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Atmospheric Measurement Techniques
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Interactive comment on "Evaluation of gridded Scanning ARM Cloud Radar reflectivity observations and vertical Doppler velocity retrievals" *by* K. Lamer et al.

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Main Comments:

1) Confusion in reconstruction details: (p.9589 and appendix material) I am a bit confused on some details of the reconstruction. The material on page 9589 line 15 seems to make it clear that only points on the Cartesian grid that are WITHIN the radar resolution volume (that is the cylinder shown in figure 3) are "influenced" by a given measurement.

(Point 1A) This does not seem to match up with the description in the Appendix of

the Cressman scheme which defines a minimum radius (Rd1) based on there mapping/Cartesian grid spacing. If I understand correctly, if only Cartesian grid points within the radar-resolution-volume are used then there would be no need for Rd1.

(Point 1C) On 9589 line 21 you write " In small distance from radar, the radar volume is very small compared to grid cell and it may not contain any grid point. In those cases, the value r_i , theta_i is considered to influence those grid points located in area at grid resolution distance from r_i , theta_i." I do NOT understand the later part of this sentence (poor grammar?). Please rephrase for clarity.

We rephrased p.9589 and added parts of the appendix material to this section to increase clarity (see paragraph below). The key point is that during gridding two scenarios can occur. First case, the radar volume is bigger than the grid resolution and contains grid points. In this case we look at the grid cells within the radius of influence Rd1 which surrounds the observation and only points on the Cartesian grid that are WITHIN the radar resolution area (that is the cylinder shown in figure 3) are "influenced" by a given measurement. Second, the radar volume is smaller than the grid resolution, which happens for instance at small distances from radar or for large grid resolutions. In this case we look at the grid points surrounding the observational point. If those grid points are at a distance less than the grid resolution (within the radius of influence Rd2) they are "influenced" by the observational value.

Radar observations centered at polar coordinate ri, θj are considered to be representative of the area defined by range ri, θ3dB, and pulse length dr with polar coordinates [P1 = (ri - dr/2, θi - θ3dB/2), P2 = (ri - dr/2, θi + θ3dB/2), P3 = (ri + dr/2, θi - θ3dB/2), P4 = (ri + dr/2, θi + θ3dB/2)] (Fig. 3). The radar resolution area increases with increasing distance from the radar, and thus it is necessary to have a variable radius of influence. In some cases, the radar observation area is larger than the grid cell area, thus the radar observation area contains grid cells (within the radius of influence Rd2, Appendix 1). The algorithm estimates the polar coordinates for all grid points and only those grid pixels inside of radar area ri, θj, (bounded by polar coordinates P1-4) are considered to have a value influenced by observational value ri, θj,. In other cases (for instance at small distances from radar or for large grid resolutions), the radar observation area is very small compared to grid cell area and it may not contain any grid point. In those cases, the observational value ri, θj is considered to influence those grid points located within the grid resolution (radius Rd1, Appendix A). Each grid point is allowed to 'have a memory' of all 'influencing' observational points and their distance from the grid point. Finally, once each radar resolution volume is examined, and the observational values that influence each specific grid point are identified, one of the following gridding methods is applied to estimate the radar value at the grid point: Maximum value, mean value, Cressman and Barnes (see Appendix A for details on the available gridding methods).

(Point 1B), what then is the purpose of the bounding Box show in Figure 3?

We agree with the reviewer that the bounding box showed in figure 3 might be confusing. To complement the changes made to p.9589 we propose a revised figure.

Figure 3: Vertical cross section of radar resolution volume with fixed azimuth. Identified are: the beam width (θ3dB), the pulse length (dr), the center of the radar volume in polar coordinates (ri, θj), the edges of radar volume in polar coordinates (P1-4), the radius of influence (Rd1 and Rd2) and the influenced grid cells (shaded red). (a) represents cases where the radar observation area is larger than the grid cells and (b) represents cases where the radar observation area is smaller than the grid cells.

