mask results derived from our method and ARM algorithm with the MPL detected features in January and July, 2014 when both radar and lidar observations are available. It is found that the increased detections by our method as compared with the ARM algorithm are mostly those also identified as features by MPL. Figure 2 shows an example in January 9, 2014. The green color represents the increased detections that are also identified as features by MPL while the red represents the increased detection that are not detected by MPL. The features that are not observed by MPL are mainly related to a total attenuation of lidar signals by optically thick clouds below or appear below the cloud base from which large precipitating hydrometeors may fall out that can not be observed by MPL.

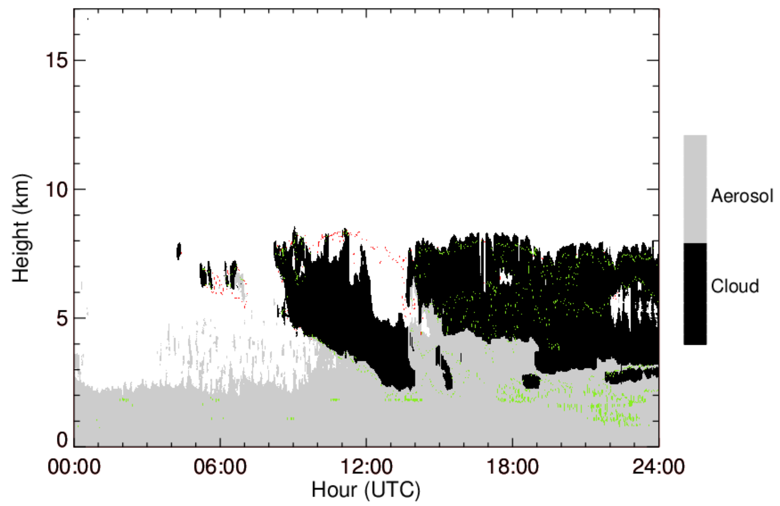


Figure 2. Increased hydrometeor detections by our algorithm versus ARM algorithm in comparison with the MPL feature mask in January 9, 2014. The black and gray regions represent the cloud and aerosol detected by MPL. The green part represents the increased detections that are also identified as features by MPL detection. The red part represents the increased detection that are not detected by MPL.

We analyzed data in January and July, 2014 when both KAZR and MPL observations are available, and showed the percentage of the increased detections identified by both KAZR with our method and MPL observations as compared to the total increased detections in Figure 3. We see that most of the increased detections are also detected as features by MPL. The percentage drops to a minimum of 70% at about 9 km, where the total increased cloud range bins are only about 110 and there are 35 range bins that are identified by our method are not observed by MPL. Considering all the increased detections by our method, 98.6% of them are confirmed by MPL as features.

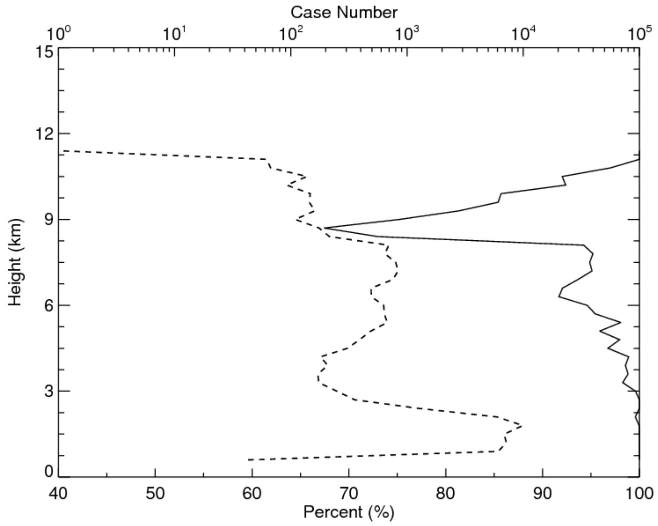


Figure 3. The solid line is the percentage of increased detections seen by both KAZR with our method and MPL as compared with the total increased detections. The dot line is the number of increased detections.

