Response to interactive comment on “Insights into wind turbine reflectivity and RCS and their variability using X-band weather radar observations” by Martin Lainer et al., by Jochen Bredemeyer (Referee)

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Martin Lainer (on behalf of all co-authors), 12.03.2021

Color Code: **Referee comments**, **Author responses**, **Relevant changes in the manuscript**

We thank the Referee for his constructive and well structured comments.

In the following part we will give point by point answers and/or comments to all points raised by the Referee. We try our best to further improve the paper based on the review. Relevant changes in the manuscript will be explained/cited with highlighted green color coded text. For simplicity we only provide links towards the section of the manuscript. For the detailed changes please refer to the visual mark up version produced by *latexdiff*. Be aware that the visual mark up did not work for all the Figures and their captions smoothly as well as for the references.

My overall statement: I find this paper very valuable, since it develops in a comprehensive form the deviation of a single WT’s RCS from a a measured dBZ gained from a precipitation radar. Special care is taken to set up a measurement to isolate the radar return from specific wind turbines. Much work is invested to present a meaningful statistical analysis.

Remark on nearly all Figures: The tics and axis names are to small, and some important marks in the diagrams are also too small. This makes some figures quite unreadable.

Many thanks for the good rating of our performed study. Regarding the point of the Figures, all of them are improved in the revised version, regarding e.g. the readability (labels, legends, tics, color codes).

Abstract (Paragraph 1) and Introduction (i.e. Par. 45):
The radar in use is a "precipitation radar". Please use at least once this term.

We were using the term weather radar mostly. Weather radar + X-band defines in our opinion pretty well the system and its capability. It could be mentioned once that this weather radar is sensitive mostly to hydrometeors in the precipitation-size range.

In Section 2 we now say: “The measurements presented in this paper have been collected with a dual-polarization, simultaneous transmission and reception (STAR), mobile Doppler weather radar, which operates at a frequency of 9.48\,\unit{GHz} (X-band). This radar system is sensitive mostly to hydrometeors in the precipitation-size range.”.

In the introduction we use once more the expression X-band in conjunction with the weather radar system.

Par. 30:
"RCS is an optimal variable to estimate the effect of a wind turbine on the performance of a radar system, in fact existing numerical models for estimating the back-scattering efficiency of wind turbines rely on this quantity."

According to [1] ("scattering cross-section:") the incident field is assumed to be planar over the extent of the target. This is in principle not the case for objects on the ground and causes some restrictions.

We think it is more appropriate to focus on the reflectivity measurements in the paper (as pointed out by Referee #1). Still we would like to present the RCS as an generalized concept which can be more of use and interpreted by the radar community rather than the weather radar community. We suggest to clarify within Par. 30:

“RCS is an optimal variable to estimate the effect of a "point target" on the performance of a radar system. With the term "point" we mean a target, which is much smaller than the radar sampling volume and with a size such that the incident field could be assumed to be planar over the whole extent of the target. However, the RCS concept is often generalized and extended to larger objects, starting with small airplanes, but then reaching even large airplanes and wind turbine. As a matter of fact, existing numerical models for estimating the back-scattering efficiency of wind turbines rely on this quantity. It is the projected area needed to isotropically re-irradiate the same power as the target scatters in the direction of the receiver and is usually expressed in decibel units related to one square meter (dBsm) (Knott et al., 2004; Skolnik, 1990). The detailed background on how the RCS is computed within our system is given in Sec. 3.“

70:
I am missing a hint or a justification why the radar pulse width was selected 0.5µs but no other values. Is there a technical restriction? Same for PRF.

The overall requirements for us to be met were to have a maximum range resolution but still containing most of the WT object and a high as possible Nyquist velocity. With a pulse width of 0.5µs we achieved a good target range resolution of 75m. Compared to the 0.33µs pulse shape, the one for 0.5µs is also more uniform and thus preferred in our system. It has been decided to keep this value constant for all the measurements. The antenna movement is slow, ensuring data collection every 0.1° (one radial) azimuth, while the PRF is set high enough to ensure a large number of pulses for each radial and a reasonably good unambiguous velocity (Nyquist) range.

Section 2: we add correspondingly the following: “For the campaigns we are consistent and stick to one pulse width of 0.5µs to have a good target range resolution of 75m, where most of the radiation energy is scattered by the WT object. The 0.5µs pulse shape is, compared to the one for 0.33µs, more uniform and thus preferred in our system. The antenna movement for the measurements in 2019 is slow, ensuring data collection every 0.1° in azimuth (one radial), while the PRF is set high enough (2kHz) to ensure a large number of pulses for each radial and a reasonably good unambiguous velocity range."

125:
"... co-polar correlation coefficient are represented on 2019-03-24."
Are these coeffecients in use later when developing eq. (7) using eq. (3) ? (3) is defined for circular polarization.
"During the fixed-pointing scans, the antenna of the radar was not moving and always pointing to the same wind turbine"

Yes, to derive equation 7, we have used the Probert-Jones approximation of the sampling volume.