(Point 1D) Perhaps rephrasing will make it clearer. But regardless of what you do with volumes to small to contain ANY Cartesian grid point, there may still be some Cartesian gird points that are not within ANY radar resolution volume (due for example to unevenness in the elevation/azimuthal spacing).

We do hope that rephrasing made it clearer. Given that we use two different radius of influence, the possibility of inaccurately assigning any grid point as a cloud pixel is limited by grid resolution.

2) Linear interpolation (9590 Line 2). With respect to time, you have basically used a nearest-neighbor interpolation in time for the "case 2" points and used linear interpolation in time for "case 1" points. I am not enamored of the linear interpolation, which is likely responsible for some of the shifts you show in figure 6 for the cirrus case. Why not use nearest-neighbor for "case 1"points, as well. This at least would ensure that reflectivity values correspond to measured values.

The gridding in Euclidian x-z plane is performed first and the area distribution histograms of Ka-SACR reflectivities before and after gridding using all available interpolation schemes are shown on Figure 6. Thus, using of the nearest-neighbor method instead of linear interpolation is not responsible for any of the shifts in figure 6b (the cirrus case). Our method will be closer to observations in the case of high-resolution Cartesian grid (when all gridding methods will perform satisfactory) than in the case of low-resolution Cartesian grid (when differences between gridding methods will become more obvious and the effect of smoothing become stronger). This can be seen when comparing Figs 6a (low level stratus, less than 500 meters deep, at +- 5 km from radar, 25x25 m resolution in Cartesian x-z space, see Fig 11a) and 6b (high level cirrus, 2.5 km deep, at +-20 km from radar, 50x50 m resolution in Cartesian space, see Fig 5b and compare to observations shown in Fig. 5a). Please see the discussion that starts at the last paragraph on the page 9591, line 23, end ends on the page 9592, line 17.

Regarding interpolation in time, we use a nearest-neighbor interpolation in time for the "case 2" points and used linear interpolation in time for "case 1" points. Authors are aware of the fact that the use of nearest neighbor in time in preferential than the use of linear interpolation scheme, and the nearest neighbor was our first choice when developing the method. We have however realized that the choice of linear interpolation produces reflectivity time series more consistent to the high temporal resolution observed reflectivity than those reflectivity time series produced by using the nearest neighbor method. Ka-SACR post-processed reflectivity in polar coordinates at theta=0 (or x=0 in Euclidian space) is shown on Figure 8b in function of scan numbers. The time spacing between scans at x=0 is uniform and equal to 21 seconds. Using of the nearest neighbor interpolation in time should produce a reflectivity field very similar (identical in its best) to that shown on Figure 8b. If we compare this reflectivity field to that observed by vertically pointing KAZR (2 seconds temporal resolution), we see how the different temporal resolution impacts the data. In our gridding technique, the choice of time resolution is 3 seconds, so the temporal variability of gridded variables should be very close to the variability of KAZR. Obviously, the nearest neighbor method is not the one that would be preferential. Figure 8a shows gridded time-height reflectivity field using linear interpolation (“cases 1”) and the nearest neighbor method (cases2). This reflectivity compares better to the high temporal resolution KAZR reflectivity than the one shown on Figure 8b that would ideally correspond to reflectivity gridded using the nearest neighbor method in time.

3) Additional information 9584 Line 5: Please provide additional information. Specifically, in regard to the Clothiaux et al. cloud masking, what threshold were used for “on and off”, how large is the spatial-box-filter, and how many iterations?

The details of the feature mask algorithm were recently published at the Journal of Atmospheric and Oceanic Technology. The reviewer is kindly asked to see the following paper and its early, online view for more details: Kollias P., I. Jo P. Borque P., A. Tatarevic, K. Lamer, N. Bharadwaj, K., Widener, K., Johnson and E. Clothiaux 2013: Scanning ARM Cloud Radars – Part II: Data Quality Control and Processing. Online release, Journal of Atmospheric and Oceanic Technology 2013; e-View doi: http://dx.doi.org/10.1175/JTECH-D-13-00045.1. In a nutshell, the feature mask algorithm is applied in two steps. First, the radar received power at each elevation angle is used to estimate the noise floor using the Hildebrand and Sekhon (1974) technique. In cases where a large portion of the recorded range gates contain atmospheric returns, the algorithm does not have enough signal-free data points to produce an accurate estimate the noise floor, leading to highly inaccurate overestimates. For those cases, to avoid misclassication of hydrometeor returns to noise, a “climatologically-derived”

estimate of the noise power obtained from a large collection of noise floor values estimated from many consecutive RHI scans is used instead. Using the recorded SACR receiver noise power noise floor estimates at each elevation angle a first binary feature mask (FM1) along each radar profile (elevation angle) is produced.

