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Interactive Comment

Interactive comment on "Performance of high-resolution X-band weather radar networks – the PATTERN example" *by* K. Lengfeld et al.

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Revision of the paper Performance of high-resolution X-band weather radar networks – the PATTERN example by K. Lengfeld, M. Clemens, H. Münster, and F. Ament

Reviewer Comment: This paper presents a network of inexpensive incoherent X-band radars scanning fast and a low elevation angle to provide high resolution rainfall estimate. Networking of X-band radars (non necessarily dual-polarized) has been the subject of many publications in the recent years. To publish a new paper on this subject, very innovative contents must be provided. In this paper some techniques adopted in a network of 4 radars are shown. Main result is maybe the comparison of reconstructed reflectivity field with the corresponding one collected by a C-band radar of the DWD

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network in convenient location for comparison. Result is encouraging.

However, several issues concerning X-band networking, including radome attenuation or the incidence of signal extinction during intense event.

Author's Reply: The influence of the radome itself on reflectivity measurements seems to be small. Due to its cylindrical shape water runs off very quickly in case of a rain event and hardly influences the measurements. This has been added to the section "Radar Network".

Specific attenuation during rain events is in the expected range for X-band frequencies (see Fig. 3.5 in Doviak and Zrnic, 1993). In case of intense events the radar signal can be completely attenuated for single X-band radars. Within the network we have the advantage of observing the rain event from different sides with several radars.

Doviak, R. J. and D. S. Zrnic, 1993: Doppler Radar and Weather Observations. Academic Press, 562 pp.

Reviewer Comment: The dataset is limited to events with Z<40 dBZ which I think is too low to proof the concept

Author's Reply: The datasets includes reflectivities of up to almost 60 dBZ. The color scale in Fig. 8 and 12 is misleading and depicts all reflectivities that occur in less than 5% of the maximum in white. We changed the background color in the two figures, so that reflectivities that occur in less than 5% of the maximum are also visible.

Reviewer Comment: The presented setup uses MRR and rain gauge in addition to radar. It is not clear whether such ancillary systems are required to properly use the radar network.

Author's Reply: The setup described in the paper is designed for scientific purposes. The X-band radars are modified ship navigation radars and have not been used for precipitation observation before. Therefore, the deployment comprises beside the four X-band radars seven MRRs and rain gauges for calibration and quality control. In

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operational use it is possible to apply common adjustment procedures using ground-based precipitation observations by gauges, disdrometers etc. However, we think that vertical profiling instruments, like MRRs, provide an opportunity to compare directly observed reflectivity within a common volume. Here one additional MRR and rain gauge in the area covered by all four radars would be sufficient to run the network and obtain reliable precipitation data.

We added a paragraph about the costs and purposes of the scientific setup described in this paper and the requirements regarding setup for operational use at the end of section “Radar Network”.

Reviewer Comment: In the introduction “LAWR” systems are considered to be in completion with dual-polarization systems at the same frequency. Authors could try to highlight better the advantages of their network with respect dual-polarization systems.

Author’s Reply: The LAWR systems are considered to be completion with dual-polarization systems at different frequencies, e.g. C- or S-band systems. Compared to these systems our X-band radars derive reflectivity measurements in much higher spatial and temporal resolution (60 m in range and 30 s for X-band, 250 m - 1km in range and 5 min for C- or S-band). Another advantage is the lower cost (approx. 60.000 Euro per X-band radar including tower, container and PC unit) that makes these systems valuable for investigating areas of special interest where highly resolved precipitation is required, e.g. in cities. We made this point clearer in the revised manuscript by modifying the introduction and adding a paragraph about the costs at the end of section “Radar Network”.

Reviewer Comment: Summarizing, although encouraging aspects have been noticed, further work (including activities prospected by the authors, particularly those relate to hydrological validation) should be done to reach the level of a publishable paper.

Author’s Reply: We appreciate the comments and thank the reviewer for the helpful suggestions to enhance the quality of the manuscript. We agree that more detailed description of the applied methods is needed and that the advantages of the proposed X-band radar network need to be stated more clearly and did so in the revised manuscript. However, we believe that this more detailed description of the algorithms and methods applied for calibration, clutter detection and the comparison to large scale C-band radar clearly enhances the quality of this paper. To our knowledge, papers about similar X-band radar networks (e.g. Allegretti et al., 2012 and Trabal et al., 2009) describe case studies and not, as in this manuscript, long term comparisons with other radar systems. Also the use of the advantages (high temporal resolution and multiple coverage within the network) for clutter detection has to our knowledge not been statistically investigated. Therefore, we believe that the revised manuscript will provide novel and relevant contributions to the science community. However, hydrological validation is beyond the scope of this paper. The goal is to provide reliable precipitation data (i.e. precipitation estimates that have been validated not only for case studies but over a period of several months) in high temporal and spatial resolution that could serve as input for hydrological models.

