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Atmospheric Measurement Techniques Discussions

Interactive comment on "Reconstruction of 3-D cloud geometry using a scanning cloud radar" *by* F. Ewald et al.

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We thank referee #2 for his/her careful reading, comments and suggestions which we address in the following. The authors' answers are printed in italics:

Remark: The figure numbers in the referee comments are corresponding to the figures in the original manuscript. The figure numbers in the authors' answers are corresponding to figures at the end of this text.

General comments

It's an unusual paper. Based on its title I expected to read how cloud 3-D structure (liquid water path, droplet size and optical depth) can be retrieved from scanning radar measurements. Instead it is more on radar scan resolutions and interpolation between them. After reading this manuscript to the very end, I've realized that it complements to Fielding et al. (2013) paper on using ground-based radar to retrieve 3-D cloud structure rather than overlaps with it. Perhaps, the title of the manuscript should be clarified in order to find its specific readership. The paper definitely deserves to be published in the AMT but after substantial changes. Some of them are suggested below.

→ *Thank you for your feedback. We thought about various changes of the manuscript title. For now we removed the "3D" from the title to counter the impression of a complete reconstruction of a 3-D structure (liquid water path, droplet size and optical depth):*

"Reconstruction of cloud geometry using a scanning cloud radar"

alternative titles could be:

"Reconstruction of cloud shape using a scanning cloud radar"
"Cloud shape reconstruction using a scanning cloud radar"

Any further suggestions are appreciated!

In order to clarify our goals and to avoid wrong expectations we significatly changed the introduction of our manuscript as described in the following answer.

Specific comments

- 1.) The introduction is too short and a bit misleading; it briefly talks about the problems in remote sensing of inhomogeneous clouds but does not link them with the goals of the current paper. From the other hand, some of the statements in the introduction are hard to interpret. Specifically, - what is “the part of the cloud oriented towards sun and sensor” and why the Nakajima-King technique works only there (lines 9-10); - what are “the complex-shaped cloud edges” and how they are compared to the “simple-shaped cloud edges” (line 19); - what is meant by “the unknown cloud surface orientation” in line 21; - what is “volume reconstruction” in line 25. Finally, I believe that the introduc- tory section needs a better description of Fielding et al. (2013) paper and its link to the current manuscript.

→ *Thank you for this feedback. In order to clarify the problem and link it with the goals of our paper, we changed our introduction significantly. Specifically we changed the statements you mentioned as being hard to interpret. The introduction now refers to studies which examine the problem that 1D effective radius retrievals have when confronted with a unknown cloud surface orientation. We hope that the introduction now clearly state our opinion that 1D retrieval can be improved decisively, if the these geometric effects can be compensated for. Since most of the introduction has been rewritten the revised introduction is quoted in full:*

> *Clouds play an essential role in Earth’s climate due to their impact on Earth’s radiation budget. Still they are one of the greatest sources of uncertainty in future projections of climate (Houghton et al., 2001). Most radiative processes connected to clouds are extremely sensitive to cloud microphysics and their temporal evolution. In particular, the relationship between aerosol and cloud microphysics remains in the focus of current research (Rosenfeld and Feindgold, 2003; Kaufman et al., 2005; Koren et al., 2005). The process of aerosol activation and the subsequent growth of cloud droplets define the vertical structure of cloud microphysics as dis-*

> *cussed by Rosenfeld et al. (2008).*

(second paragraph unchanged)

> *A few studies (Platnick, 2000; Chang and Li, 2002; Chang, 2003) have identified methods to explore the vertical profiles of water-cloud droplet effective radius. Though all methods are limited to stratiform clouds or the uppermost cloud layers. In order to change that Martins et al. (2011); Marshak et al. (2006) and Zinner et al. (2008) proposed passive cloud side remote sensing methods to retrieve vertical profiles of cloud microphysics from cloud sides observed from a ground, air or space perspective. Although passive remote sensing has been very successful when applied to satellite data (e.g., Moderate Resolution Imaging Spectrometer (MODIS), Platnick et al., 2003) it reaches its limits when applied to highly structured cloud fields at high spatial resolution. And it is just this type of challange the proposed remote sensing of cloud sides is confronted with.*
> *One of the biggest problems remains the illumination and shadowing of cloud surfaces due to their different exposition to the sun. Effective radius retrievals like (Nakajima and King, 1990) are based on observations of spectrally different absorptions of cloud droplets of different sizes. Illumation, shadowing, leakage and channeling of photons into adjacent cloud columns also have an influence on spectral absorption in 3-dimensional clouds Davies (1978); Davis et al. (1979); Varnai and Marshak (2002). Therefore passive retrievals can be improved decisively, if these geometric effects could be compensated for.*
> *In theirs studies (Varnai and Marshak, 2002; Marshak et al., 2006) systematically quantified the impact of three-dimensional radiative effects on the retrieval of cloud droplet effective radius. Both pointed*

out that heterogeneity effects by shadowing and illumination at a spatial resolution of km$donotcanceloutwhenaveragedovera$ km^2 *region. Locally, Vant-Hull et al. (2007) even found differences up to* μm$betweenilluminatedandshadowedcloudparts.Wethinkthatthecombination$