To remove remaining small artifacts, a second 2-dimentinal 5-by-5 boxe mask is applied following range-elevation angles. If the number of hydrometeor returns within the box is equal or exceeds 16 , the power return at the center of the 5-by-5 box is labeled as a significant return in the second and final feature mask FM2(i,θ). This process is repeated two or three times until all noisy gates are removed.

4) Insects 9584 Line 20: With respect to the insect identification, what threshold was used for the LDR? I might expect to dependence of the LDR with elevation angle, does the data show such exists?

The details of the insect-filtering algorithm were recently published at the Journal of Atmospheric and Oceanic Technology. The reviewer is kindly asked to see the following paper and its early, online view for more details: Kollias P., I. Jo P. Borque P., A. Tatarevic, K. Lamer, N. Bharadwaj, K., Widener, K., Johnson and E. Clothiaux 2013: Scanning ARM Cloud Radars – Part II: Data Quality Control and Processing. Online release, Journal of Atmospheric and Oceanic Technology 2013; e-View doi: http://dx.doi.org/10.1175/JTECH-D-13-00045.1. In figure 8 of the aforementioned paper, the reviewer can see the distribution of LDR values in insects and hydrometeors as a function of elevation angle. No noticeable dependency of the insect LDR to SACR elevations is observed. Below is a summary of the insect-filtering algorithm described in Kollias et al., 2013: The insect-filtering algorithm is applied only to Ka-SACR returns at heights with temperatures higher than 5 ËŽC. According to Luke et al., 2008, insects are rarely found in temperatures colder than 10 ËŽC. If there are significant radar detections at temperatures warmer than 5 ËŽC, the next step is to use the ceilometer cloud base height detections within a one-hour window around the time of interest. If there are no cloud base height detections in the lowest 3 km within the one-hour window (this situation is frequently encountered during the summertime over the SGP site), then all low-level SACR detections are flagged as insects. If the ceilometer detects cloud bases in the lowest 3 km within the one-hour window the average cloud base height is used to constrain the maximum height to which the insect-filtering algorithm is applied. A LDR threshold value of -15 dB is initially used to conservatively distinguish insect (LDR > -15) and hydrometeor returns (LDR $\leq$ -15). A two-dimensional filtering mask similar to the one applied for the FM is then applied to remove remaining insect-contaminated radar returns. Our ability to distinguish clouds from insects is limited near the cloud edges. In the future, the algorithm will be continuously evaluated and improved using coincident DWR and LDR measurements at 35- and 94-GHz frequencies when available.

Also, how do you deal with the situation where your think insects are present, but the range-volume is also likely within cloud? (For example, you might mark x/z grid points influence by a bug-filled measurement as “unknown” with respect to cloud detection and then use some nearest-neighbor (or other interpolation) to decide detection and reflectivity values for these points.

The possibility of having radar volumes that contain both insects and cloud echoes is small. This is based on the study of Luke et al., 2008 that analyze radar Doppler spectra from the ARM SGP site to develop a radar Doppler spectra-based insect-filtering algorithm. Luke et al., often found insects about the cloud tops of very shallow cumuli clouds but rarely inside clouds. Furthermore, as noted in the revised version of the text above, the insect-filtering is done conservatively to ensure the removal of insect even if it requires to eliminated cloud returns contaminated by insects. In the future, the algorithm will be continuously evaluated and improved using coincident DWR and LDR measurements at 35- and 94-GHz frequencies when available.