Allegretti, M., Bertoldo, S., Prato, A., Lucianaz, C., Rorato, O., Natorpietro, R., and M. Gabella, 2012: X-band mini radar for observing and monitoring rainfall events, Atm. Climate Sci., 2, 290-297.

Trabal, J. M., Colom-Ustariz, J., Cruz-Pol, S, Pablos-Vega, G. A., and D. J. McLaughlin, 2013: Remote Sensing of Weather Hazards Using a Low-Cost and Minimal Infrastructure Off-the-Grid Weather Radar Network., IEEE T. Geosci. Remote, 51, 2541-2555.

Reviewer Comment: Minor issues and inaccuracies found in the paper are listed below:

RC: 8235-3: I was not aware of Einfalt (2003). Interesting is that figures of requirements of rainfall data for specific applications. Often I have heard very vague requirements from hydrologists. Are authors aware of different views within hydrologists? (this is just a point for discussion)

AR: In Einfalt (2003) it is stated that required resolution of precipitation estimates for

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rainfall-runoff simulation is at least 100 m and 1 min. Nevertheless, we know from personal conversations with several hydrologists that the requirements depend on the kind of application. For rural areas coarser resolution (1 km and 5 min) is sufficient because of relatively homogenous landscapes. Another point is that hydrological models often operate with these coarse resolutions. However, in more heterogeneous areas, e.g. cities, higher resolved precipitation estimates are needed.

RC: 8235-18: Bringi et al., 1990 is a highly cited paper, but it is typically for PHIdp-based correction and not for X-band radar.

AR: We cited Bringi et al. (1990) only for the statement that radars operating at higher frequencies are cheaper because of the smaller antenna size. This statement is valid for dual-polarization systems as well as for single polarizations systems. Since this is a well known fact, we removed the reference here.

RC: 8236-24: Describing a dual-polarization system, it seems that authors have a specific one and a specific configuration in mind. I heard about lower-power dual polarization systems. Since price is an issue, what is the saving of a LAWR with respect to a dual-polarization system?

AR: The low power dual-polarization systems are technically based on the same type of radar as the ones used in the PATTERN network. Comparing acquisition price of the "low-cost" X-band radar system of about 60.000 Euros with the conventional X-band radar, it costs less than 20%. This price includes the radar with PC and the tower/container construction (see figure 2b in the paper). We added an estimation about the costs.

RC: 8237-8: "low-cost radar systems are a scientifically valuable tool to investigate spatial structure" From the incipit of the paper, it seems the goal had to be to provide data with high quality and resolution rainfall-runoff applications.

AR: The reviewer is right. We extended the motivation section with regard to this point.

RC: 8237-15: “repitition” -> repetition

AR: Done

RC: 8237-20: I think authors are saying something misleading: “In addition, the X-band radars provide precipitation estimates near the ground (McLaughlin et al., 2009) due to their relatively short maximum range”: actually within the same range, even S band systems using same elevation angle provide estimates close to the ground.

AR: We agree with the reviewer. The small X-band radars can provide precipitation estimates near the ground in areas far away from C- or S-band radar sites. We changed the text according to this point.

RC: 8239-15: Uncertainty in reflectivity estimation due to fluctuation is more than 1 dB. Why reflectivity is provided every 30 seconds and not every sweep? Moreover, how do authors define “resolution”?. To me, azimuth resolution is at least 2.8, not 1.

AR: We agree and corrected the text regarding the resolution. The angular resolution of the radar is 2.8° (according to its antenna beam width). The received signals/reflectivities are averaged over a sequence of transmitted pulses within an angular range of 1°. As the radar is transmitting with a pulse repetition frequency of 800 Hz and the antenna is continuously rotating with an angular velocity of 24 rounds per minute. Therefore, the average is based on about 67 pulses per angular range of 1° and averaging interval of 30 s (5-6 pulses per sweep). We agree that in this context the term “oversampling” is not correct and has been removed.

RC: 8239-18: “Observe”-> measure; this sentence let understand that reflectivity is a path measurement.

AR: Done

RC: 8239-20: Can authors provide a reference or an example of “filtering peaks within adjacent pulses”?

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AR: We use the following speckle filter to eliminate peaks within adjacent pulses: Data of a single pulse at a specific range gate is omitted if it is by 2.5 dBZ larger than both the corresponding measurements at the previous and following pulse. This filter suppresses effectively interferences from other x-band sources. The filter is insensitive with respect to the selection of the threshold, since the disturbing signals are in general very strong. The value of 2.5 dBZ was determined by analyzing raw pulse-to-pulse radar data output and manual detection of artificial signal. This description has been added to describe the peak filtering.

RC: 8240- 22: "inertial guess"? Does this method always find a reliable noise level? Would it be possible to know the stability in time of the noise level of these systems?

AR: It is supposed to be "initial" instead of "inertial" guess. We changed it the revised manuscript. The initial guess is chosen for the very first reflectivity field. It overestimates the expected noise level by approx. a factor of 10. We average noise level over ten pervious time steps (5 minutes) and, therefore, we get valuable noise levels after the first 10 time steps after systems start.