- I am particular considered about their increased detection around 2km since in their example (Fig. 6) many false positives exist at that height. The authors claim that this is dust since the MPL backscatter is larger, but the larger backscatter only exists near the surface. Most of the radar detections around 2km have lower backscatter and appear to be false positives. Even if they are dust, isn't it undesirable to have them in your cloud mask?

Response: Following the reviewer's suggestion, we examine the MPL depolarization ratio for the same case shown in the original Fig.6 in the manuscript. We found that the depolarization ratios of increased detections by our method are larger than those at surroundings, indicating the particles are very likely large dust particles. Figure 4 shows the depolarization ratio of MPL for January 8, 2014.

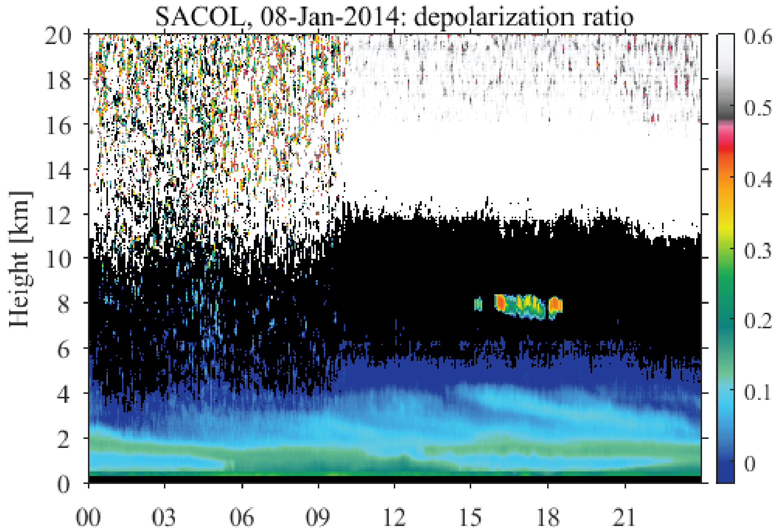


Figure 4. Depolarization ratio of MPL for January 8, 2014.

Although the dust is not desired for cloud mask, the appearance of those particles does prove the ability of our method on recognizing weak signals.

- I would also suggest that the author assess improvement using more than 2 months of data. Part of the strength of both the CloudSat and MMCR algorithms which the authors refer to is that they have process a lot of data between them.

Response: We applied our algorithm to six months of data including 3 months for summer and 3 months for winter, and our method is robust. See more in the following replies and related revisions of the manuscript.

- Some effort should also be made to compare to the newer ARM KAZR and ARM scanning radar cloud mask. The ARM MMCR are now longer used at any of the ARM sites.

Response: This is a good suggestion for our future work.

- A few other thoughts that would improve the manuscript. It would be instructive to see the steps of the detection method (i.e. Fig. 3) illustrated using an image of real data. Also, to aid in determining if you are detecting dust in the radar cloud mask, using the MPL depolarization instead of backscatter would identify dust more clearly. Finally I would suggest adding a confusion matrix as a complement to Fig. 7 would which show that any agreement there isn't due to some cancellation of errors

Response: Thanks for the suggestions. The observation of January 8th, 2014 is used to illustrate the steps of our detection method as shown in Figure 5. Figure 5a is the original SNR input. Figure 5b shows the SNR distribution after noise reduction process. We can see that the SNR distribution becomes much smoother than Fig. 5a. This step is crucial for the enhancement of the contrast between signal and noise. Figures 5c and 5d are results by applying the binary mask and using a spatial filter, respectively. We have added the MPL depolarization shown in Figure 4 to the Figure 6 in the manuscript. We have counted the number of range gates that are detected as noise by our method but signal by ARM algorithm, that are detected as signals by our method but noise by ARM, and that are detected by both for the expanded six months. The results are shown in the Figure 6. It is clear that the cancellation of errors can be negligible.