5) Relative frequency vs. cummlative frequency. Figure 2 and p. 9586 Line 1: It is hardly surprising that with a sensitivity limit of - 50 dBZ at 1 km, that there are very few cloud detections below -40 dBZ.

We think we should explain in greater detail how Figure 2 was made. Here is a more detail explanation that we also add in the revised manuscript: All totally overcast stratocumulus clouds cases (a total of 600 hours) observed by the WACR (Table 1) during the Cloud, Aerosol and Precipitation in the Marine Boundary Layer (CAP-MBL) field experiment (Rémillard et al. 2012) are used in this figure. The marine stratocumulus observations are classified to periods with no radar-detected drizzle below the cloud base when the radar detected echo base is less than 100 m below the ceilometer detected cloud base height and to periods with radar-detected drizzle below the cloud base otherwise. The above classification does not exclude the presence of drizzle particles above the cloud base but nevertheless is used to separate the dataset in drizzling and non-drizzling periods. For each class and each-hour of observations, the radar-derived hourly cloud fraction (number of columns containing at least one range gate populated by cloud relative to the total number of columns observed) is estimated for different levels of radar sensitivity.

The radar sensitivity at the cloud layer height is -50 dBZ and at this radar threshold, all clouds in the record are detected (cloud fraction equal 1 or 100%). In order to make Figure 2, we gradually eliminate from the recorded data radar reflectivities below a moving radar threshold and we estimate the percent of profiles that still contain detected cloud echoes. Thus, when the threshold is set for example at -40 dBZ, we will lose 10% of profiles because they do not contain echoes higher than -40 dBZ. Thus, the reviewer should interpreter the high cloud fraction at -40 dBZ as the percent of cloud profiles that have develop a radar reflectivity of -40 dBZ or higher.

One can wonder how many more detections there might be if the radar had a sensitivity of - 100 dBZ and how this might significantly change a plot of the cumulative distribution. Because the total number of detection can never be know absolutely, I think it would be far-far better to show a histogram of occurrence for reflectivity (in say -5 dBZe bins) normalized by the number of observations (NOT – I repeat NOT the number of cloudy detections). This number will not change if the radar sensitivity greatly improves and should much equally if not more clearly show that the number of detection below -40 dBZe is decreasing rapidly such that one expects fewer and fewer detections below -50 dBZe.

The point raised by the reviewer is a good one. It is a well-known fact that radars do not detect all clouds. Profiling lidars are far superior in providing true cloud fraction, especially for high altitude clouds. However, the point of the plot is not to show how good or bad cloud radars are, but rather, to illustrate in the radar world, how the cloud fraction will degrade with distance (equivalent to radar threshold). We are trying to raise the point of the impact of distance from the radar on gridded products and the cloud fraction biases induced by the loss of sensitivity with range. The plot is valid in radars, if a more sensitive radar (e.g., -100 dBZ sensitivity) or a lidar was available, the only thing that will change with be the starting cloud fraction for the lowest radar threshold.

6) 9590 Line 2, you write “Furthermore, it should not be higher than a quarter of the scan duration.” Why ?

The time resolution can be interpreted as the amount of observational time assumed collected instantaneously. For more precision we suggest that this value should not exceed $\frac{1}{4}$ of the scan or 5 seconds.

7) p. 9596. While it is not surprising that VH_RHI would not be a true constant, it seem rather odd to me that a linear model would fit the variations. Is it possible that this linear component really represents an error in the determination of the true <V_f> ? Or some systematic error in azimuth or elevation angle ?

This linear fit can represent, as we mentioned in the text, terrain effect (e.g. orographic lifting, sea breeze effect, differential heating convection), but it might also account for an uneven Vf distribution across range.

8) Summary, p. 9599 Line 22. Because the cloud masking is a spatial (low-pass) filter,

simply removing dBZe values after the fact will not make true range-independent mask (and it is unclear to me if such would even be a good approximation).

The authors removed the suggestion from the manuscript. We will let the decision to the users.

9) 9600, Line 10. You write “Near cloud edges, the maximum value interpolation method performs best since the quality of the radar observables strongly depend on signal-to-noise conditions.” Where in the text did you demonstrate this?