Fig. 2 too small, unreadable

Figure 2 is redesigned. A different wind speed bin width of 4 m/s is applied and the color bar changed. Now the legend is much better visible.

150:
"The wind turbine clutter is clearly visible at the range from 7.7 to 8.6km as high ZH, HV and low ZDR and all three turbines can be distinguished from other ground clutter signals"

In order to make the WT clutter better visible, we plotted (regarding also the comment of Referee #1) the 35 dBZ contours on all PPIs. It is the fact, that with ZDR it is very difficult to distinguish the WT from the surrounding clutter echoes. The expressions in the text on it, are now more carefully formulated.

165:
"In the following part of the paper, all the horizontal reflectivity ZH measurements and retrieved RCS data ..."
See restrictions of RCS mentioned above and discuss the applicability.

We will delete the text part "...and retrieved RCS data ...". Also Referee #1 mentions the restrictions of RCS for such a huge target. Hence, we would keep a low profile and focus on the measured radar reflectivity values and simply write the conversion factor for going from dBZ to dBm2 , which is , for instance, ~34.4 for WT1 at 7740 m distance.

Section 3: Added Table 5 with all 3 conversion factors to go from dBZ to dBm2. Section 3.1: removed some parts where we explicitly mention RCS.

175:
eq. (1) is simply a form of the radar equation and should be referred to as it is.

We suggest to write something like:

Section 3: "According to Battan (1973) the radar equation for a single, isolated target is: ... where [Pr] = mW is the received lossless power by a directional antenna."

185:
"Accounting for the actual distribution of power within the beam generated by a circular parabolic antenna, a correction factor of 1/(2 ln2) was introduced by Probert-Jones (1962):"
The development of the later eq.(7) has some uncertainties, i.e. the usage of eq. (3) which applies to circular polarization. Please mention that and discuss what the restrictions may be applying linear polarization.

The main focus of this paper is on the backscattered radiation received by the channel that is sensitive to the horizontal polarization. Your question regarding what state of polarization is actually transmitted by our X-band radar is intriguing and interesting; however, such discussion goes far beyond the scope of the present analysis and study.

What we can tell you, is that we are far from being sure that the relative phases of the simultaneously transmitted H and V components are perfectly adjusted (0˚ shift) transmit purely linear slant polarization (45˚ or 135˚). On the contrary, some practical measurements, which have been performed at the Site Acceptance Test with a spectrum analyzer and a receiving horn which was rotated by 45˚ steps (horizontal, vertical, and two slant-observations), seem to show that the X-band radar is transmitting something that is more similar to circular than to linear slant.

195:
"The Rayleigh approximation of the backscattering cross section of a single water drop d can be expressed as ..." Is there a reference to literature?

An appropriate reference to literature would be the book by e.g. Fabry, F. Radar Meteorology: Principles and Practice, 1st ed., Cambridge University Press: Cambridge, UK, 2015. In particular, page 11-13, Sec. 2.2.2 Scattering Regimes and 2.2.2.1 Objects with sharp boundaries.

Another recent good book is by Ryzhkov and Zrnic: Radar Polarimetry for Weather Observations, Springer, 2019.

We add the citations mentioned above for the equation (5).

215:
"The statistical overviews in Figs. 5 and 6 show the maximum (1st row), median (2nd row) of ZH and the maximum retrieved RCS (3rd row) for all three wind turbines."
So equation (7) is used for that representation, please make a note.

You were right, Eq.7 was used to derive the RCS for the Figures 5 and 6. However in regard to the changes ma

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250:
"Figure 7 shows the variability of the location and intensity of the RCS maxima. The farther apart the blue and black histograms are, the higher is the variability of the distribution of the maxima."

Please explain this in more detail.

In Figure 7, both curves represent RCS values according x-axis. However, the legend says "Pmax" and "RCSmax", which is confusing. Please correct or clarify.

"The blue histograms are calculated at a fixed position (as listed in Table 13)"

Mistake: Table 13 ?? –> Table 3

Unfortunately Figure 7 had to be removed from the manuscript and thus all comments on it are omitted. The reason is already explained in the answer to Referee #1.

265:
From the 2020 measurement, it may be interested to zoom much deeper into time to see the fluctuation across a short period, i.e. within some seconds in contrast to the long-term diagram as of Fig. 8.

Figure 9: "dBZ" and "dBsm" refer to absolute values. If the meaning is a variation, i.e. for a bin, always use "dB" alone without reference!
Same mistake as in line 265 "about 4dBsm higher". There are maybe more of these in the entire text. In line 285 however, it’s correct: "... bin width of 0.5dB".

Regarding your first comment here, we note that a future study will go into and analyze much shorter time periods, where very interesting effects could be observed also in context to polarimetric parameters. In this manuscript, where we give a first overview about the campaigns, we would not go yet into such details. But totally true it is of high interest to the community.

We will go through all units, to be sure that variations/differences etc. will be shown correct as dB. Thanks for the careful review on this.

All units have been checked and corrected.