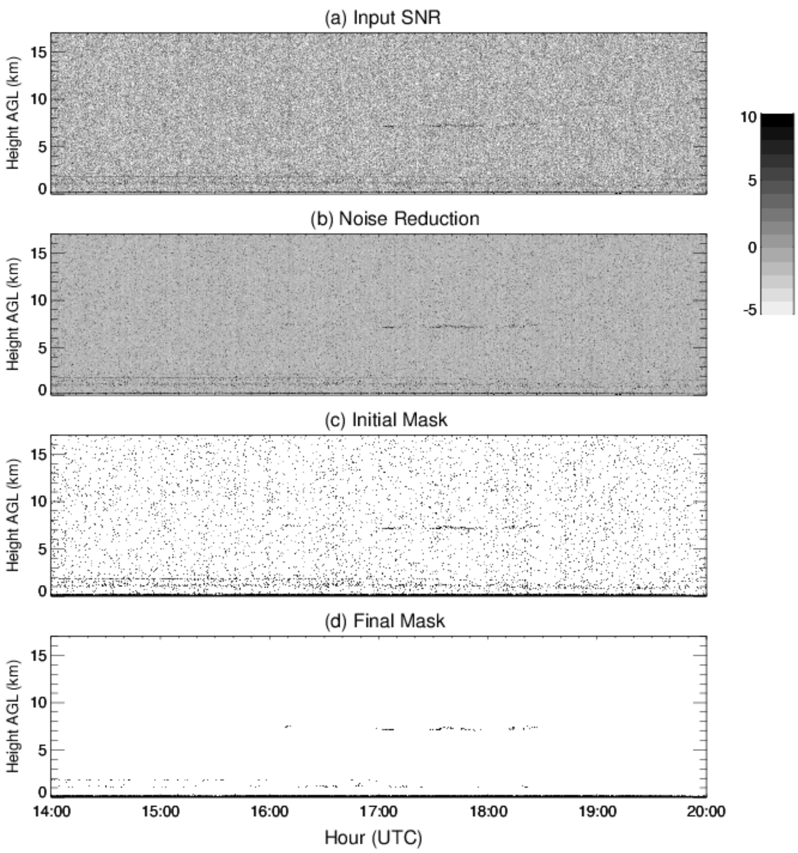


Figure 5. The illustration of the steps of our method for the case of January 8th, 2014.