In a recent study Fielding et al. (2013) worked out ways to retrieve the 3D field of LWC to adress the problem of 3-dimensional clouds in radiation closure measurements. To this end they conducted numerical studies to find suitable scan strategies for a successful reconstruction of the 3-dimensional LWC field. In their work they also investigated the influence of cloud radar sensitivity on modeled surface radiation fluxes. In order to provide a complete description of liquid water content and cloud droplet size they use a common approximation based on a power law relationship between LWC and cloud effective radius (Martin et al., 1994; Liu and Hallet, 1997).

This study will complement the previous work from Fielding et al. (2013) in its aim to analyze the impact of scan resolution and interpolation methods on the reconstruction of a LWC field for one specific cloud. It differs from the approach of Fielding et al. (2013) in that LWC and effective radius is not completely reconstructed on the basis of cloud radar measurements alone. Rather it tries to provide a cloud volume which cloud complement subsequent passive retrievals using radiance measurements from cloud sides.

In an effort to set up ground-based remote sensing of cloud sides, the presented 3-D cloud reconstruction technique will provide valuable additional information for passive retrievals from this perspective. For this task the center of consideration is put on the reconstruction of cloud surfaces oriented towards passive sensors. Not only this specific application but basically every remote sensing technique, especially passive, can benefit from such a reconstruction of cloud sides.

In this study, we therefore want to address the following questions:

1. *How scan resolution and scan strategy impacts the reconstruction of a single cloud*
2. *Which interpolation method is best suited for this reconstruction*

3. *How cloud radar sensitivity influences the performance of this task*
4. *Test the feasibility of this approach to real-world applications*

(last paragraph unchanged)

- 2.) Unfortunately, I am not familiar with the different interpolation methods used in the manuscript: nearest-neighbour interpolation, Shepard method, barycentric interpolation, and natural neighbour interpolation (section 3.3). What is the difference between them? How does the “natural neighbour interpolation” differ from the “nearest-neighbour interpolation?” It was hard for me to appreciate the comparison done by the authors and their conclusion to choose the “barycentric interpolation.” This is especially true since the RMSE for all four interpolations are very close.

  → *You are right. Up to now the manuscript was missing a descriptive introduction of the used interpolation methods. We also changed the analysis of interpolation artifacts in the original Fig. 5. The comparison of artifacts visible in the LWC is now done for LWC and LWP with the LES data itself (cp. Fig 3 and text changes in answer to referee #2). We wrote a new section to describe the concept and advantages/disadvantages of the used interpolation methods:*

  Delaunay triangulation and Voronoi tessellation
  All used interpolation methods can be explained within the framework of the Voronoi tessellation which is based on the Delaunay triangulation. In Fig. 1 both concepts are illustrated for a set of known measurements in two dimensions which are represented by the blue point set and the singular red point where the measured field is unknown and is subsequently interpolated. Fig. 1 on the left

shows the Delaunay triangulation for a set of exemplary measurements. The Delaunay triangulation maximizes the minimum angle within all triangles in the triangulation in such a way that no point lies inside any circumcircle of all the triangles (Delaunay, 1934). In this way the three vertices of a triangle are the three nearest points for each point within the triangle. This triangulation is directly related to the Voronoi tessellation as its dual graph which is shown on the right in Fig. 1. The Voronoi cell for a single point is defined by all median lines between this point and vertices of triangles the same point belongs to. In this way the voronoi cell marks the nearest-neighbor region for this point.

Nearest-neighbour interpolation

This property of the Voronoi tessellation directly relates to the Nearest-neighbour interpolation. It is the simplest interpolation method and is based on the Euclidean distance $d(x, x_j)$ between some points x and x_j. The value of a function F for a given point x is simply the value f_j for the nearest point x_j that minimizes the Euclidean distance $d(x, x_j)$:

$$F(x) = f_j \text{ for some } x_j \text{ with } d(x, x_j) = \min_j d(x, x_j) \quad (1)$$

This method neglects the values of all other neighboring points. The interpolated field therefore exhibits jump discontinuities and rough edges.