280:
"From the polar plots in Fig. 9(a, c) we see that the relative orientation of the turbine/nacelle is insensitive to the maximum values, evident by the round and not too much disturbed distributions"

Is this correct for a) _and_ c) ? For a) I agree. I think for the median values (red) this is correct for a) and b) depicting the dBZ. Is the averaging time always the 10 min as of Fig. 8 ? In sub-figures c) and d) the difference of medium RCS across the two positions "radial 90/270°" and "tangential 0/180°" is lower than I would expect.

Could that be validated from other sources/measurements for X-Band (references)? I have seen many RCS simulations for WTs in C band that claimed differences >20dB. From own measurements close to reflecting WTs we got differences of >30dB with rotor planes in frontal (0°) and side (i.e. 90°) view [2]. However, there is obviously a difference from the radar's point of view. It observes the target over a larger distance that includes terrain effects.

Old Fig. 9 (new Figure 10) changed regarding to Referee #1. There we now do not show RCS anymore, but a version with Doppler filtered data to separate the static WT clutter parts. Between (a) and (c) in the old Figure only an offset regarding added Table 5 is present. The time window for the median values in Figure 8 was 10 min. In the polar plots we use all available observation as shown in black/grey in new Fig. 8a and b. Some uncertainty is introduced because we have the orientation only every 10 min. For a direction of 90° for instance we assign all ZH measurements to and then calculate the median from the whole sub data set.

To find an appropriate source for validation purpose is difficult, as the measurement setup (point of view, distance, clutter) is quite unique. Accommodating also with your last comment, we suggest that we cite your study [2] on the C-Band results.

290:
"Future work should take also into account numerical simulations ..." Yes, that might be interesting. I have not seen many in the X band. However, methods like MoM or even MLFMM might not be suitable due to the huge number of triangles to work with. Asymptotic methods l(like PO, GO), however, might neglect some eletromagnetic (near) field effetcs.

Thank you for this short overview of available methods that could be applicable. Colleagues from the University of Bern perform MoM calculations with HFSS. In future we might consider a small collaboration on the WT subject.

300:
"For example on 2020-03-12 or 2020-03-22 blade pitch angles of WT1 were aligned at roughly 90◦ over hours..."

In Fig. 10 it would be helpful also to have an additional curve that simultaneously shows the orientation across the time axis.

You are absolutely right, it is a very good idea too show in old Fig. 10 (now Fig. 12) the time series of the WT1 relative orientation. In order to keep a good overview we decided to not plot an additional curve into Fig 12a. Instead we show the exact same time interval with aligned tic labels in subplot 12b underneath.

As written, we included an additional subplot in Fig 12, that shows the relative nacelle orientation.

345:
Why is the relative yaw angle Psi normalized, and the other angles are not?

For PSI it made sense from a geometrical point of view as if any linear response would be present, it would be destroyed by the left/right and forward/backward symmetry (polar view). For the blade angle it was not necessary as they only go from about 0 to 90°. Still it is questionable (and we raise this point in the paper now) if any linear is present given the complex structure of the blade surface. The blade surface non-linearity is shortly discussed in the revised manuscript (s. also comments by Referee #1).

410:
Ground radars in X (or K) band are used in aviation only as SMR (surface movement radars) or for the pecision approach radar (PAR). Unfortunately, for surveillance or air defense radars in S band, the actual antenna beam widths are much too large to discriminate single WTs at a far distance. Those measurement results, obtained from a similiar measurement campaign, would be really interesting.

We are fine with your comment, and suggest to mention the following here:

Section 4: “The maximum returns are describing a general worst case scenario, which is of interest, for example, to the mostly civilian aviation safety sector when measurements from K- or X-band SMR (surface movement radars) or PAR (precision approach radars) are validated. For the military aviation sector it would also concern radar systems for guidance and surveillance, both for ground-based and airborne systems.”

425:
"... the computational requirements are huge..."

Yes, and be aware of the electromagnetic solvers methods and their limitations (mentioned above).

Yes, for simple user like us, it is not easy to thoroughly understand the limitations behind the necessary assumptions of the various numerical techniques when solving Maxwell equations. For now we try not to go into more detail regarding possible simulation techniques in the current paper.

430:
"Thus dedicated measurement campaigns with e.g. mobile radars offer another approach to assess wind turbine reflectivity and RCS in a broad range of real environmental scenarios"

Yes, this is necessary. As an example, We did that for C band precipitation radar [2].

As written before we would like to cite your interesting study [2] with the C-Band measurements here.

Section 4: We include: “Bredemeyer (2019) used an UAS (unmanned aerial system) as a passive bistatic radar (PBR) at nacelle altitude for reflectivity measurements of a wind turbine in the C-band (5.64 GHz). From short distances below 300 m they got RCS differences of more than 30 dB between WT rotor planes perpendicular and parallel to the PBR.”

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[1] IEEE Std 211-1997: IEEE Standard Definitions of Terms for Radio Wave Propagation. https://ieeexplore.ieee.org/servlet/opac?punumber=5697

[2] J. Bredemeyer, K. Schubert et.al.: "Comparison of principles for measuring the reflectivity values from wind turbines", International Radar Symposium - IRS 2019, Ulm, Germany