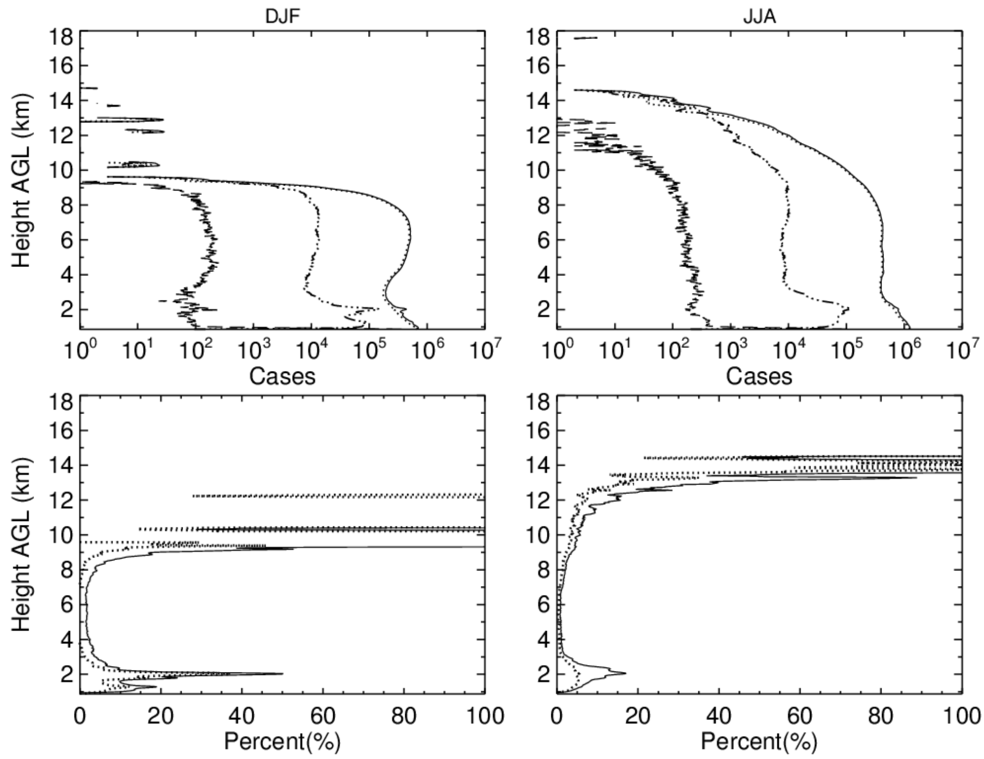


Figure 6. Same as the Figure 7 in the manuscript, but for six months. The dash lines in the upper two panels represent the number of range gates detected as noise by our method but signal by ARM. The dot-dash line is the increased number of range gates that are detected as signal by our method. The dot line, which is close to the solid line, represent the range gate number that are detected as signals by both methods. The solid line is the total number of bins that are identified by our method as signals.

MINOR COMMENTS

line 25: the authors does examine returns at various significance levels

Response: Sorry for the incorrect statement. We have modified this sentence as **"**A noise reduction scheme that can reduce noise distribution to a narrow range is proposed in order to detect cloud pixels with more weak signals. A spatial filter with central weighting, which is widely used in current cloud radar hydrometeor detection algorithms, is also employed in our method to examine radar return for significant levels of signals.**"**

line 27: change "reducing noise" to "reducing the noise"

Response: "the" is added.

line 29: remove comma

Response: comma is removed.

line 33: change "hydrometeor identifications" to "hydrometeor identifications in simulated clouds"

Response: We have made this change.

line 35-36: "move around our planet" is awkward wording

Response: "move around our planet" is deleted.

line 41: replace "stage of" with "component of"

Response: Replaced.

line 43: change "cannot be accurately represented" to "are difficult to represent"

Response: Changed.

line 50: change "models" to "models,"

Response: A comma is added.

line 60: remove "are powerful instruments"

Response: Removed.

line 63: change "and they have excellent sensitivity" to "making them sensitive"

Response: Changed.

line 68: change "in" to "at"

Response: Changed.
lines 71-76: Here you should also mention that the MMCR are no longer used by the ARM program and have been replaced with KAZR.

Response: We have mentioned that MMCRs have been replaced with KAZR at ARM sites.

line 86: remove successfully modified and

Response: Removed.

lines 88-95: all of this can be removed, none of this discussion is necessary
Response: We keep this part because the bilateral filter idea is applied to the cloud

feature detection for the first time.