Shepard's Method

One interpolation method that overcomes this problem is the Shepard method (Shepard, 1968) also known as Inverse Distance Weighting. Here, the value of a function F for a given point x is

a weighted average of all known values f_j at the known points x_j. The known values f_j are averaged with their weight w_j, the inverse of the Euclidean distance $d(x, x_j)$ to the power of the parameter p:

$$w_j(x) = \frac{1}{d(x, x_j)^p} \quad (2)$$

The value $F(x)$ is then the averaged sum of all known f_j with w_j:

$$F(x) = \frac{\sum_{j=0}^{N} w_j(x) f_j}{\sum_{j=0}^{N} w_j(x)}, \text{ if } d(x, x_j) \leq d_{\text{max}} \text{ for all } j \quad (3)$$

Due to the inverse of the distance the weights w_j decrease for points far away from x. The power parameter p determines how fast these weights decrease. For points in $\mathbb{R}^k$ the power parameter has to be $p > k$ because otherwise $F(x)$ would be dominated by points far away instead of points nearby. For $p \to \infty$ this method converges towards the result of the Nearest-neighbour interpolation. One advantage of this method is the smoothness of the interpolated field. The disadvantages are its high computation cost as the number of points increase and the so called bull's-eye effect which creates circular regions around data points.

Barycentric interpolation

The interpolation method is based on the barycentric coordinate system. In $\mathbb{R}^2$ this coordinates are also known as areal coordinates. They are proportional to the areas of the three triangles that are

formed by joining x with each vertex x_j of the triangle ΔR enclosing point x. For ΔR all values of the barycentric coordinates for point x are positive. As shown in Fig. 1 the value $F(x)$ at x (red point) is a linear interpolation of the values f_j at the known vertices x_j (yellow, magenta, cyan) of ΔR. The value f_j at each vertex x_j is thereby weighted by the area of the opposing triangle. The weights are normalized with the total area of ΔR (see Fig. 1).
Arithmetically, the barycentric interpolation is a variant of Lagrange polynomial interpolation. There, values of $F(x)$ are represented as a linear combination of values f_j and the Lagrange basis polynomials ℓ_j:

$$F(x) := \sum_{j=0}^{k} f_j \ell_j(x), \qquad \ell_j(x) := \prod_{0\leq m\leq k m\neq j} \frac{x - x_m}{x_j - x_m} \tag{4}$$

For a given set of measurement points x_j the part w_j in $\ell_j(x)$ is independent from point x for which $F(x)$ is interpolated. With so called "barycentric weights" w_j the Lagrange basis polynomials can be written as

$$\ell_j(x) = \ell(x)\frac{w_j}{x - x_j}, \qquad \ell(x) = \prod_{0\leq i\leq k}^{k} (x - x_i), \qquad w_j = \frac{1}{\prod_{i=0,i\neq j}^{k}(x_j - x_i)} \tag{5}$$

The term $\ell(x)$ can be eliminated by dividing (Eq. 4) by the interpolant of the constant function $F(x) = 1$. This then yields the "second form of the barycentric formula":

$$F(x) = \frac{\sum_{j=0}^{k} \frac{w_j}{x-x_j} f_j}{\sum_{j=0}^{k} \frac{w_j}{x-x_j}} \tag{6}$$

Based on (Eq. 5) it becomes clear that the barycentric weights w_j can be precomputed for a given set of measurement points x_j which speeds up the subsequent interpolation of $F(x)$. Moreover Berrut (1988) proved the convergence and numeric stability of barycentric interpolation for scattered as well as for equispaced points. In particular, the measurement pattern of a scanning cloud radar with its linear beams and its diverging scan curtains comprises scattered as well as equispaced measurement points. The produced fields are continuous and the interpolation adapts itself to the local measurement geometry.

Natural neighbour interpolation
The natural neighbor interpolation (Sibson , 1981) is based on the Voronoi tessellation of a given point set x_j. Contrary to the barycentric interpolation this interpolation includes not only the three vertices of the enclosing triangle for point x but all its natural neighbors. The natural neighbors can be understood by the adjacent Voronoi cells of point x when point x is contained in the Voronoi tessellation of the given point set. The area of each former Voronoi cell that is lost to the newly formed Voronoi cell of point x determines the interpolation weight w_j for the value f_j at x_j (see Fig. 1, right). The natural neighbor interpolation produces continuous and smooth fields while it remains computationally complex (Park, 2006).
For one elevation height the next figure shows the Delaunay triangulation (Fig. 2, left) and the Voronoi tessellation (Fig. 2, right) of the proposed S-RHI scan pattern shown in Fig. 3. For both methods with increasing radial distance the grid cells adapt naturally to the increasing lateral distance between adjacent scans. All discussed methods are not limited to $\mathbb{R}^2$ but can be generalized to $\mathbb{R}^k$. In the

case of cloudradar measurements ($\mathbb{R}^3$), the Delaunay triangulation is based on tetrahedrons while the Voronoi tessellation is based on convex polyhedrons.