It is well known that the quality of Doppler radar observations depends on two factors: the Signal-to-Noise Ratio (SNR) and the radar Doppler spectrum width that is an indicator of how uncorrelated the radar samples are. Near cloud edges the reflectivities are very low and close to the noise floor and thus the signal to noise ratio is low. As a result, all radar Doppler observables (reflectivity, mean Doppler velocity, spectrum width, LDR) will have high uncertainty. This is the reason we propose the use of the max value interpolation at these areas.

A few things you should probably add to the discussion section:

Additional Point for Discussion #1: Limits of Frozen Advection. The comparison of the vertically point with scanning radar is a good idea. But it does not test the value of the frozen advection assumption. That is, the reconstruction is not a representation of the cloud field that would be captured by a camera or satellite. It is not an instantaneous snap shot. The cloud continues to evolve during the âĹij20 minutes of the scan. While the comparison with the vertically pointing radar says something about the quality of the time-interpolation it does address the validity of features in the 3D reconstruction on spatial scales that are larger than the distance between the two radars.

The point raised by the reviewer is a valid one. The gridded fields are not an instantaneous snap shot and their interpretation should be made with this in mind. This is a challenge that all profiling sensors are facing. Even with profiling radars, often we interpreter a time-height (curtain) plot as frozen in time. In this particular scan strategy we are interest to capture the "3-D" structure of boundary layer eddied, their aspect ratio and orientation. According to a recent paper (Kogan, Yefim L., 2006: Large-Eddy Simulation of Air Parcels in Stratocumulus Clouds: Time Scales and Spatial Variability. J. Atmos. Sci., 63, 952–967. doi: http://dx.doi.org/10.1175/JAS3665.1) the typical overturning time of large eddies in boundary layer clouds is 9-10 min and often cloud parcels experience more than once cycles. Thus, we would like to suggest that the frozen advection assumption is valid for time periods that are needed to sample 3-D large eddied in boundary layer clouds (typical horizontal size of eddies 200-1000 m, which is 40-200 sec for a 5 m/sec horizontal wind). For higher altitude cloud, gravity waves are the main source of dynamical modulation and the observed features are longer in spatial scales.

Additional Point of Discussion #2: Purpose of reconstruction. I believe the type of reconstruction you are doing is both a necessary activity and valuable. Nonetheless, I think that it would be unwise to use this reconstruction to then retrieve cloud microphysical quantities. As you show nicely in figure 6, the remapping will change the reflectivity distribution and (as you note later) even the size of some features in the cloud field. Rather, I would argue that to the degree one wants a 3D field of say liquid-water-content, it would be better to retrieve this quantity on the "measurement grid" (as much as possible) and then later remap this retrieval to a Cartesian grid much as you are doing for reflectivity. Do you agree? Either way, I think you should point out that small changes in reflectivity and velocity can have a large effect on retrievals and point out the potential for errors (including biases) if the reconstructed data are used for retrievals.

We fully agree with the reviewer. The purpose of the reconstruction is for the direct radar observables. In case of advance microphysical retrievals (e.g. dual-wavelength LWC retrievals) we strongly recommend to conduct the retrievals at the radar native coordinates (range, elevation, azimuth) where the observables can be best matched and

subsequently gridded the retrieved parameters. We also agree with the reviewer that we should make this point in the manuscript. Thus, we add in the last section (summary) of the manuscript the following sentences: "The gridding of the radar observables (Doppler velocity and radar reflectivity) is recommended for the purpose of investigating the clouds 3D morphology and dynamical structure. Microphysical retrievals, especially those based on dual-wavelength measurements available from the SACRs should be performed at the SACR native coordinate system since small changes in the SACR observables due to the gridding can have a large effect on retrievals."

Minor Comments:

1) Abstract p. 9580 line 5 (and similar for Summary 9599 Line 6) you write " ... a common scan strategy is to repetitively slice the atmosphere from horizon to horizon as clouds advect over the radar (Cross-Wind Range Height Indicator – CWRHI)." I do not believe this is a "commonly" used approach. However, assuming I am wrong please provide several references demonstrating such. Presumably these papers will also have address the limitations and effectiveness of this approach, which should at least be discussed in the context of your present analysis.