lines 95-96: don't understand the sentence here

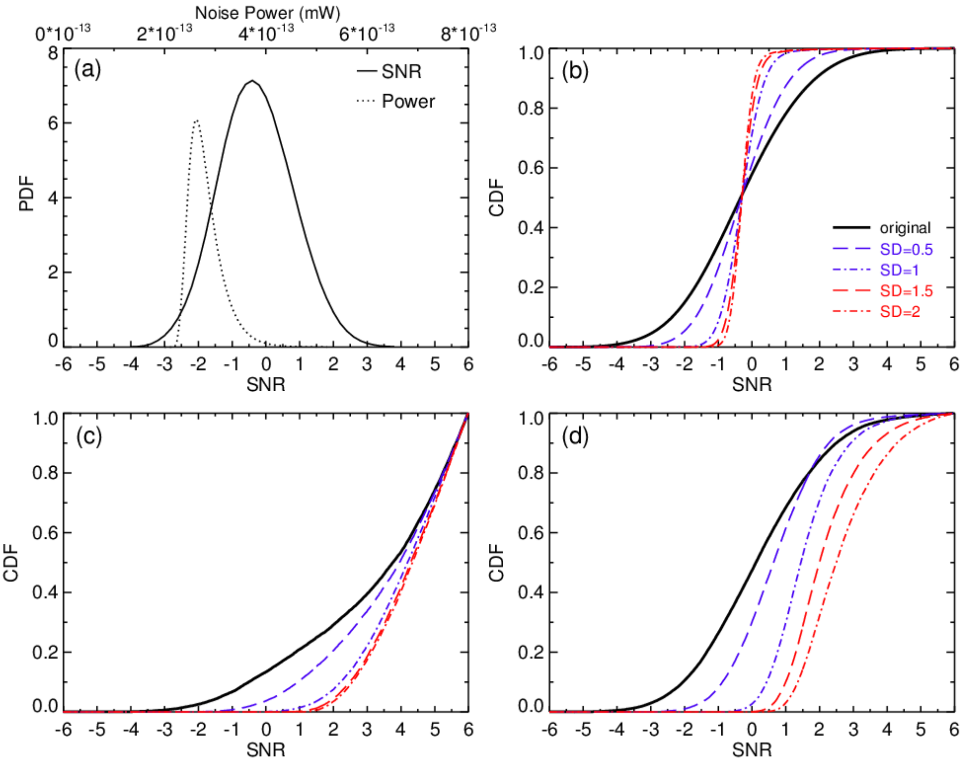
Response: Here we mean that the cloud mask is similar to the image process. (i.e. effectively separate noise from target while keep its feature intact).

line 141: what are "internal and external sources"

Response: We refer the noise generated within the circuit that may be caused by changes of current or temperature as internal sources, and noise induced from the antenna as external sources.

Fig. 1a: why does the power "cutoff" at the high-end of the distribution

Response: It is because the noise power at the high-end of the distribution is larger than the maximum of the upper x axis. This issue is solved by expending the maximum to $8*10^{-13}$ as shown in the following figure.



line 152-154: is there a reason to expect noise to be range dependent?

Response: Here we want to check the reason for the negative mean value of SNR.

line 157-158: change "randomly Gaussian distributed" to "random"

Response: Changed

line 187: "about three standard deviations" or "at three standard deviations"?

Response: not exactly at three standard deviations.

lines 188-203: most of this discussion is unnecessary: it is generally understood that average will reduce noise.

Response: Here would like to show large filter will also blur the boundary of cloud.

lines 207-208: clarify "cloudy or clear side"

Response: cloudy side means the central pixel is cloud signal, clear side means the central pixel belongs to noise.

line 213: replace "prevent" with "reduce"

Response: Replaced

line 225: replace "must be limited to a mediujm size since" with "is a compromise between"

Response: Replaced

lines 245-247: The first sentence says sigma_n is estimate, the second sentence says that sigma_n = sigma_0 / 2. Which is it?

Response: We mean that the new background noise is estimated from the noise reduced data and the value is half of the original background noise.

line 297: replace "good" with "well"

Response: Replaced

line 301: remove "in nature"

Response: Removed.

line 331: remove "respectively"
Response: Removed

line 348-349: This isn't correct. There are many false clouds in the radar mask that don't correspond to large lidar backscatter.

Response: We modified this sentence as "This feature layer is also apparent in lidar observations with both relative large backscatter intensities and depolarization ratios**".**

line 364: remove "wispy-high-level"

Response: Removed.

line 395-396: remove first sentence here. Don’t speculate on unpublished results.

Response: The sentence is removed.

Fig. 6e: add a zoom-in view on the cirrus like in Fig. 6b/c

Response: A zoom-in view on lidar data is added.