- 3.) Why the “resolutions coarser then approximately 2 ° to 4 ° have to be avoided.” According to Table 2, the difference between 4 and 5 degrees resolution is negligibly small. The difference is also hard to see clearly in Fig. 3. Perhaps, the choices of resolution should be related to specific applications.

  → *We removed the quoted sentence since such a detailed subdivision can not be deduced from Table 2 or Fig. 3. Nevertheless there is a clear difference visible in Fig. 3 between results with 2 ° compared to results with 5 ° scan resolution. The message of this study should be that a 5 ° scan resolution is to coarse to reproduce the radiance field of the original cloud side (although 5 ° would be nice for a shorter scan duration).*

- 4.) The analysis of power spectrum density is very interesting. However, it is difficult to interpret it without understanding of what each interpolation does. Also, why the “true” spectrum is larger even for large scales?

  → *Thank you for this hint! We rechecked our PSDs calculation and found an mistake which cut out a slighly different domain region between original and reconstructed LWC fields. After thorough checks only the Shepard method seems to “lose“ total liquid water by 14% compared to the original LWC field (cp. Fig. 4 at the end of this text). The interpolation methods are now introduced and described in Sec. 3.3*

- 5.) I would recommend adding a droplet size distribution to the field in Fig. 1.

  → *We wanted to set the droplet size constant so the scan strategy and interpolation methods can be isolated and properly evaluated. For this reason the*

droplet size should remain fixed in the revised version of the manuscript. We would like to keep this manuscript as compact as possible without touching a completely new topic concerning sensitivities to size distributions.

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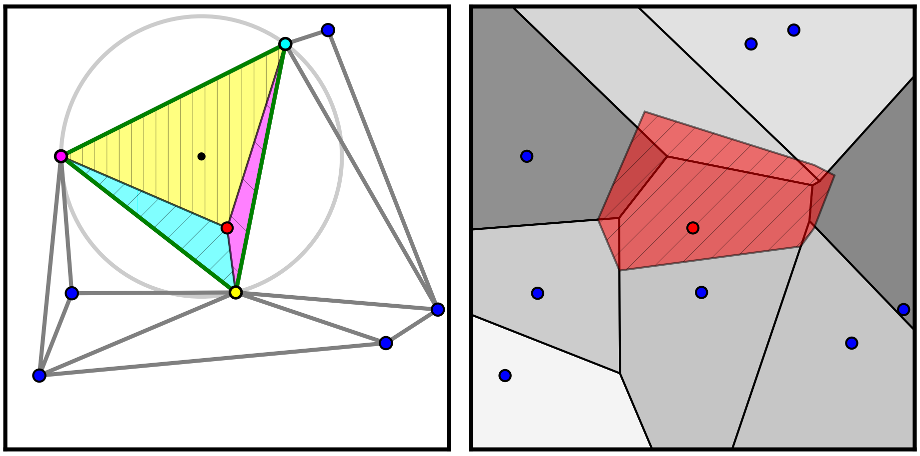


Fig. 1.