RC: 8241- 14: "Static clutter is caused e.g. by trees and houses": do not forget natural reliefs.

AR: Done

RC: 8241- 16: Signals from other radars are typically referred to as interferences. A more clearer distinction of clutter and the suitability of filtering methods for a specific clutter is suggested.

AR: We agree with the reviewer and distinguished between clutter and interferences more clearly in the revised manuscript and clarified which filter is used for identification of either the one or the other.

RC: 8242-3: "combinig" -> combining

AR: Done

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RC: 8242-24: I had difficulties in understanding the sentence starting with "In some images . . ."

AR: Done

RC: 8243-8: Maybe there is some confusion between beams and gates in explanation of (2).

AR: Done

RC: 8244,end of section: It is not clear to me whether identified cluttered radar cells are reconstructed or not at the end of the process.

AR: We agree that the procedure applied to clutter range gates is not described sufficiently in the paper. We clarified the procedure in the revised manuscript by adding the following paragraph to section "Clutter Detection Algorithm":

Range gates identified and flagged as clutter are removed. Two different approaches were used to fill these gates with information: a) For individual radars, data gaps are filled by using an inverse distance weighting interpolation procedure with a freely selectable area of influence. b) In regions covered by multiple radars within the network, gaps caused by clutter are filled using the information of at least one other radar (averaged information when more than one radar is available).

RC: 8245,calibration with MRR: Several questions: It seems that maximum measured reflectivity is 40 dBZ. Is there a threshold applied or not?

AR: See comment above.

RC: Are differences of frequencies of the two radars accounted for?

AR: Yes, we implemented the following to section "Calibration":

The received signals of the MRR are transformed to drop size distributions (DSDs) using single particle backscattering cross sections that are calculated with Mie theory

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(using the code of Morrison and Cross, 1974). To allow comparisons between MRRs and weather radars, the reflectivity Z is derived from the MRR DSDs using Rayleigh approximation (Peters et al., 2005). For the X-band radar, scattering is assumed to appear mainly as Rayleigh scattering which is a good approximation for light and moderate rainfall. For high rain rates, it is difficult to completely separate the non-Rayleigh scattering effect from the rain attenuation. In this rain intensity range, attenuation by liquid water is of the same order or outweighs non-Rayleigh scattering effects. The good agreement between X- and C-band systems (Fig. 12 in our manuscript) is also found by Barbieri et al. (2014). This confirms the applicability of the Rayleigh approximation for X-band radars.

Barbieri, S., Piciotti, E., Montopoli, M., Di Fabio, S., Lidori, R., Marzano, F., Kalogiros, J., Anagnostou, M., and L. Baldini, 2014: Intercomparison of dual-polarization X-band mini-radar performances with reference radar systems at X and C band in Rome supersite, Proc. of ERAD 2014, Garmisch-Partenkirchen, Germany.

Morrison, J. A., and M. J. Cross, 1974: Scattering of a plane electromagnetic wave by axisymmetric raindrops. Bell Syst. Tech. J., 53, 955-1019.

Peters, G., Fischer, B., Münster, H., Clemens, M., and A. Wagner, 2005: Profiles of Raindrop Size Distributions as Retrieved by Microrain Radars. J. Appl. Meteor., 44, 1930-1949.

RC: Is a 4 dB RMSE acceptable for calibration?

AR: For 30 seconds integration intervals an RMSE of 4 dB is acceptable. The RMSE will become smaller with increasing integration interval. However, the bias is the important parameter for the calibration.

RC: Are MRR data corrected from attenuation?

AR: Yes, attenuation is accounted for according to Peters et al. (2010). We described the procedure briefly in the revised manuscript.

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Peters, G., Fischer, F., and M. Clemens, 2010: Rain Attenuation of Radar Echoes Considering Finite-Range Resolution and Using Drop Size Distributions, J. Meteor. Ocean. Tech., 27, 829-842

RC: 8248,5: Explanation of “oversampling” is not convincing. How can be that grid pixels are not covered by beams that are contiguous. Maybe authors are referring to centers of “radar pixels”.

AR: Yes, the reviewer is right, we refer to centers of radar pixels and changed this in the revised manuscript.

RC: 8248,8: Where do these coefficients comes from (guess they are for X band) and how they are selected based on rain.

AR: The coefficients are used in the C-band radar network of the German Weather service. In order to allow for comparison with the DWD network we applied the same Z-R-relation to the PATTERN network.

RC: 8248,16: What is the elevation angle of the Fuhlsbüttel radar used for this comparison?

AR: We used the precipitation scan of the Fuhlsbüttel radar at 0.7° elevation.

RC: 8248,25: Could authors speculate about the reason of relative bias?

AR: The main reason for this bias is the different resolution of both systems. Maximum reflectivities observed by the high-resolution X-band radar are smoothed by the C-band radar. Different calibration of both systems might be an additional reason for the small bias. We included this in the revised manuscript.

Interactive comment on Atmos. Meas. Tech. Discuss., 7, 8233, 2014.