The reviewer is correct. We have revised the manuscript as follows: "…a suggested scan strategy is to …"

2) Introduction p. 9580 line 5. Suggest you change ". . . cloud radars are the primary instruments" to ". . . radar and lidars are . . ."

Comment accepted. The manuscript is changed according to the reviewer's suggestion.

3) 9851 line 19. Parenthetical Expression "... objectives (large distances vs. cone of silence) . . ." is not helpful. I do not know what "cone of silence" is or why this is "an objective". Suggest should be "(Mapping precipitation over large areas vs. providing high-sensitivity and high-resolution detection of cloud and precipitation).

We agree with the reviewer's comment. In the revised manuscript the content of the parenthesis is altered are follows: "mapping precipitation over large area vs. providing high resolution measurements over the site"

4) 9584 Line 9. I do not think the expression "land contamination" reflects a good way to think about this problem. There are no doubt difference between marine stratus at the shoreline and marine stratus well off shore. I suggest you write something more along the lines of "The close proximity of this site to the ocean enabled observations of marine stratus because low level winds often advect these clouds shoreward."

We accept the reviewer's suggestion and we added in the manuscript the following phrase: "The close proximity of this site to the ocean enabled observations of marine stratus because low-level winds often advect these clouds shoreward."

5) 9585 Line 23: Of course, it is possible that drizzle is within the cloud but not yet fallen below cloud base or even more commonly is evaporating rapidly and so not detected. You should probably mention these caveats.

The reviewer is correct. The possibility of drizzle size drops above the ceilometer cloud base is real. Thus, we rephrase lines 22-25 as follows: "The marine stratocumulus observations are classified to periods with no radar-detected drizzle below the cloud base when the radar detected echo base is less than 100 m below the ceilometer detected cloud base height and to periods with radar-detected drizzle below the cloud base otherwise. The above classification does not exclude the presence of drizzle particles above the cloud base but nevertheless is used to separate the dataset in drizzling and non-drizzling periods. "

6) 9600 Line 19 you write " . . . the Ka-SACR is able to resolve all important structures." This is way over reaching!! You have not defined what constitutes "all important structures" (are structures at spatial scales of 5 km or 10 cm important) nor in my mind established the validity of structures. In fact, I would say the opposite, you have shown by way of example that some structures are stretched or blurred.

The reviewer is right. We need to define what constitutes "all important" structures. We rephrase the line 19 as: "... the Ka-SACR is able to resolve the largest eddies in the boundary layer cloud that are responsible for most of the turbulent transport of momentum, heat and mass."

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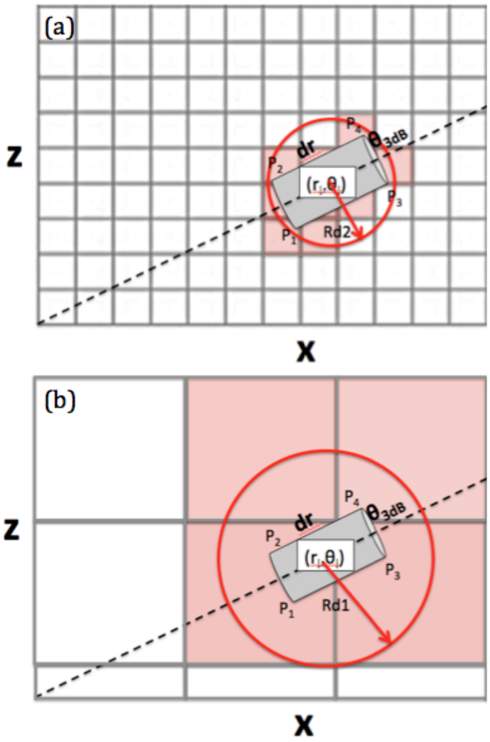

Fig. 1. Figure 3: Caption provided in the discussion