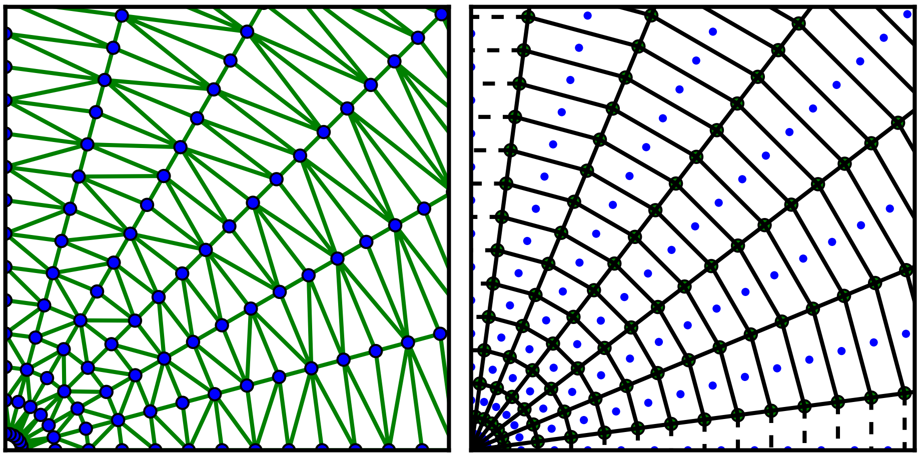
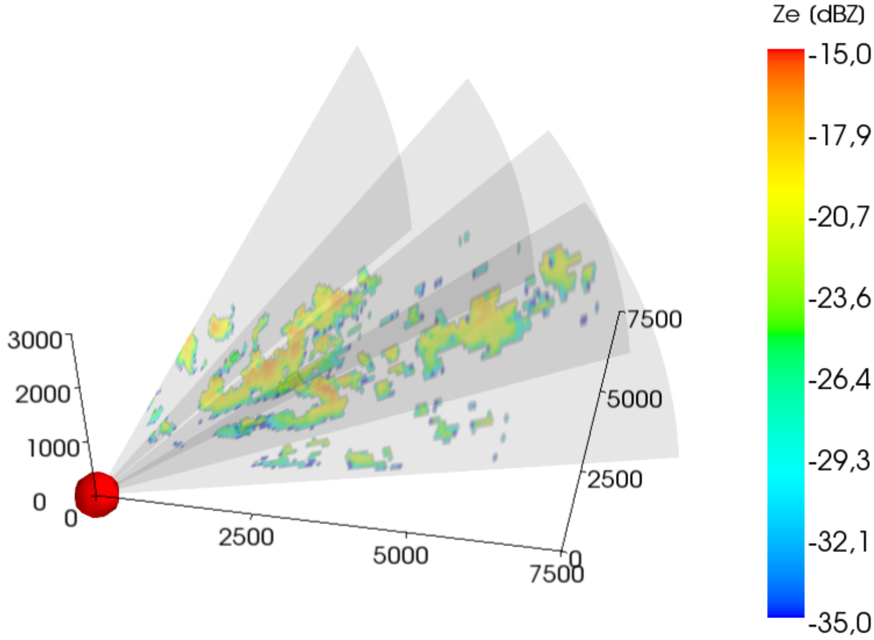


Fig. 2.


Ze (dBZ)
-15,0
-17,9
-20,7
-23,6
-26,4
-29,3
-32,1
-35,0
3000
2000
1000
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0
2500
5000
7500
0
2500
5000
7500

Fig. 3.

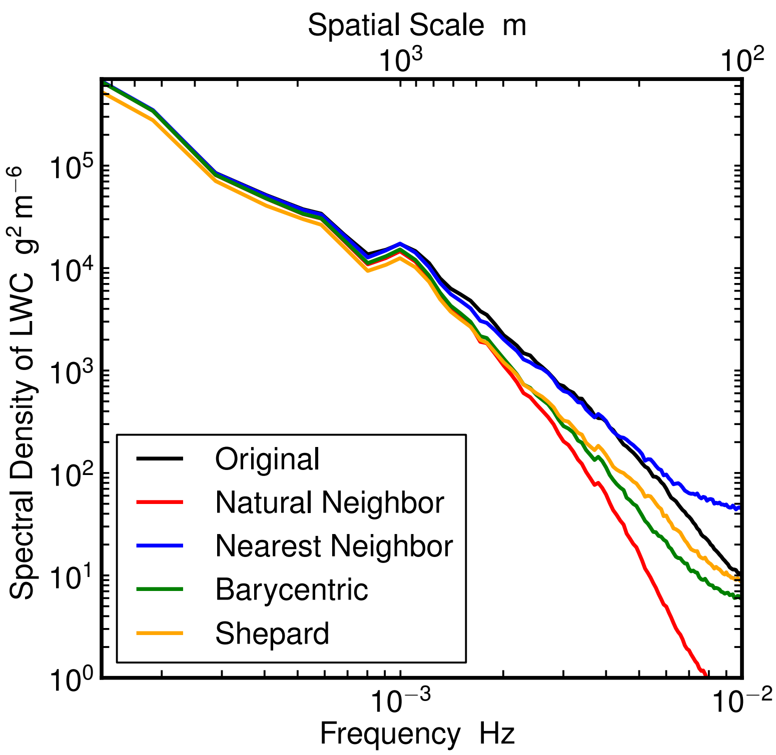
Spatial Scale m
10^3
10^2
Spectral Density of LWC $g^2\,m^{-6}$
10^5
10^4
10^3
10^2
10^1
10^0
Original
Natural Neighbor
Nearest Neighbor
Barycentric
Shepard
10^{-3}
10^{-2}
Frequency Hz

Fig. 4.